Priorities for inclusive urban food system transformations in the Global South

Paule Moustier, Michelle Holdsworth, Dao The Anh, Pape Abdoulaye Seck, Henk Renting, Patrick Caron, Nicolas Bricas

Joachim von Braun
Kaosar Afsana
Louise O. Fresco
Mohamed Hag Ali Hassan *Editors*

Science and Innovations for Food Systems Transformation

OPEN ACCESS

Springer

Science and Innovations for Food Systems Transformation

Joachim von Braun • Kaosar Afsana
Louise O. Fresco • Mohamed Hag Ali Hassan
Editors

Science and Innovations for Food Systems Transformation

Springer

Editors
Joachim von Braun
Center for Development Research (ZEF)
University of Bonn
Bonn, Germany

Kaosar Afsana
James P Grant School of Public Health
BRAC University
Dhaka, Bangladesh

Louise O. Fresco
Wageningen University and Research
Wageningen, The Netherlands

Mohamed Hag Ali Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS)
Trieste, Italy

This work was supported by Joachim von Braun

ISBN 978-3-031-15702-8 ISBN 978-3-031-15703-5 (eBook)
https://doi.org/10.1007/978-3-031-15703-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

In December 2019, I received a letter from the United Nations Secretary-General requesting that I lead what he had just put together – the United Nations Secretary-General's Food System Summit 2021. My first thought at the request was that I did not need more work – I had enough on my plate. However, upon further deliberation, I could not help but consider the contradictory views on food and what it means to different people. By taking this role, I might have the opportunity to marshal a global consensus and provide the issue with momentum to generate actions for a clear way forward. I decided that I needed to attend the Summit to ensure that the issues that affect food systems from my part of the world be profiled globally, especially because, while Africa contributes 7% to global climate change, it is most exposed and its populations hit the worst due to poor resilience. I also wanted to ensure that I could bring out the engagement and voices of those most affected. Like the Secretary-General, I believe that the solutions to our challenges are already in our midst, simply needing to be profiled and harnessed for the benefit of all. Therefore, I was thrilled that, in the same letter, the Secretary-General had made it clear that the Summit was going to be anchored in science and that an independent group of the world's best scientific experts were being brought together.

The Scientific Group was thus set up as an independent group of experts under the leadership of Professor Joachim von Braun, a renowned and respected expert in science policy and a policy advisor to governments. A person with deep academic and scientific roots around the world, his work and views on zero hunger and what the world should be doing to come through on its promise by 2030 are very well know. The Vice Chairs of the Scientific Group, Profs. Kaosar Afsana from BRAC University (Bangladesh), Louise O. Fresco from Wageningen University (Netherlands) and Mohamed Hag Ali Hassan from Sudan (World Academy of Sciences), fostered scientific excellence and appropriate diversity in the Group as well.

The Scientific Group began work with a clear mandate: to draw on existing scientific research, collaborate with global science networks, advise the Summit and help the world understand food systems, specifically the status of things, what is at stake and how to go forward from where we are today. At the core of the Summit were the 2030 Agenda and how we get back on track. The Group was charged with ensuring that the Summit was anchored in science, drawing out the challenges of our food systems, and consolidating knowledge as to how to resolve these challenges. In a nutshell, the Scientific Group was to build consensus on the critical drivers for global food systems' transformation, including the priorities we need to implement between now and 2030 to get back on track.

The Scientific Group was composed of 28 experts from across scientific networks of institutions, designed to pull in global expertise and leading scientific views and to bring in views across all groups of society, from indigenous peoples, women, producers and so many more. It was also designed to draw in all of the food systems issues influencing and impacting our world, from people to our planet to the prosperity of both all around the world – all brought together in an intelligent and digestible way. Through rigorous work, open engagement and "Science Days", these experts engaged and consulted widely, and through meetings with other areas of the Summit. They kept abreast of key challenges that the world, societies and governments were concerned about, as informed by hundreds of dialogues, and were on top of the key emerging opportunities and possible practical game-changers through the work of Action Tracks and related peer reviews.

The UN Food Systems Summit Scientific Group dug deeply into their wide institutional networks of expertise, as per their TORS,[1] to bring forth the foremost scientific evidence. They looked at the progress that has been made so far and made recommendations on science-based approaches to achieving SDGs while revealing trade-offs associated with food system transformation. Through the networks of partners from all regions of the world, the Scientific Group brought diverse viewpoints, ensuring the inclusion of a diversity of frameworks and regional voices. The Group linked science-based synthesis to ongoing initiatives under the UN system, including the Committee on World Food Security (CFS) High-Level Panel of Experts, the CGIAR, science-based institutions and many other relevant knowledge institutions, to help advance future food systems.

This volume – a critical product of the Scientific Group – does a number of things, the most important of which is building a consensus on our understanding of food systems. This is particularly important given the breadth of the area under discussion, the diversity of views and interests, the number of other sectors that are impacted and the overall complexity of the food system globally.

The volume then goes on to identify science-driven innovations and opportunities that must be pursued in an integrated manner for a successful transformation of food systems. Here, the Group dwells on the key role of science and research as a prerequisite for innovations that will accelerate the transformation of current food systems to healthier, more sustainable, equitable and resilient systems. The volume also includes a number of chapters by partners of the Group that highlight the most critical areas, information and knowledge in different sectors and the gaps in

[1] The TORs can be found on the website of the Scientific Group here: https://sc-fss2021.org/about-us/tor-and-letters-un-leadership/

knowledge that still exist. The Scientific Group recommends actions that, if implemented, have the potential to transform our food systems. The chapters in this volume further emphasize the complexity of the food systems and a clear direction for the transformation of our food systems with a number of things that can be done together. Throughout this volume, it is clear that there is no one-size-fits-all: while the concepts are similar, the translation of science into policies that inform investments is only possible if placed within the specific context of where the work will be done in a country, in different parts of the world.

I am very proud of the work captured in this volume; most of all, I am grateful that the Scientific Group contributed to what I consider the most important outcome of the Summit – the fact that we have global censuses that our food systems must transform if we are to achieve the 2030 Agenda. Second, I am proud that the Scientific Group mobilized the global science community behind the Summit, from the least heard voices and the least referred-to science that sits with indigenous peoples to the most lucrative science behind big AG. All were brought forward and the opportunities and trade-offs evaluated, ensuring that everybody feels heard, but also that the most important aspects of how we go forward are clear.

As I conclude, I want to bring out the following areas that we must keep our eyes on as we move forward from the Summit to the Hub that will coordinate Summit follow-up and the UN agencies that will help the Hub to keep the world engaged – including tracking of the Summit's commitments. These are the need to: strengthen national capacities for implementation, especially in emerging economies, develop a clear financial agenda for investments needed to address increasing hunger, but also the overall 2030 Agenda; and better coordinate and advance institutional innovations that can improve the science, such as policy interfaces to enhance implementation in countries and better global level networked science services. Lastly, there is a need to facilitate stronger synergies of food system actions with other key areas, including climate policy, Covid-19-related policies, trade policies, conflict policies and related food price inflation that will exclude even more people from accessing the right level of nutrition and, at worst, leave them with no food at all.

The work and contribution of the Scientific Group of the Summit have provided incredible direction on how we move forward from here. There will always be need for new insights, and there will always be a need to sharpen the science/policy/action interface, but, for now I am incredibly grateful that through this volume the Scientific Group gives us the steering wheel that we need to move forward towards a food systems approach that could get us back on the 2030 Agenda, on food, health and diets, environment and the prosperity of people and the planet.

The UN Secretary-General's Special Envoy for the United Nations Food Systems Summit 2021
New York, NY, USA

Agnes M. Kalibata

The Approach of the UNFSS Scientific Group and an Overview of the Volume

The Scientific Group's Design and Approach

In April 2020, the Deputy Secretary-General of the United Nations invited Joachim von Braun to chair the Scientific Group for the UN Food Systems Summit. The mandate was as follows: "The Scientific Group is responsible for ensuring that the Summit brings to bear the foremost scientific evidence from around the world and helps expand the base of shared knowledge about experiences, approaches, and tools for driving sustainable food systems that will inform the future. The work of the Scientific Group ensures the robustness and independence of the science underpinning dialogue of food systems policy and investment decisions. It also informs the content of the Summit, its recommended outcomes, and the asks and commitments that emerge from the Summit."[2] It was new for a UN Food Summit to establish an independent Scientific Group with such a significant mandate.

The Scientific Group (ScGroup) constituted a team of 28 food systems scientists – social scientists, economists and scientists working within the natural and biological sciences, ecology and food technology – from all over the world, identified in consultation with research organizations.[3] They served in their personal capacities. ScGroup members developed a series of original scientific papers, which were peer-reviewed and scrutinized by governments, civil societies and members of the general public.[4] The inclusive approach of the ScGroup resulted in the earlier drafts of the chapters of this volume being widely distributed as inputs in preparation for the Summit. In addition, diverse viewpoints were sought from wide networks of partners of the ScGroup from all regions of the world.[5] These research partners were selected

[2] See https://sc-fss2021.org/wp-content/uploads/2020/11/Terms_of_Reference_web.pdf

[3] https://sc-fss2021.org/about-us/membership/

[4] https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/

[5] The Science Reader for the UNFSS: https://sc-fss2021.org/wp-content/uploads/2021/09/ScGroup_Reader_UNFSS2021.pdf

based on their commitment to scientific research and diversity of knowledge frameworks and regional coverage. They included academic and research institutions, policy think-tanks, UN agencies, academies of science, indigenous peoples' knowledge communities, private-sector research and advocacy organizations.[6] ScGroup members, along with other independent experts, served as commentators and reviewers of the contributions from the partners.

This volume compiles the findings of the ScGroup and its partners. The chapters have been further edited in the wake of the Summit. The chapters culminate the fulfillment of the ScGroup's mandate and provide science- and research-based, state-of-the-art, solution-oriented knowledge and evidence to inform the transformation of contemporary food systems in order to achieve more sustainable, equitable and resilient systems.

Volume Overview

This volume is divided into seven sections. While it is organized by key themes, the interdependence of food, health and environment systems is recognized, an interdependence vital for identifying innovations – technological, political, social and institutional – that can help to synergistically achieve multiple SDGs and end hunger by 2030.

Part I, on Food System Concepts and Summarized Recommendations, presents seven priorities for accelerating the transformation to healthier, more sustainable, equitable and resilient food systems. These are: (i) end hunger and improve diets; (ii) de-risk food systems; (iii) protect equality and rights; (iv) boost bioscience; (v) protect resources; (vi) sustain aquatic foods; and (vii) harness digital technology. This section also includes a key contribution by the ScGroup concerning sharpening food systems concepts and definitions so that these concepts are better understood when we make calls for food system transformation.

Part II deals with Actions on Hunger and Healthy Diets. The section begins with a definition of a healthy diet. It was an important, but not straight-forward, task to arrive at a widely accepted definition of healthy diets in the context of a world with many diverse food systems and cultures of dietary patterns. Also, concepts of sustainable and healthy diets were elaborated and remain themes under discussion. This section also focuses on zero hunger. Approaches for ensuring access to safe and nutritious food are explored, highlighting the need for a whole-system approach in policy and research, as well as monitoring and evaluating to manage externalities. The critical importance of comprehensive modeling of the synergies and trade-offs of policy actions is demonstrated. Solutions for enabling the shift to healthy and sustainable consumption are offered, including behavior change interventions, food education, improved product design, investments in food system innovations,

[6] https://sc-fss2021.org/community/partners/

regulatory regimes for food safety and more. Both the public and private sectors have important roles in responding to and shaping the market opportunities created by changing consumer demands. Attention is paid to the role of fruits and vegetables in healthy diets, and priorities for research and action are identified.

Part III delves into Actions for Equity and Resilience in Food Systems. This section discusses the various types of inequalities persistent within food systems and identifies key drivers of said inequalities. The increased inequalities at the national and also, recently, global levels are noted as major concerns for equitable food systems. Noting that the most effective way to sustainably eradicate poverty and inequality is to boost the opportunities and capacities of the poor and those living in situations of vulnerability, a wide range of actions are explored in the chapters to enhance inclusive decision-making, protect the livelihoods of those living in situations of vulnerability while creating opportunities and design policies and institutions to support equitable food system livelihoods. Opportunities for gender equality and women's empowerment are prominently discussed, as are opportunities for engagement and empowerment of youths. The future of small farms is prominently considered, and it is emphasized that food system transformation must serve smallholders and not leave them behind. Indigenous peoples' food systems received high attention from the ScGroup, and the enhanced cooperation between indigenous people's knowledge community and the scientific community is a real achievement of the UNFSS. The specific challenges faced by indigenous communities and their priorities for action are highlighted in a contribution in this section. Novel approaches to urban food systems' transformation in the emerging economies, including the role of secondary cities, are discussed. Foreign policy and security policy dimensions of food system failures are considered, because both the pathways to food insecurity from violent conflicts and those from armed conflicts to food crises have become much more prevalent in recent decades. The fundamental need to enhance food systems' resilience to vulnerabilities, shocks and stresses is addressed and different options for diversification are offered.

Part IV focuses on Actions for Sustainable Food Production and Resource Management. Chapters in this section explore the diversity of technological, institutional and policy innovations and actions for transforming the current "nature negative" food systems into ones that are "nature positive" in order to conserve, protect and regenerate natural resources and the natural environment, including biodiversity, through "nature positive" landscape-level interventions and agroecological practices. While important advances have been made in delineating pathways for agroecology to contribute to sustainable food systems, it is clear that much more research and dialogue is needed. The call for more research and dialogue also applies to issues of sustainable livestock production and animal-based foods. Relatedly, there is a growing understanding that food systems are not simply or only terrestrial systems and that efforts must be scaled up to embrace aquatic food systems so as to assure their sustainability and resilience as well. Climate resilience and climate mitigation were key topics that were widely accepted during the UNFSS process, and their key roles in food system transformation are addressed in various chapters. Similarly, the role of water, especially scarcity and water pollution, is tackled. It is recognized that the integration of biodiversity into agriculture and holistic approaches to plant nutrition that consider its hidden costs are integral to improving health, eliminating hunger and reducing negative environmental impact. The reduction of food loss and waste is confronted, and it is clear that action is needed for incentives and behavior change that will cut food waste and technologies that will cut food loss.

Part V discusses Costs, Investments, Finance and Trade Actions. This section begins with a chapter that advances our understanding of the true cost of food – reflecting the environmental and health-related costs of food. The emerging tragedy in the efforts around food system transformation is the extraordinarily high true cost of producing and processing food, estimated at about $30 trillion, compared to the relatively low cost of overcoming hunger, estimated at about $50 billion a year. An accompanying chapter assesses the cost and affordability of a basic meal around the world. Innovative financing solutions are offered to support the investments needed for achieving the SDG2 goals and ending hunger, and it is disappointing that they did not make it into the UNFSS action agenda. Similarly, important trade issues and trade policies that can complement countries' national policies for sustainable food systems are presented but were not taken up in the UNFSS action agenda.

Part VI shares Regional Perspectives. Chapters in this section show the great diversity in food systems around the world and indicate that follow-up actions for transforming food systems will need to be equally diverse. Chapters examine the opportunities for science, technologies, policies and innovations to transform food systems in Africa, Asia, Europe, Latin America and the Caribbean, as well as in large countries such as China, India and Russia. It is clear that there is much to learn, adapt and innovate from experiences within and across countries and regions, and there is an important opportunity for knowledge communities and networks to share experiences and insights in the follow-up to the UN Food Systems Summit.

Part VII concludes by addressing Strategic Perspectives and Governance. This section sets the stage for a broad review of the role of science, technology and innovation in transforming food systems around the world. The multidimensional concept of bioeconomy for the transformation of food systems is examined for its potentials and opportunities. Recognizing the extraordinary impacts of Covid-19, the links between global food security and "One Health" – the inter-connectedness of the health of people, animals, plants, soils, water and the environment – are discussed. It is widely acknowledged that science and policy will face challenges in regard to food system transformations at the global and national levels. Science-policy interfaces for transforming food systems emerged as a contentious topic during the UNFSS preparations – including what type of interface at what level – national or international – and whether existing interfaces are sufficient or new interfaces are needed. Another chapter details the key steps needed to transition and transform our food systems. The penultimate chapter of the section, and of this volume, reiterates the calls for exploring options for a global science-policy interface on food systems. It makes clear that the implementation of the Action Agenda of the UN Food Systems Summit and the transformation of food systems calls for enhancing countries' local science and research capacities. The final chapter of the volume presents three key opportunities for science to transform food systems: (i) strengthen research cooperation between scientific communities and indigenous peoples' knowledge communities, (ii) expand financing within governments to spend at least 1% of food system GDP on food system science, and (iii) establish pathways towards strong science-policy interfaces networked across national and international levels to enable evidence-based follow-ups to the action agendas established at the Summit.

The over-arching conclusion of this volume is that the global food system needs a revamp – in policies and institutions, as well as on the social, industrial and technological fronts.

Successes of the UN Food Systems Summit and Attention to Unfinished Business

It was a bold decision by the UN leadership to unleash a multi-stakeholder process, as well as invite an independent Scientific Group to mobilize science communities around the world to advise the Summit agenda with science-based evidence. The scientific and knowledge communities welcomed this move by the UN and have become energized to address complex food system problems with a renewed commitment to identify solutions.

The ScGroup considers the UN Food Systems Summit a success, but there is also unfinished business. When benchmarking against earlier summits, five promising outcomes are highlighted: (i) *political and societal engagement* – the Summit was much more inclusive and mobilized nations and stakeholders with multiple dialogue formats – never before has the world discussed and considered food system issues with attention to nutrition, health, ecology, and much more[7]; (ii) *scientific engagement* – also never before has science had the opportunity to contribute in so many ways to the agenda of a food summit – open debate and action orientation mobilized many academies of science, research organizations, academics and practitioners; (iii) *action agenda* – the UN Secretary-General's statement of action, with its systems focus, and the five action areas to help inform the transitions needed to realize the vision of the 2030 agenda are noteworthy; (iv) *national level input and implementation* were appropriately emphasized; and (v) *significant global initiatives* on tackling hunger, healthy diets, anemia in women, agroecology, soil health, oceans and more were launched.

Yet, there are some important areas that require further attention in the future: (i) *strengthening the capacities* for implementation of actions at the national level, especially in emerging economies, is essential – this is an area for stakeholders to get together and catalyze the necessary actions, and scientific bodies can assist; (ii) *developing a strong finance agenda* for the investments needed to achieve the end of hunger and other key targets is important – the financial proposals, including

[7] See the Food Systems Summit Dialogues https://summitdialogues.org/

those from the ScGroup, did not find sufficient resonance, and other approaches are needed; (iii) encouraging institutional innovations and enhanced coordination for an *improved science – policy interface* at the global level that is well networked with regional and national interfaces remains critical; and (iv) facilitating strong global level actions in key areas such as *climate, Covid-19, and trade*, to accompany national level actions and implementation, is necessary, as is addressing emerging food price inflation.

This volume has been assembled to inform the way forward on the transformation of global food systems beyond the UN Food Systems Summit and to show how science can and must contribute to the transformation of food systems in order to end hunger and achieve the UN Sustainable Development Goals by 2030.

Center for Development Research (ZEF) Joachim von Braun
University of Bonn
Bonn, Germany

Acknowledgements

We begin by expressing our appreciation to the United Nations Leadership for convening the Scientific Group for the United Nations Food Systems Summit, and thereby elevating the role of science in underpinning the dialogues, policies, and investment decisions that have emerged from the Summit. We are especially grateful to Deputy Secretary-General Amina Mohammed and to Special Envoy Agnes Kalibata and their excellent teams for their strong commitment to and continued encouragement and support for robust and independent scientific evidence and knowledge.

We warmly thank all the members of the Scientific Group for their extraordinary contributions in bringing the foremost scientific evidence from around the world. The Scientific Group constituted a team of 28 food systems scientists – social scientists, economists and scientists working within the natural and biological sciences, ecology and food technology – from all parts of the world. From July 2020 through December 2021, the Scientific Group held 14 meetings to plan, discuss and review its submissions to the Summit.[8] Members of the Scientific Group developed a series of original scientific papers, as well as undertaking peer reviews of papers contributed by partners, and they participated in *Science Days* and other important events in the lead-up to the Summit and during the Summit itself.[9]

We gratefully acknowledge the more than 40 global research partners who delivered science- and evidence-based, policy-focused research briefs covering a wide spectrum of food systems-related thematic areas, which are collected in this volume. These research partners included academic and research institutions, the CGIAR Centers, including the International Food Policy Research Institute (IFPRI), Indigenous Peoples' knowledge networks, policy think-tanks, UN agencies,

[8]For the list of membership of the Scientific Group, see https://sc-fss2021.org/about-us/membership/. The minutes of all meetings are public, see: https://sc-fss2021.org/materials/scientific-group-reports-and-briefs/

[9]For the list of papers by the partners of the Scientific Group, see https://sc-fss2021.org/wp-content/uploads/2021/07/FSS_ScG_Briefs_draft_list_20-7-2021.pdf

academies of science and private-sector research and advocacy organizations. Many of them also organized side events around *Science Days*, drawing attention to important emerging issues.[10]

The Scientific Group valued transparency, as well as peer review and peer culture. We thank Mahendra Dev, Zhu Jing, Per Pinstrup-Andersen, Pauline Scheelbeek and Moctar Toure for their peer reviews of the Scientific Group's own papers, and we thank the many other anonymous reviewers for their peer reviews of the partners' papers.

Science Days, held on July 8–9, 2021, was organized by the Scientific Group and facilitated and hosted by FAO with about 3,000 participants. Acknowledging the importance of concerns about inclusiveness, the Scientific Group has aimed at broad inclusiveness throughout, including at Science Days, to make sure all perspectives were heard. We are indebted to FAO Chief Scientist Ismahane Elouafi and her team, especially Preet Lidder and Florian Doerr for their excellent collaboration with this important event.[11]

Colleagues at the Center for Development Research (ZEF) at the University of Bonn provided exceptional support to the Scientific Group throughout its term, from administrative support to research support, communications support, website support and event organization support. We would like to particularly thank Heike Baumüller, Paula Rothenberger, Niklas Müller and Yesim Pacal. We thank Anja Köhler at ZEF for developing the great Scientific Group website https://sc-fss2021.org/ that served us all, and that will be maintained.

Finally, we thank Rajul Pandya-Lorch for background writing, research and communications support, and Sundus Saleemi at ZEF for splendid research support of the Scientific Group throughout the Food Systems Summit processes and for management of partnerships and supporting the editorial processes of this volume. Funding support for the team at ZEF by the German Federal Ministry for Economic Cooperation and Development is gratefully acknowledged.

Co-editors of the Volume and Former Chair and Vice Chairs of the Scientific Group for the UN Food Systems Summit

Joachim von Braun
Kaosar Afsana
Louise O. Fresco
Mohamed Hag Ali Hassan

[10] See the authors and co-authors of these chapters at https://sc-fss2021.org/materials/fss-briefs-by-partners-of-scientific-group/ and the list of partners of the Scientific Group at https://sc-fss2021.org/community/partners/.

[11] For more on Science Days, see: https://sc-fss2021.org/events/sciencedays/

Contents

Part I Food System Concept and Summarized Recommendations

Food Systems: Seven Priorities to End Hunger and Protect the Planet 3
Joachim von Braun, Kaosar Afsana, Louise O. Fresco, and Mohamed Hag Ali Hassan

Food System Concepts and Definitions for Science and Political Action 11
Joachim von Braun, Kaosar Afsana, Louise O. Fresco, Mohamed Hag Ali Hassan, and Maximo Torero

Part II Actions on Hunger and Healthy Diets

Healthy Diet: A Definition for the United Nations Food Systems Summit 2021 21
Lynnette M. Neufeld, Sheryl Hendriks, and Marta Hugas

Ensuring Access to Safe and Nutritious Food for All Through the Transformation of Food Systems 31
Sheryl Hendriks, Jean-François Soussana, Martin Cole, Andrew Kambugu, and David Zilberman

A Shift to Healthy and Sustainable Consumption Patterns 59
Mario Herrero, Marta Hugas, Uma Lele, Aman Wirakartakusumah, and Maximo Torero

Fruits and Vegetables for Healthy Diets: Priorities for Food System Research and Action 87
Jody Harris, Bart de Steenhuijsen Piters, Stepha McMullin, Babar Bajwa, Ilse de Jager, and Inge D. Brouwer

Modeling Actions for Transforming Agrifood Systems 105
David Laborde and Maximo Torero

Part III Actions for Equity and Resilience in Food Systems

Advance Equitable Livelihoods 135
Lynnette M. Neufeld, Jikun Huang, Ousmane Badiane, Patrick Caron, and Lisa Sennerby Forsse

A Review of Evidence on Gender Equality, Women's Empowerment, and Food Systems 165
Jemimah Njuki, Sarah Eissler, Hazel Malapit, Ruth Meinzen-Dick, Elizabeth Bryan, and Agnes Quisumbing

The Future of Small Farms: Innovations for Inclusive Transformation 191
Xinshen Diao, Thomas Reardon, Adam Kennedy, Ruth S. DeFries, Jawoo Koo, Bart Minten, Hiroyuki Takeshima, and Philip Thornton

Diversification for Enhanced Food Systems Resilience 207
Thomas Hertel, Ismahane Elouafi, Morakot Tanticharoen, and Frank Ewert

Addressing Food Crises in Violent Conflicts 217
Birgit Kemmerling, Conrad Schetter, and Lars Wirkus

In Brief: The White/Wiphala Paper on Indigenous Peoples' Food Systems 229
Pablo Arigita Baena, Anne Brunel, Yon Fernández-de-Larrinoa, Tania Eulalia Martinez-Cruz, Charlotte Milbank, and Mikaila Way

Marginal Areas and Indigenous People Priorities for Research and Action 261
Sayed Azam-Ali, Hayatullah Ahmadzai, Dhrupad Choudhury, Ee Von Goh, Ebrahim Jahanshiri, Tafadzwanashe Mabhaudhi, Alessandro Meschinelli, Albert Thembinkosi Modi, Nhamo Nhamo, and Abidemi Olutayo

Priorities for Inclusive Urban Food System Transformations in the Global South 281
Paule Moustier, Michelle Holdsworth, Dao The Anh, Pape Abdoulaye Seck, Henk Renting, Patrick Caron, and Nicolas Bricas

Secondary Cities as Catalysts for Nutritious Diets in Low- and Middle-Income Countries 305
Kesso Gabrielle van Zutphen, Dominique Barjolle, Sophie van den Berg, Breda Gavin-Smith, Klaus Kraemer, Capucine Musard, Helen Prytherch, Johan Six, Simon Winter, and Kris Woltering

Part IV Actions for Sustainable Food Production and Resource Management

Boost Nature-Positive Production 319
Elizabeth Hodson de Jaramillo, Urs Niggli, Kaoru Kitajima, Rattan Lal, and Claudia Sadoff

Pathways to Advance Agroecology for a Successful Transformation to Sustainable Food Systems 341
Urs Niggli, Martijn Sonnevelt, and Susanne Kummer

A New Paradigm for Plant Nutrition 361
Achim Dobermann, Tom Bruulsema, Ismail Cakmak, Bruno Gerard, Kaushik Majumdar, Michael McLaughlin, Pytrik Reidsma, Bernard Vanlauwe, Eva Wollenberg, Fusuo Zhang, and Xin Zhang

Livestock and Sustainable Food Systems: Status, Trends, and Priority Actions 375
Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen, Ty Beal, Carlos Gonzalez, and Margaret Gill

The Vital Roles of Blue Foods in the Global Food System 401
Jim Leape, Fiorenza Micheli, Michelle Tigchelaar, Edward H. Allison, Xavier Basurto, Abigail Bennett, Simon R. Bush, Ling Cao, Beatrice Crona, Fabrice DeClerck, Jessica Fanzo, Stefan Gelcich, Jessica A. Gephart, Christopher D. Golden, Christina C. Hicks, Avinash Kishore, J. Zachary Koehn, David C. Little, Rosamond L. Naylor, Elizabeth R. Selig, Rebecca E. Short, U. Rashid Sumaila, Shakuntala H. Thilsted, Max Troell, and Colette C. C. Wabnitz

Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation 421
Rui Benfica, Judith Chambers, Jawoo Koo, Alejandro Nin-Pratt, José Falck-Zepeda, Gert-Jan Stads, and Channing Arndt

Leveraging Data, Models & Farming Innovation to Prevent, Prepare for & Manage Pest Incursions: Delivering a Pest Risk Service for Low-Income Countries 439
Bryony Taylor, Henri Edouard Zefack Tonnang, Tim Beale, William Holland, MaryLucy Oronje, Elfatih Mohamed Abdel-Rahman, David Onyango, Cambria Finegold, Jessica Zhu, Stefania Pozzi, and Sean T. Murphy

Food Systems Innovation Hubs in Low- and Middle-Income Countries 455
Kalpana Beesabathuni, Klaus Kraemer, Sufia Askari, Srujith Lingala, Madhavika Bajoria, Martin Bloem, Breda Gavin-Smith, Hamid Hamirani, Priyanka Kumari, Anne Milan, Puja Tshering, Kesso Gabrielle van Zutphen, and Kris Woltering

A Whole Earth Approach to Nature-Positive Food: Biodiversity and Agriculture 469
Fabrice A. J. DeClerck, Izabella Koziell, Tim Benton, Lucas A. Garibaldi, Claire Kremen, Martine Maron, Cristina Rumbaitis Del Rio, Aman Sidhu, Jonathan Wirths, Michael Clark, Chris Dickens, Natalia Estrada Carmona, Alexander K. Fremier, Sarah K. Jones, Colin K. Khoury, Rattan Lal, Michael Obersteiner, Roseline Remans, Adrien Rusch, Lisa A. Schulte, Jeremy Simmonds, Lindsay C. Stringer, Christopher Weber, and Leigh Winowiecki

Water for Food Systems and Nutrition 497
Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J. V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva, and Stefan Uhlenbrook

Climate Change and Food Systems 511
Alisher Mirzabaev, Lennart Olsson, Rachel Bezner Kerr, Prajal Pradhan, Marta Guadalupe Rivera Ferre, and Hermann Lotze-Campen

Delivering Climate Change Outcomes with Agroecology in Low- and Middle-Income Countries: Evidence and Actions Needed 531
Sieglinde Snapp, Yodit Kebede, Eva Wollenberg, Kyle M. Dittmer, Sarah Brickman, Cecelia Egler, and Sadie Shelton

Crop Diversity, Its Conservation and Use for Better Food Systems 545
Stefan Schmitz, Rodrigo Barrios, Hannes Dempewolf, Luigi Guarino, Charlotte Lusty, and Janet Muir

Safeguarding and Using Fruit and Vegetable Biodiversity 553
Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, and Luigi Guarino

Reduction of Food Loss and Waste: The Challenges and Conclusions for Actions 569
Joachim von Braun, M. Sanchéz Sorondo, and Roy Steiner

Part V Costs, Investment, Finance, and Trade Actions

The True Cost of Food: A Preliminary Assessment 581
Sheryl Hendriks, Adrian de Groot Ruiz, Mario Herrero Acosta, Hans Baumers, Pietro Galgani, Daniel Mason-D'Croz, Cecile Godde, Katharina Waha, Dimitra Kanidou, Joachim von Braun, Mauricio Benitez, Jennifer Blanke, Patrick Caron, Jessica Fanzo, Friederike Greb, Lawrence Haddad, Anna Herforth, Danie Jordaan, William Masters, Claudia Sadoff, Jean-François Soussana, Maria Cristina Tirado, Maximo Torero, and Matthew Watkins

The Cost and Affordability of Preparing a Basic Meal Around the World 603
William A. Masters, Elena M. Martinez, Friederike Greb, Anna Herforth, and Sheryl L. Hendriks

The Global Cost of Reaching a World Without Hunger: Investment Costs and Policy Action Opportunities 625
Bezawit Beyene Chichaibelu, Maksud Bekchanov, Joachim von Braun, and Maximo Torero

Financing SDG2 and Ending Hunger 661
Eugenio Díaz-Bonilla

Trade and Sustainable Food Systems 685
Andrea Zimmermann and George Rapsomanikis

Part VI Regional Perspectives

Policy Options for Food System Transformation in Africa and the Role of Science, Technology and Innovation 713
Ousmane Badiane, Sheryl L. Hendriks, Katrin Glatzel, Fadi Abdelradi, Assefa Admassie, John Asafu Adjaye, Miltone Ayieko, Endashaw Bekele, Thameur Chaibi, Mohamed Hag Ali Hassan, Mame Samba Mbaye, Fatima Ezzahra Mengoub, Douglas W. Miano, John H. Muyonga, Tolulope Olofinbiyi, Racha Ramadan, and Simbarashe Sibanda

The Role of Science, Technology and Innovation for Transforming Food Systems in Latin America and the Caribbean 737
Elizabeth Hodson de Jaramillo, Eduardo J. Trigo, and Rosario Campos

The Role of Science, Technology, and Innovation for Transforming Food Systems in Asia 751
Paul J. Moughan, Daniel A. Chamovitz, S. Ayyappan, Morakot Tanticharoen, Krishan Lal, and Yoo Hang Kim

The Role of Science, Technology, and Innovation for Transforming Food Systems in Europe 763
Claudia Canales and Robin Fears

Transforming Chinese Food Systems for Both Human and Planetary Health 779
Shenggen Fan, Jikun Huang, Fusuo Zhang, Wenhua Zhao, Hongyuan Song, Fengying Nie, Yu Sheng, Jinxia Wang, Jieying Bi, and Wenfeng Cong

Key Areas of the Agricultural Science Development in Russia in the Context of Global Trends and Challenges 799
Nadezhda Orlova, Evgenia Serova, Vladimir Popov, and Marina Petukhova

Food System in India. Challenges, Performance and Promise 813
Ashok Gulati, Raj Paroda, Sanjiv Puri, D. Narain, and Anil Ghanwat

Part VII Strategic Perspectives and Governance

The Role of Science, Technology and Innovation in Transforming Food Systems Globally 831
Robin Fears and Claudia Canales

The Bioeconomy and Food System Transformation 849
Eduardo Trigo, Hugo Chavarria, Carl Pray, Stuart J. Smyth, Agustin Torroba, Justus Wesseler, David Zilberman, and Juan F. Martinez

In the Age of Pandemics, Connecting Food Systems and Health: A Global One Health Approach 869
Gebbiena M. Bron, J. Joukje Siebenga, and Louise O. Fresco

How Could Science–Policy Interfaces Boost Food System Transformation? 877
Etienne Hainzelin, Patrick Caron, Frank Place, Arlène Alpha, Sandrine Dury, Ruben Echeverria, and Amanda Harding

The Transition Steps Needed to Transform Our Food Systems 893
Patrick Webb, Derek J. Flynn, Niamh M. Kelly, and Sandy M. Thomas

Engaging Science in Food System Transformation: Toward Implementation of the Action Agenda of the United Nations Food Systems Summit 909
Joachim von Braun

Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit 921
Joachim von Braun, Kaosar Afsana, Louise O. Fresco, and Mohamed Hag Ali Hassan

Part I
Food System Concept and Summarized Recommendations

Food Systems: Seven Priorities to End Hunger and Protect the Planet

Joachim von Braun, Kaosar Afsana, Louise O. Fresco, and Mohamed Hag Ali Hassan

The world's food system is in disarray. One in ten people is undernourished. One in four is overweight. Almost half the world's population cannot afford a healthy diet. Food supplies are disrupted by heatwaves, floods, droughts and wars. The number of people going hungry in 2020 was 13% higher than in 2019 owing to the COVID-19 pandemic and armed conflicts. (FAO, IFAD, UNICEF, WFP and WHO 2021).

The planet suffers too. The food sector emits about 30% of the world's greenhouse gases. Expanding cropland, pastures and tree plantations drive two thirds (5.5 Million ha per year) of the loss in forests, mostly in the tropics (Pendrill et al. 2019). Poor farming practices degrade soils, pollute and deplete water supplies, and lower biodiversity.

As these interlinkages become clear, approaches to food are shifting – away from production, consumption and value chains toward safety, networks and complexity. Recent crises around global warming and COVID-19 have compounded concerns. Policymakers have taken note.

In September, the UN Secretary General will convene a Food Systems Summit. This is only the 6th UN summit on food since 1943 and the first with heads of states in the UN General Assembly. A group of leading scientists has been tasked with ensuring the science underpinning the 2021 Summit is robust, broad and independent – we write as its chair and co-chairs. While such approaches are familiar

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

K. Afsana
James P Grant School of Public Health, BRAC University, Dhaka, Bangladesh

L. O. Fresco
Wageningen University and Research, Wageningen, The Netherlands

M. H. A. Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), Trieste, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_1

in other areas like climate change and biodiversity, this marks the first time scientists have been explicitly brought in to multilateral discussions around food (Nature Editorial Board 2021).

The global food system needs a revamp – in policies and institutions as well as on social, business and technology fronts (OECD 2021). Science is one lens for making sure that changes are integrated and add collectively to deliver better outcomes. But it is challenging. Food spans many disciplines – not least agriculture, health, climate science, AI and digital science, political science and economics. The indirect effects of policies on climate change, biodiversity loss and adverse health effects need to be factored in to the true costs of food; these could triple **<yes?]** the current global value attributed to food markets (Hendriks et al. 2021). A range of voices is vital. The Scientific Group is engaging with hundreds of experts, across civil society, indigenous peoples, producer organizations, youth organizations and the private sectors.

Here we highlight key roles scientists should play to accelerate the transformation to healthier, more sustainable, equitable and resilient food systems. These seven priorities reflect the Scientific Group's evidence base, comprising more than 40 reports and briefs (see https://sc-fss2021.org/materials/fss-briefs-by-partners-of-scientific-group/).

1 Seven Priorities

Science-driven advances are needed in the following areas.

1.1 End Hunger and Improve Diets

Scientists need to identify optimal conditions and investment opportunities to make healthy and nutritious foods more available, affordable and accessible. Measures that do all three are most effective in cutting hunger and improving diets. For example, improving irrigation on small farms in Tanzania and Ethiopia has enhanced productivity, lowered prices for consumers and increased farmers' income (Passarelli et al. 2018).

Three big game changers are: enhancing research and development (R&D) in agriculture and food to increase productivity sustainably, adding income and nutrition components to social protection programs, and slashing food waste and losses. Research priorities include powering fridges and preserving plants with solar energy. Developing new forms of packaging using recycled materials, coatings of nanomaterials and even edible films, would keep foods fresh for longer and reduce losses. School feeding programs offering nutritious meals for students, plus incentives like take home rations for parents to keep children in education, have increased school participation in Mali by 10% (Aurino et al. 2019). Under Covid-19 lockdowns these programs become even more relevant, as in Addis Ababa schools.

Researchers also need to study behavioral barriers to healthy eating, such as snacking under stress. They should develop policy guidelines for educational food labels and taxes and regulations on unhealthy foods (such as sugar, trans-fats and high-fructose corn syrup). The health properties of fortified foods and cultivated meats need establishing.

1.2 De-risk Food Systems

The more global, dynamic and complex food systems become, the more they are open to novel risks. Scientists need to better understand, monitor, analyze and communicate such vulnerabilities. For example, droughts, biofuels expansion and financial speculation after the sudden imposition of trade barriers led to food price hikes in 2008 (Kalkuhl et al. 2016). The COVID-19 pandemic and armed conflicts have shaken food value chains across Africa this year, driving up food prices. Successful initiatives combining on the ground observations of food systems and nutrition with forecasting include FEWS NET (https://fews.net/) and the joint FAO-World Food Program Early Warning System (https://www.wfp.org/publications/fao-wfp-early-warning-analysis-acute-food-insecurity-hotspots).

Policies and economic solutions are needed. For example, novel insurance products facilitated by remote sensing and weather forecasts would provide cover for lost crops and livestock. Solar powered irrigation systems would reduce risk from drought. Smart-phone apps would provide farmers with information on local crop pests, weather risks and market opportunities; these are already used in Kenya, Senegal, India and Bangladesh (Baumüller 2017). Payment schemes are needed to encourage farmers to manage and capture carbon in soils and trees and trade it.

1.3 Protect Equality and Rights

Poverty and inequalities associated with gender, ethnicity and age restrict many people's access to healthy foods. Socio-economic researchers need to suggest inclusive ways to transform more than 400 million smallholder farms. They must identify pathways out of inequitable and unfair arrangements over land, credit and labor and empower the rights of women and youth. For example, if female-headed households in Southern Ethiopia had same resources as male-headed ones, their productivity in maize would increase by 40%, to match that of the latter (Gebre et al. 2021).

Protecting the land rights of smallholders, women and indigenous peoples is paramount. Technology can ensure transparency and efficiency. For example, Ghana uses Blockchain ledgers of land use and ownership rights for allocating land (Mintah et al. 2021). At the trans-national scale the Land Matrix Initiative (https://landmatrix.org/) collects and shares data on big land acquisitions and investments, covering almost 100 countries. Similar solutions are needed to protect the land rights of

Indigenous Peoples (see http://www.fao.org/publications/card/fr/c/CB4932EN/). Efforts to build local research capacity, educational programs around food and farming, as well as training and financing opportunities in rural areas are needed.

1.4 Boost Bioscience

Researchers need to find ways to restore soil health and improve the efficiency of cropping, breeding of crops, and re-carbonizing the biosphere. Linkages among all Earth systems must be considered together – a One Health approach.

Alternative sources of healthy protein need to be advanced, including more plant-based and insect-derived proteins, including for animal feed. Plant breeding techniques that capture nitrogen from the air, to reduce the need for fertilizers and increase nutrients, should be investigated. Genetic engineering and biotechnology should be applied to increase productivity, quality and pest and drought resistance of crops; recent examples include varieties of bananas resistant to Fusarium Wilt diseases, and pest-resistant BT eggplants. Property rights, skills and data-sharing should be addressed, to widen access to bioscience technologies.

1.5 Protect Resources

Tools are needed to help people manage soils, land and water sustainably. For example, hand-held digital devices and remote sensing can track concentrations of soil carbon and other nutrients. AI and drones allow farmers to spot areas that need irrigation, fertilization and pest control. Soil microbes can be harnessed to improve soil structure, ability to store carbon and yields. Researchers need to adapt and scale such technologies.

Biodiversity and genetic bases need to be protected. Seed varieties need to be preserved and their phenotype and genotype characteristics explored in the contexts of climate change and nutrition. Traditional food and forest systems, including those of Indigenous Peoples, need to be better understood and supported in national agricultural research systems. Cooperation for mutual benefit should be explored, as the Tribal Adaptation Menu in Indigenous Peoples' areas in the US has for climate adaptation https://forestadaptation.org/sites/default/files/Tribal%20Climate%20Adaptation%20Menu%2011-2020%20v2.pdf.

1.6 Sustain Aquatic Foods

Most of the focus on food to date has been on land-based agriculture. Seafood and seaweed have much to offer nutritionally and environmentally. Aquatic foods need to be better integrated into understanding of food systems (see https://www.nature.com/

articles/d41586-020-03303-3). Researchers should look for ways to increase nutritional diversity in aquatic foods and sequester carbon in the marine environment.

Ecological science perspectives and global cooperation and institutions are needed to bring the harvesting of oceans to sustainable levels and protect biodiversity. Science-based approaches must address the sustainability of fish feeding systems; for example, explore using insect rearing, oil-rich modified legumes and micro-algae as fish feed.

1.7 Harness Technology

Robots, sensors and artificial intelligence are increasingly used on farms and in food processing. For example, robots harvest crops and milk cows. Sensors can monitor the origin and quality of ingredients and products along the food processing chain to reduce losses and guarantee food safety. But most farmers and producers still don't have access. To spread the benefits, devices need to become cheaper and easier to purchase and use. Rental services should be developed, such as an Uber-like app for tractors in India. Rural electricity will be needed, and training and education programs. Again, managing property rights and sharing data are key.

2 First Steps

The 2021 Food Systems Summit is a great opportunity to end hunger by 2030 and set in train a sustainable food system. Previous UN food summits have delivered change. The 1943 conference led to FAO; the 1974 meeting strengthened the CGIAR and led to the founding of IFPR; the 2002 session accelerated the human right to food; and the 2009 meeting established monitoring systems to prevent food price crises.

The breadth of the 2021 agenda could be a hindrance, though, in achieving its goals. To avoid failure, delegates should focus. They should prioritize establishing a guiding framework – for transforming diverse national and local food systems, as well as global networks, with the challenges of trade, finance, climate, innovation and governance.

Debates will be fierce. Food is a contentious topic. Disagreements abound, over goals, pathways and speed of change, and the roles of science and technology, the private sector and the UN. For example, some see agroecology as the only acceptable way of farming, with minimal technology. Biotechnology and gene editing are viewed as both an opportunity and a danger. Livestock exacerbate the climate crisis. (The Scientific Group has aimed to offer a balanced view by noting the diversity of perspectives.)

3 Actions and Targets

Once plans are agreed, the UN Food Systems Summit will need to move to implementation. Here are our suggestions.

First, boost finance. On the research front, we propose that governments allocate at least 1% of the fraction of their nations' GDP that relates to food systems to food-related research. Many countries spend only half of that. Least-developed countries should be given aid to reach a similar level. To end hunger for the poorest, we propose a special fund be set up. This would be supported by development aid donors and bonds backed by the IMF and World Bank. Research and modeling would be required into implementation and impacts.

Second, increase scientific capacity. Use the funding above to strengthen research capacity in low and middle income countries. Expand research collaborations between the public and private sectors, among farmers, start-ups in food value chains and science communities. Sharing research infrastructure and data between the global south and north would be a good start.

Third, strengthen science-policy interfaces. In stark contrast to many other fields, agriculture, food security and nutrition do not have an international agreement or convention to consolidate actions. We call on the UNFSS and UN Member States to explore an intergovernmental treaty or framework convention on food systems, by analogy to the conventions on climate, biodiversity and desertification agreed upon in Rio in YEAR. We recommend that all science organizations and academies with food-relevant research be included in a preparatory process.

Bringing the tools of science to the table will help transform the global food system to end hunger and achieve the Sustainable Development Goals by 2030.

Acknowledgment This chapter was originally published as an article in Nature, 597, 28–30, (2021).

References

Aurino E et al (2019) School feeding or general food distribution? Quasi-experimental evidence on the educational impacts of emergency food assistance during conflict in Mali. J Dev Stud 55 (sup1):7–28. https://doi.org/10.1080/00220388.2019.1687874

Baumüller H (2017) Towards smart farming? Mobile technology trends and their potential for developing country agriculture. In: Skouby KE, Williams I, Gyamfi A (eds) Handbook for ICT in developing countries: 5G perspectives. River Publishers, Delft, pp 191–201. ISBN: 978-87-93379-91-6

FAO, IFAD, UNICEF, WFP and WHO (2021) The state of food security and nutrition in the world 2021. FAO, Rome. http://www.fao.org/3/cb4474en/online/cb4474en.html

Gebre GG et al (2021) Gender differences in agricultural productivity: evidence from maize farm households in southern Ethiopia. GeoJournal 86:843–864. https://doi.org/10.1007/s10708-019-10098-y

Hendriks S et al (2021) The true cost and true price of food. A paper from the Scientific Group of the UN Food Systems Summit, June 2021. https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf

Kalkuhl M et al (2016) Food price volatility and its implications for food security and policy. Springer, Cham. http://link.springer.com/book/10.1007%2F978-3-319-28201-5

Mintah K et al (2021) Blockchain on stool land acquisition: lessons from Ghana for strengthening land tenure security other than titling. Land Use Policy 109. https://doi.org/10.1016/j.landusepol.2021.105635

Nature Editorial Board (2021) Does the fight against hunger need its own IPCC? Nature 595:332. https://doi.org/10.1038/d41586-021-01904-0

OECD (2021) Making better policies for food systems. OECD Publishing, Paris. https://doi.org/10.1787/ddfba4de-en

Passarelli S et al (2018) Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. Food Secur 10:981–997. https://doi.org/10.1007/s12571-018-0812-5

Pendrill F et al (2019) Environ Res Lett 14:055003

Food System Concepts and Definitions for Science and Political Action

Joachim von Braun, Kaosar Afsana, Louise O. Fresco, Mohamed Hag Ali Hassan, and Maximo Torero

For fruitful deliberations and concerted action at the science-political interface the very concept of food systems and drivers of change need to be clearly understood and employed by all

1 Introduction

Food systems exist at different scales: global, regional, national and local. Local food systems around the world are very diverse and location-specific. They share some key features, but any attempt to change them should reflect their uniqueness embedded in traditions, cultures, economic structures, and ecologies of locations. Change in food systems comes about through external and internal drivers as well as through feedback mechanisms between these drivers. External drivers are for instance from climate or health systems, internal drivers are for instance from

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

K. Afsana
James P Grant School of Public Health, BRAC University, Dhaka, Bangladesh

L. O. Fresco
Wageningen University and Research, Wageningen, The Netherlands

M. H. A. Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), Trieste, Italy

M. Torero
Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_2

productivity gains as a consequence of innovations or from changes in consumer behavior.

The way in which changes in food systems impact sustainability in its diverse social, economic, and ecological dimensions is critical. With the Sustainable Development Goals (SDGs) there is an accelerating momentum worldwide, to adopt systems approaches to bring consumption and production patterns together to achieve sustainable development through an integrated approach to food systems (United Nations 2020).

2 Defining and Conceptualizing Food Systems

A practical definition of food systems should meet two essential criteria:

- it should be suitable for the purpose at hand, which is to support the global and national collective efforts to bring about positive change in food systems, by accelerating progress on meeting the 2030 Agenda and the SDGs in particular end hunger, improve diets and protect ecologies; and
- it should be sufficiently precise to define the domains for policy and programmatic priorities, and it should be sufficiently general to not exclude any aspects of the economic, social, and ecological dimensions of sustainability.

The significance of criterion (1) is that the definition should guide not only scientific inquiry, but also actions of all types, toward a common purpose, i.e. food systems change and in the long run even food systems transformation (von Braun et al. 2020). The point of criterion (2) is to avoid the intellectual hubris that accompanies many efforts of characterizing and graphically depicting food systems' complexities in great detail. Efforts to map food systems visually may help scientists as well as decision makers to identify key interactions and the mechanisms, both natural and social, which regulate those interactions. Yet, food systems' maps that try to be fully comprehensive tend to collapse under the density and complexity of the interactions to be described and analyzed. At the other extreme, food systems' maps and models that focus too narrowly on a reduced set of phenomena gain apparent explanatory power at the price of realism, adequacy or the exclusion of important economic, social or bio-physical environmental forces. There is no clearly defined pathway out of this dilemma. Much depends on the relevant policy question as well as on the context and scale of the food systems under consideration.

Food systems embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products, that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal, and physical environments, in which they are embedded (FAO 2018). The range of actors importantly includes science, technology, data, and innovation actors (Herrero et al. 2020).

Sustainable food systems are those that contribute to food security and nutrition for all in such a way that the economic, social, cultural, and ecological bases to generate food security and nutrition for future generations are safeguarded (Global Panel on Agriculture and Food Systems for Nutrition 2020). It should be noted that desirable food systems are necessary but not sufficient to assure good nutrition – even the best food system cannot assure good nutrition in a situation of poor hygiene, unclean drinking water, poor child care, and widespread infectious diseases. Moreover, the availability of plentiful and healthy food does not guarantee adequate consumption patterns or prevent excess body weight.

The concept of *food systems transformation* has been linked to the aspirations of the 2030 Agenda and refers to the objective of pursuing fundamental change of food systems, for instance, to aim for climate neutrality and achieving the SDGs. *Transformation* is a never-ending process in food systems. *Transition* is the movement from one state to another. And *evolution* is the process of change. These are not interchangeable terminologies. Most food systems need all three.

Conceptualizing food systems entails defining systems boundaries and systems building blocks and linkages among them, while simultaneously being connected to neighboring systems such as health, ecological, economy and governance, and the science and innovation systems (see Fig. 1). Food systems are in a continuous state of change and adaptation. For the Food Systems Summit this means to identify actions which enhance positive side-effects of or to remediate or mitigate negative side-effects of policies. The elimination of net-negative externalities of food systems in terms of ecology and health costs would guide toward recognizing the true costs and price of food. A sustainable circular bio-economy concept as an overarching systems frame, in which food systems are embedded, could be considered in the solution-finding process.

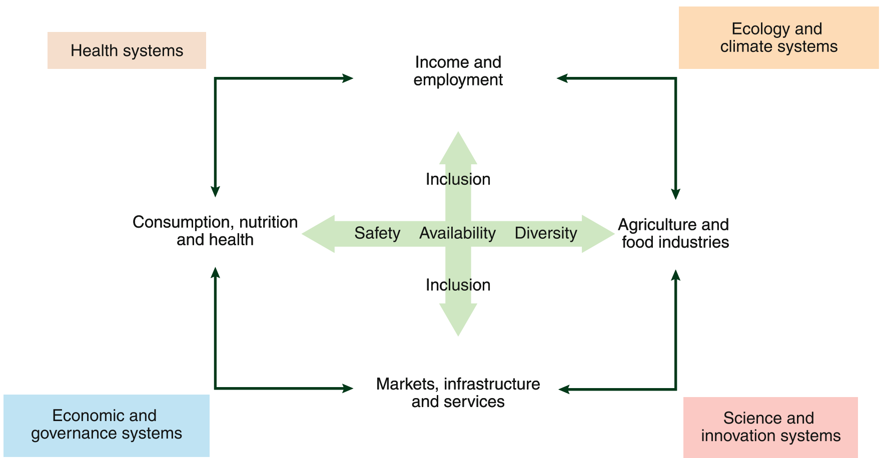


Fig. 1 The food system in the context of other systems (positive systems concept). (Source: designed by authors, adapted from InterAcademy Partnership (2018) and von Braun (2017))

3 An Action-Oriented Concept of Food Systems

Systems can be conceptualized from a *positive* or from *a normative* perspective. The *positive concept* attempts to design systems' structures and functions as they occur in the current real world and identify points of entry for desirable systems' change. The *normative concept* postulates a set of objectives and aims to shape the systems to serve the stated objectives. Both concepts aggregate and simplify real world structures and processes. Neither of these approaches escape the yardsticks of scientific evidence. For theoretical clarity of underlying value judgments, however, the two approaches need to be distinguished. As the Food Systems Summit is based on clearly stated objectives already defined in the SDGs, a *normative* approach is justified. Yet, normative approaches need to be put to the test by positive approaches in order not to steer into a dead end of unrealistic wishful thinking. Thus, normative and positive approaches are complementary. To build upon existing efforts, we suggest a concept of food systems that may help to frame action-oriented agenda setting, such as the one reflected in the five Action Tracks for the Food Systems Summit in support of the SDGs. These Action Tracks are described as:

1. Ensuring Access to Safe and Nutritious Food for All (enabling all people to be well-nourished and healthy);
2. Shifting to Sustainable Consumption Patterns (promoting and creating demand for healthy and sustainable diets, reducing waste);
3. Boosting Nature-Positive Production at Sufficient Scale (acting on climate change, reducing emissions and increasing carbon capture, regenerating and protecting critical ecosystems and reducing food loss and energy usage, without undermining health or nutritious diets);
4. Advancing Equitable Livelihoods and Value Distribution (raising incomes, distributing risk, expanding inclusion, creating jobs); and
5. Building Resilience to Vulnerabilities, Shocks and Stresses (ensuring the continued functionality of healthy and sustainable food systems).

The five *Action Tracks* capture various key opportunities and challenges of food systems and relate to one or more food systems components, but *they do not define a food systems concept* as such. Therefore, the pursuit of the Action Tracks needs to be conscious of an overarching food systems concept. Pursuing each Action Track in isolation from the others would lead to inefficient solution proposals that neglect system-wide effects. We thus offer a perspective that attempts to position the five Action Tracks in a food systems framework (Fig. 2): We expect food security and nutrition, livelihood improvements, and production with environmental sustainability; we want resilience to shocks (i.e. low variability, and a quick recovery from negative shocks); and we know that consumption patterns are a powerful lever for change. "Ensuring Access to Safe and Nutritious Food for All (enabling all people to be well-nourished and healthy)" is supported by the other four Action Tracks, yet there is also feedback from improved nutrition to the other four Action Tracks.

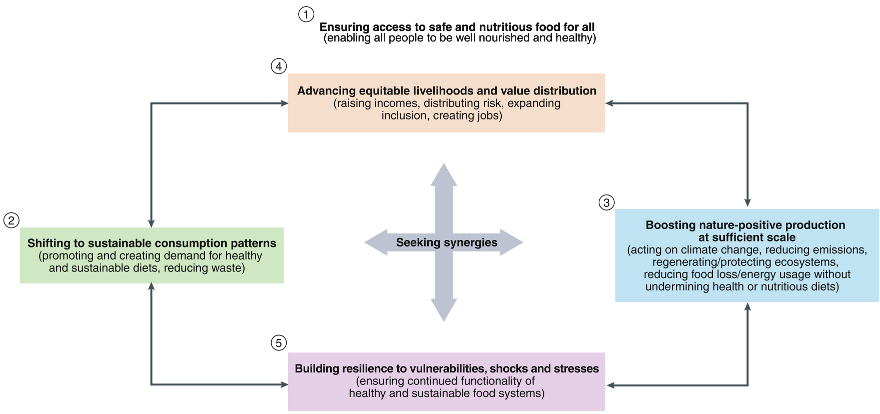


Fig. 2 Action Tracks in a Food System (a normative systems perspective). (Source: Designed by authors)

The Action Tracks need to consider functional relationships among them in systemic ways.

The systems perspective must not overlook some key cross-cutting issues and themes, which need due attention, for example, Covid-19 has highlighted the intertwining of food and health systems. Science and new and emerging technologies and innovations, including gene editing, digitization, Internet of Things, and Artificial Intelligence, are critical for improving productivity, efficiency, equity, and sustainability of food systems. The role of women and gender are important determinants for productive, healthy and sustainable food systems, and are fundamental for equity. Trade, market structures and dynamics of food industries require policy attention (OECD 2021). And there is a tendency to think of food systems as terrestrial systems only, but it will be vital to broaden the understanding of food systems to include their links to water cycles, oceans and fisheries.

4 Concluding Remarks

The discourse on food systems must not abstract from the issue of culture and values, making it seem as if it is merely a technical question. This especially - but not only - applies to the greatly diverse indigenous food systems, and the culture and knowledge embedded in them.

The Food Systems Summit needs to facilitate action to overcome systems failures that contribute to the hunger, malnutrition, and obesity problems; to the ecological problems of deforestation, green-house gas emissions, biodiversity losses and species extinctions; to the problems of poor livelihoods in farming communities especially of women and youth; and to the fundamental issues of food system related violations of rights – human right to food, broadly defined. The Summit needs to come up with visions for food systems transformations in their respective contexts. While a strong sense of urgency is called for due to the big food systems malfunctioning, the time horizon of the food systems transformations needs to reach far beyond 2030, given demographic change, climate change, technological change and people – nature linkages in the Anthropocene.

If food systems shall deliver on the stated objectives (i.e. the SDGs), the Food Systems Summit needs to be open to new thinking, to new concepts, and to establishing new institutional and organizational arrangements. Addressing symptoms of systems failures will not be sufficient. Investing in science is essential to innovate, develop, and implement game-changing propositions that fit the respective food systems contexts. Science and policy have a lot to gain from cooperation through a strong and effective science – policy interface to help guide the follow up to the Summit (InterAcademy Partnership 2018).

Acknowledgements We gratefully acknowledge the peer review of a background paper on which this comment is based by these reviewers:

Per Pinstrup-Andersen, Professor (em) of Food, Nutrition and Public Policy at Cornell University and Adjunct Professor, Copenhagen University.
Pauline Scheelbeek, Assistant Professor in Nutritional & Environmental Epidemiology, London School of Hygiene & Tropical Medicine.
Mahendra Dev, Professor, Director and Vice Chancellor, Indira Gandhi Institute of Development Research, India.
Zhu Jing, Cheung Kong Chair Professor and Dean of College of Economics and Management, Nanjing Agricultural University (NAU), China.
Dr. Moctar Toure, Vice President of The World Academy of Sciences (TWAS) for the advancement of science in developing countries, representing the Africa Region.

The text was originally published in Nature Food, 2, 748–750 (2021).

References

FAO (2018). http://www.fao.org/3/ca2079en/CA2079EN.pdf
Global Panel on Agriculture and Food Systems for Nutrition (2020). https://www.glopan.org/foresight2/
Herrero M et al (2020) Nat Food 1:266
InterAcademy Partnership (2018) Trieste and Washington, DC. https://www.interacademies.org/sites/default/files/publication/iap_fnsa_global_web_complete_28nov.pdf
OECD (Organization for Economic Co-operation and Development) (2021) Paris. https://www.oecd.org/food-systems/
United Nations (2020) Sustainable development goals, New York. https://sdgs.un.org/goals
von Braun J, Chichaibelu BB, Cullen MT, Laborde D, Smaller C (2020) Berlin. https://www.zef.de/fileadmin/downloads/SDG2_policybrief.pdf

Part II
Actions on Hunger and Healthy Diets

Healthy Diet: A Definition for the United Nations Food Systems Summit 2021

Lynnette M. Neufeld, Sheryl Hendriks, and Marta Hugas

1 Definition

A healthy diet is health-promoting and disease-preventing. It provides adequacy, without excess, of nutrients and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances.[1]

2 Approaches to Translating a Healthy Diet into Specific Food-Based Recommendations

Moving beyond the available broad definitions so as to operationalize what constitutes a healthy diet has been a source of debate within the nutrition community for decades. Innumerable definitions exist, with many similarities and several

[1] The hyper-linked sections seek to provide further clarifications in relation to terminology and concepts. Specifically, it is important to distinguish between *diets* (combinations of food consumed by individuals or populations over time) and individual foods, which have characteristics that make them more or less nutritious. Annex 1 below provides a definition of nutritious foods, and related evidence, gaps, and controversies. In Annex 2, we similarly highlight such issues in relation to food safety and the identification and management of health-harming substances in foods.

L. M. Neufeld (✉)
International Union of Nutrition Scientists (IUNS), Knowledge Leadership, Global Alliance for Improved Nutrition (GAIN), Ottawa, Canada
e-mail: lynnetten@gmail.com

S. Hendriks
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa

M. Hugas
European Food Safety Authority (EFSA), Madrid, Spain

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_3

contradictions emerging over time (Cena and Calder 2020). In part, the contradictions arise from diversity in the underlying health issues that the diets were intended to address. Approaches to operationalizing the broad definitions and a move toward specific food-based recommendations have typically used one of three approaches: i) observing existing dietary patterns associated with a lower prevalence of specific diseases; ii) perspective approaches based on evidence related to one or several outcomes; and iii) indicative approaches providing evidence-based guidance to be adapted to a specific context. Several examples of each and their related strengths and weaknesses are discussed below.

1. Some research about healthy diets has observed dietary patterns in populations for which certain diseases, usually non-communicable diseases (NCDs), appear less prevalent. Dietary patterns in these population groups are studied, then tested in other contexts for their potential to promote health or prevent disease. One well-known example is the Mediterranean diet (Mocciaro et al. 2017), which has been the topic of much research (Cena and Calder 2020). There are several limitations to using such dietary patterns as the basis for recommendations, most importantly, because they do not consider all potential health outcomes. These examples do not account for local availability and the affordability of food types or the cultural traditions and acceptability of foods. Another approach has been to model optimal dietary patterns for a specific food group based on consumption and mortality data (Afshin et al. 2019). However, several challenges remain, including the lack of dietary data from many populations and sub-groups.
2. A second approach has been to quantify the specific dietary intake patterns associated with multiple outcomes, both human and environmental or planetary health. This dual outcome approach is not new. Principles for guiding a "sustainable, healthy diet" based primarily on eating local and minimizing processed food were published as early as 1986 (Dye Gussow and Clancy 1986). From the start, these principles have received considerable criticism from the nutrition, agriculture, and food sectors (Dye 1999). The recent *EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems* (Willett et al. 2019) provided recommendations for the consumption of specific quantities of foods or groups of foods that promote human health and can be produced within planetary boundary considerations. As with earlier efforts, the EAT-Lancet Commission diet has received criticism on several fronts, including the lack of consideration of food affordability (Hirvonen et al. 2020). However, the Commission calls for research to adapt the diet to local contexts. Future studies may provide evidence of the potential to do so.
3. Finally, the World Health Organization (WHO) has identified a series of guiding principles for healthy diets that seek to address all forms of malnutrition and related health issues. Unlike the approaches above, this indicative approach is designed to permit the contextualization of recommendations to individual characteristics, cultural contexts, local foods and dietary customs (WHO 2020). Building on such evidence, *food-based dietary guidelines* (FBDG) are intended to guide the development and revision of national food and agricultural policies.

FBDGs have been developed by over 100 countries (FAO 2020). The content of FBDG may vary by country or region, but generally includes a set of recommendations for foods, food groups, and dietary patterns that minimize the risk of deficiencies, promote health, and prevent disease in specific contexts.

3 Conclusion

This chapter defines a healthy diet for the Food Systems Summit, placing human health promotion and disease prevention at the center. In doing so, it draws attention to food safety. Without the assurance of safety, diets cannot nourish, and will instead cause illness.

However, to inform policy and programmatic action, this definition must be translated into specific food-based recommendations. In doing so, the sustainability of food systems, food affordability, and cultural and other preferences must be considered. There will always be tensions between the indicative or guiding principles and approaches that propose more quantified recommendations. The former leaves much room for interpretation, while the latter tends to underestimate the complexities of extrapolating prescribed diets to varying age, sex, life stage, culture, food availability, or affordability, among other considerations. The Food and Agriculture Organization (FAO) and WHO have now set out a series of guiding principles for achieving contextually appropriate sustainable, affordable, healthy diets (Food and Agriculture Organization of the United Nations, World Health Organization 2019; HLPE 2017) that are aligned with the guiding principles for healthy diets (#3 above) and form the basis for such actions.

We hope that this overview can help to align terminology and concepts used in the Food Systems Summit concerning healthy diets, and we encourage readers to read Annex 1 and 2 below for further information.

Annexes

Annex 1: Defining Nutritious Foods

The Distinction Between Diets and Foods

Over any particular period of time, an individual will eat many *foods* and combinations of foods. Diets are the combination of foods consumed over time, through which we achieve adequacy without excess of all nutrients (including energy). Foods that make up a healthy diet should be safe (see Annex 2) and nutritious. In this section, we will explore the concept of nutritious food, along with related evidence, gaps and controversies.

A nutritious food is "*one that provides beneficial nutrients (e.g., protein, vitamins, minerals, essential amino acids, essential fatty acids, dietary fibre) and minimizes potentially harmful elements (e.g., anti-nutrients, quantities of sodium, saturated fats, sugars)*" (GAIN, (2017) drawing on definitions published by Drewnowski (2005) and Katz et al. (2011)). While conceptually simple, there is no straightforward, universally accepted approach to classifying individual foods as more or less nutritious. Similarly, some context specificity is required in the categorization of individual foods as nutritious. The same food, for example, whole fat milk, may provide much-needed energy and other nutrients to one population group (e.g., underweight three-year-old children), but be less "healthy" for another due to high energy (calories) and fat content (e.g., obese adults).

"Nutrient profiling," or the rating of foods based on their nutrient density (i.e., nutrient content per 100 g or per 100 kcal of energy or per serving), has evolved substantially in recent years as an approach to classifying individual foods as more or less nutritious (Drewnowski and Fulgoni III 2020). Such scores now provide the basis for several regulatory and health-promoting efforts, including front of pack labeling and health claims (Croker et al. 2020). Recent efforts have also proposed more complete profiling approaches that, in addition to nutrient density, take into consideration the food groups of ingredients (e.g., fruit or vegetable content) and further develop the content of ingredients (e.g., types of fat) that should be limited (Drewnowski and Fulgoni III 2020). To date, nutrient profiling has been used predominantly for packaged foods in many high-income and several middle-income countries. Considerable limitations remain for extending its utility to unpackaged foods and in contexts in which a large portion of food is not commercially produced.

Several Evidence Gaps and Controversies That Influence Our Ability to Characterize Health Diets and Nutritious Foods

While much progress has been made in the characterization of healthy diets and the classification of individual foods as nutritious parts of said healthy diets, several gaps in evidence and controversies remain.

- *Imperfect characterization of population nutrient requirements to avoid deficiency and promote health:* Reference values for the nutrient intakes of humans have been established, focusing on the avoidance of deficiency and excess. Nutrient requirements vary by age, sex, and life stage (e.g., pregnancy), and among individuals such that no single nutrient requirement value can be defined, even within age/sex groups. *Estimated average requirements* are therefore developed and converted *into recommended daily nutrient intake* levels that will, at the population level, ensure that the requirements of 95% of the population are met (FAO, WHO 2002). *Upper tolerable limits* are set at the minimum level above which potentially harmful effects may be observed and are essential for understanding health risks and avoiding excess. FAO (2021) and many national governments have published nutrient requirements. However, several limitations exist, including diverse methodological approaches to setting estimated requirements and the extrapolation of requirements from one age group to another, among others. Some experts are now calling for additional research to estimate requirements using a consistent approach (Yaktine et al. 2020).

In addition to the focus on the positive (and negative) effects of individual nutrients, much research has focused on the potential health effects – both positive and negative – of specific foods, food groups or dietary patterns (Cena and Calder 2020). This is critically important, as it advances our understanding of the link between diet and health, as well we the importance of food, which contains many more bioactive components than just the commonly-known nutrients. Evidence of the health-promoting qualities of bioactive components in many food groups (e.g., fruits and vegetables, nuts and seeds, fermented dairy) and the health-harming effects of excessive quantities of some nutrients or dietary components (e.g., trans fat, salt, sugar) forms the basis of the guidelines proposed by FAO (Burlingame 2012), WHO (2020), and the High-Level Panel of Experts (FAO 2020). While the basic tenets of these guidelines are unlikely to change, evidence continues to evolve for all dietary components and, to some extent, is constrained by the imperfect estimates of nutrient requirements and tolerable upper limits discussed above. Some have also called for greater transparency and better management of commercial interests in researching the associations between food products and health outcomes (Lesser et al. 2007). Emerging evidence suggests that, eventually, dietary recommendations may be personalized to optimize human health outcomes based on individual characteristics (Fenech et al. 2011; Precision Nutrition 2020), but science is still far from achieving this goal.

- *Imperfect knowledge of the nutrient and "anti-nutrient" content of food:* Our ability to fully characterize dietary patterns of populations and individuals (where data permit) is highly dependent on the quality of the food composition tables, i.e., databases containing the amounts of nutrients in foods per specific portion sizes. Unfortunately, there are many issues with food composition tables, including a lack of data or out-of-date information for many countries and world regions, particularly for less common foods (e.g., edible insects) and substances that influence nutrient absorption (e.g., tannins, phytate), as well as a similar dearth of good and/or up-of-date information on nutrients added (or lost) as a result of processing, including food fortification or plant breeding (biofortification), poor or unclear analytical approaches and the lack of consideration for nutrient bioavailability, among others (Micha et al. 2018). Fortunately, this issue is well recognized, and substantial advances have been made through the efforts of the INFOODS project of FAO (2020).
- *Lack of consensus and standardized definitions related to food processing and health implications*: A growing body of evidence suggests that highly-processed foods (or ultra-processed foods) are health-harming for humans (Hall et al. 2019). Recent studies have also highlighted the impact of such foods on the environment (Seferidi et al. 2020), an issue that was even raised in the early discussions on sustainable diets (Dye Gussow and Clancy 1986; Dye 1999). Recent studies have

primarily used the NOVA classification of ultra-processed foods (Monteiro et al. 2019; Monteiro et al. 2018). However, at present, there is no single accepted definition that clearly lays out the specific aspects of food processing that may be health-harming (Gibney 2018; Gibney et al. 2017). The implications of highly-processed foods, particularly those high in sugar, trans fat or salt, are not under debate. Urgent consensus is needed on how to classify such foods, define food processing categories and operationalize the implications for the private sector.

Annex 2: Avoiding the Consumption of Health-Harming Substances

Bringing Safety to the Definition of Healthy Diets

Food safety refers to "*all those hazards, whether chronic or acute, that may make food injurious to the health of the consumer*" (FAO 2003). Food safety issues can arise from food contamination with biological hazards, pathogens, or chemicals (natural or processed contaminants, residues of pesticides or veterinary medicine, etc.) during the production, processing, storage (including, but not limited to a lack of adequate cold storage), transport and distribution of food, as well as in the household. Standards and controls are in place to protect consumers from unsafe foods (HLPE 2017). In addition to the disease burden, food-borne disease in low- and middle-income countries (LMICs) is also a concern because of a broad range of economic costs and their impacts on market access (Unnevehr and Ronchi 2014).

Current knowledge suggests that biological hazards and antimicrobial resistance may present a higher disease burden than chemical hazards. However, there is still uncertainty due to difficulty in measuring and attributing long-term and chronic effects. Chronic effects due to chemicals (natural or processed contaminants, pesticide residues, etc.) are more challenging to trace and their actual impact on disease burden more difficult to quantify. The study by the Foodborne Disease Burden Epidemiology Reference Group of the World Health Organization (FERG/WHO)[2] estimated that the global burden of food-borne diseases was comparable to that of HIV/AIDS, malaria and tuberculosis, with LMICs bearing 98% of this burden. The FERG/WHO report (WHO 2015) quantified the burden of disease from the most critical food-borne toxins (aflatoxin, cassava cyanide and dioxins). Some work has also been done to estimate the burden of illness due to four food-borne metals (arsenic, cadmium, lead, methyl-mercury), which is estimated to be substantial (Gibb et al. 2019). As with nutrition, our evidence related to food safety and health continues to evolve. For example, the clinical outcome of exposure to food-borne pathogens may be modulated by the human gut microbiome (Josephs-Spaulding et al. 2016).

Despite the heavy burden of disease among LMICs, the systems and practices for monitoring food-borne hazards and risks, food safety system performance and related disease outcomes are predominantly utilized in high-income countries

[2] WHO 2015.

(HICs). While there are many promising approaches to managing food safety in LMICs, few have demonstrated a sustainable impact at scale. It is also essential to distinguish between food safety and food quality: food safety ensures that food is fit for human consumption and not harmful to human health, and most often falls under the competence of veterinary, health or agricultural inspectors, while food quality is a market category that is usually the responsibility of food or market inspectors (Independent Evaluation Group (IEG) 2014).

Several Evidence Gaps and Controversies That Influence the Ability to Assess and Ensure the Safety of Foods as Part of a Healthy Diet

- *Food safety has complex interactions with other societal concerns*. Safety must be built into foods, and this puts responsibility for food safety all along the value chain, including on producers, processors, transporters, retailers, and consumers. If food chain actors lack the requisite knowledge, resources, and skills, then safety cannot be assured. Some food safety perceptions and knowledge may be shared generationally and may not be scientifically grounded. In many LMICs, food is often purchased from traditional markets close to the point of production and undergoes limited transformation (Jaffee et al. 2019). Several traditional ways of processing food can be highly effective at reducing risk, but food-borne illness may still be linked to poor hygiene conditions, close contact with animals, and limited access to clean water from the market through to the household. Informal market drivers and incentives for safe food are often weak, although adverse food safety events can leave the sellers vulnerable to reputational harm. As such, food safety has implications for livelihoods. Likewise, food-borne diseases can have important consequences for women's resilience. Women predominate in traditional food processing and sales and are usually responsible for food preparation at home.
- *The preferred method for improving food safety and quality is preventive, and many, although not all, potential food hazards can be controlled along the food chain*. Engaging the food industry at all levels to understand their role in preventing food contamination through the application of good practices, i.e., good agricultural practices (GAP), good manufacturing practices (GMP), good hygienic practices (GHP), and the Hazard Analysis Critical Control Point system (HACCP), is challenging. The HACCP principles have been formalized by the Codex Committee on Food Hygiene and provide a systematic structure that actors within the food industry, both large and small, can use to identify and control food-borne hazards. Governments should recognize the application of a HACCP approach by the food industry as a fundamental tool for improving the safety of food (FAO 2003). However, the level of safety that these food safety systems are expected to deliver has seldom been defined in quantitative terms.

  In addition to HACCP, the Codex Alimentarius Commission (CAC) sets standards for addressing the safety and nutritional quality of foods for most segments of the food chain so as to protect consumer health and fair practices. The CAC establishes standards for maximum levels of food additives, limits for contaminants and toxins, and residue limits for pesticides and veterinary drugs.

- *Some countries, especially LMICs, have not adopted modern food safety control systems, even though there is a significant burden of food-related illness.*[3] Many countries lack effective public health surveillance systems, so the burden of food-borne disease and broader economic ramifications are not well understood. Food safety capacity may be concentrated either geographically, for example, in the capital city, or for niche markets intended for export. Building on these analyses, the World Bank recommends that governments consider how to make "smart" food safety investments, such as investing in foundational knowledge, human resources and infrastructure, including those that address basic environmental health issues, like access to clean water, improved sanitation and reduced environmental contamination in the soil, water and air (FAO 2003).

Food safety priorities for countries include addressing risks from farm to table, transitioning from reactive to proactive approaches to food safety, and adopting a risk analysis approach to ensure prioritized decision-making. The building of food safety capacity will assist governments in economic development by improving the health of their citizens and opening countries to more food export markets and tourism (Jaffee et al. 2019).

References

Afshin A, Sur PJ, Fay KA, Cornaby L, Ferrara G, Salama JS, Mullany EC, Abate KH, Abbafati C, Abebe Z et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the global burden of disease study 2017. Lancet 393:1958–1972

Badiane O, Makombe T (2020) Beyond a middle income Africa: transforming African economies for sustained growth with rising employment and incomes [Internet]. International Food Policy Research Institute (IFPRI); 2015 [cited 2020 Oct 25]. Available from: https://ebrary.ifpri.org/digital/collection/p15738coll2/id/130121

Burlingame B (2012) Sustainable diets and biodiversity – directions and solutions for policy research and action Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United Against Hunger. FAO, Rome

Cena H, Calder PC (2020). Defining a healthy diet: evidence for the role of contemporary dietary patterns in health and disease. Nutrients [Internet]. Multidisciplinary Digital Publishing Institute (MDPI); 2020 [cited 2020 Oct 13];12. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7071223/

Chaudhary A, Gustafson D, Mathys A (2018) Multi-indicator sustainability assessment of global food systems. Nat Commun 9:1–13. Nature Publishing Group

Croker H, Packer J, Russell SJ, Stansfield C, Viner RM. Front of pack nutritional labelling schemes: a systematic review and meta-analysis of recent evidence relating to objectively measured consumption and purchasing. J Human Nutr Diet; 2020;33:518–537 Wiley.

Drewnowski A (2005) Concept of a nutritious food: toward a nutrient density score. Am J Clin Nutr. Oxford Academic 82:721–732

[3] Jaffee et al. 2019.

Drewnowski A, Fulgoni VL, III. New Nutrient Rich Food Nutrient Density Models That Include Nutrients and MyPlate Food Groups. Frontiers in Nutrition [Internet]. Frontiers Media SA; 2020 [cited 2020 Oct 12]; Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7387572/

Dye GJ (1999) Dietary guidelines for sustainability: twelve years later. J Nutr Educ 31:194–200

Dye Gussow J, Clancy KL (1986) Dietary guidelines for sustainability. J Nutr Educ 18:1–5

FAO (2003) Assuring food safety and quality: Guidelines for strengthening national food control systems [Internet]. Rome. Report No.: 76. Available from: http://www.fao.org/3/a-y8705e.pdf

FAO (2020) Food-Based Dietary Guidelines. [cited 2020 Oct 25]. Available from: http://www.fao.org/nutrition/education/food-dietary-guidelines/background/en/

FAO (2021) Nutrition requirements [Internet]. Food and Agriculture Organization of the United Nations. [cited 2021 Jan 18]. Available from: http://www.fao.org/nutrition/requirements/en/

FAO, WHO (2002) Human vitamin and mineral requirements [Internet]. Available from: http://www.fao.org/3/y2809e/y2809e00.htm#Contents

FAO, WHO (2019) Sustainable healthy diets: guiding principles.

Fenech M, El-Sohemy A, Cahill L, Ferguson LR, French T-AC, Tai ES, Milner J, Koh W-P, Xie L, Zucker M et al (2011) Nutrigenetics and nutrigenomics: viewpoints on the current status and applications in nutrition research and practice. J Nutrigenet Nutrigenomics 4:69–89

Gibb H, Barchowsky A, Bellinger D, Bolger P, Carrington C, Havelaar A, Oberoi S, Zang Y, O'Leary K, Devleesschauwer B (2019) Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury. Environ Res 174:188–194. Academic

Gibney M. Ultra-processed foods: definitions and policy issues. Curr Dev Nutr; 2018;3:nzy077.

Gibney M, Forde C, Mullally D, Gibney E (2017) Ultra-processed foods in human health: a critical appraisal. Am J Clin Nutr 106:717–724

Global Alliance for Improved Nutrition (GAIN). What constitutes a nutritious and safe food? [Internet]. Geneva, Switzerland: Global Alliance for Improved Nutrition (GAIN); 2017. Available from: https://www.gainhealth.org/sites/default/files/publications/documents/gain-nutritious-food-definition.pdf

Hall KD, Ayuketah A, Brychta R, Cai H, Cassimatis T, Chen KY, Chung ST, Costa E, Courville A, Darcey V et al (2019) Ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of Ad libitum food intake. Cell Metabolism. 30:226

Herforth A (2020) Cost and affordability of healthy diets across and within countries. FAO, Rome, p 108

Hirvonen K, Bai Y, Headey D, Masters WA (2020) Affordability of the EAT-Lancet reference diet: a global analysis. Lancet Global Health 8:e59–e66. Elsevier

HLPE. Nutrition and Food Systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome; 2017. Report No.: 12.

Independent Evaluation Group (IEG). The World Bank Group and the Global Food Crisis: An Evaluation of the World Bank Group Response [Internet]. Washington, DC: The World Bank; 2014. Available from: http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-0091-7

INFOODS: FAO/INFOODS Databases [Internet]. [cited 2020 Oct 26]. Available from: http://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/

Jaffee S, Henson S, Unnevehr L, Grace D, Cassou E (2019) The safe food imperative: accelerating progress in low- and middle-income countries [Internet]. Washington, DC: The World Bank Group; 2019 p. 211. Available from: https://doi.org/10.1596/978-1-4648-1345-0

Josephs-Spaulding J, Beeler E, Singh OV (2016) Human microbiome versus food-borne pathogens: friend or foe. Appl Microbiol Biotechnol 100:4845–4863

Katz DL, Doughty K, Njike V, Treu JA, Reynolds J, Walker J, Smith E, Katz C (2011) A cost comparison of more and less nutritious food choices in US supermarkets. Public Health Nutr 14: 1693–1699. Cambridge University Press

Lesser LI, Ebbeling CB, Goozner M, Wypij D, Ludwig DS (2007) Relationship between funding source and conclusion among nutrition-related scientific articles. PLOS Med 4:e5. Public Library of Science

Micha R, Coates J, Leclercq C, Charrondiere UR, Mozaffarian D (2018) Global dietary surveillance: data gaps and challenges. Food Nutr Bull. 39:175–205

Mocciaro G, Ziauddeen N, Godos J, Marranzano M, Chan M-Y, Ray S (2017) Does a Mediterranean-type dietary pattern exert a cardio-protective effect outside the Mediterranean region? A review of current evidence. Int J Food Sci Nutr. Taylor & Francis 69:524–535

Monteiro CA, Cannon G, Moubarac J-C, Levy RB, Louzada MLC, Jaime PC (2018) The UN decade of nutrition, the NOVA food classification and the trouble with ultra-processing. Public Health Nutr 21:5–17

Monteiro C, Cannon G, Levy R, Moubarac J, Louzada M, Rauber F, Khandpur N, Cediel G, Neri D, Martinez-Steele E et al (2019) Ultra-processed foods: what they are and how to identify them. Public Health Nutr 22:936–941

Precision Nutrition—the Answer to "What to Eat to Stay Healthy", JAMA [Internet]. DeepDyve. [cited 2020 Nov 22]. Available from: https://www.deepdyve.com/lp/american-medical-association/precision-nutrition-the-answer-to-what-to-eat-to-stay-healthy-sP0Civl A47

Program of Accompanying Research for Agricultural Innovation. From potentials to reality: transforming Africa's food production (Investment and policy priorities for sufficient, nutritious and sustainable food supplies) [Internet]. Akedemiya and Center for Development Research Univeristy; 2020. Available from: https://www.researchgate.net/publication/344614700_From_potentials_to_reality_Transforming_Africa's_food_production_Investment_and_policy_priorities_for_sufficient_nutritious_and_sustainable_food_supplies

Seferidi P, Scrinis G, Huybrechts I, Woods J, Vineis P, Millett C (2020) The neglected environmental impacts of ultra-processed foods. The Lancet Planetary Health. Elsevier 4:e437–e438

Smetana SM, Bornkessel S, Heinz V (2019) A path from sustainable nutrition to nutritional sustainability of complex food systems. Front Nutr 6:39

Unnevehr L, Ronchi L. Food Safety Standards: Economic and Market Impacts in Developing Countries [Internet]. Washington, DC: The World Bank Group; 2014. Report No.: 341. Available from: http://documents1.worldbank.org/curated/en/681851471859603213/pdf/107910-VIEWPOINT-PUBLIC-TAG-TOPIC-investment-climate.pdf

World Health Organization (WHO). WHO estimates of the global burden of foodborne diseases: foodborne disease burden epidemiology reference group 2007–2015 [Internet]. World Health Organization; 2015 [cited 2020 Oct 26]. Available from: https://apps.who.int/iris/handle/10665/199350

World Health Organization (WHO). Healthy diet [Internet]. Healthy diet. 2020 [cited 2020 Oct 25]. Available from: https://www.who.int/news-room/fact-sheets/detail/healthy-diet

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A et al (2019) Food in the Anthropocene: the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems. Lancet 393:447–492

Yaktine AL, King JC, Allen LH (2020) Why the derivation of nutrient reference values should be harmonized and how it can be accomplished. Adv Nutr 11:1102–1107. Oxford Academic

Ensuring Access to Safe and Nutritious Food for All Through the Transformation of Food Systems

Sheryl Hendriks, Jean-François Soussana, Martin Cole, Andrew Kambugu, and David Zilberman

1 Introduction

Action Track 1 of the Food Systems Summit offers an opportunity to bring together the crucial elements of food safety, nutrition, poverty and inequalities in the framework of food systems within the context of climate and environmental change to ensure that all people have access to a safe and nutritious diet. These elements are embedded in fundamental human rights, including the right to food, the rights to safe water and sanitation (essential for safe food), and the right to be free from discrimination.

Food systems provide a framework for advancing access to safe and nutritious food for all (including all crops, fish, forest foods and livestock). Food systems encompass all of the elements and activities that relate to the production, processing, distribution, preparation and consumption of food, as well as the output of these

S. Hendriks (✉)
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa
e-mail: sheryl.hendriks@up.ac.za

J.-F. Soussana
INRAE (National Research Institute for Agriculture, Food and Environment), Paris, France

M. Cole
School of Agriculture, Food and Wine, University of Adelaide, Adelaide, Australia

A. Kambugu
Infectious Disease Institute, Makerere University, Kampala, Uganda

D. Zilberman
Agricultural and Resource Economics Department, University of California at Berkeley, Berkeley, CA, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_4

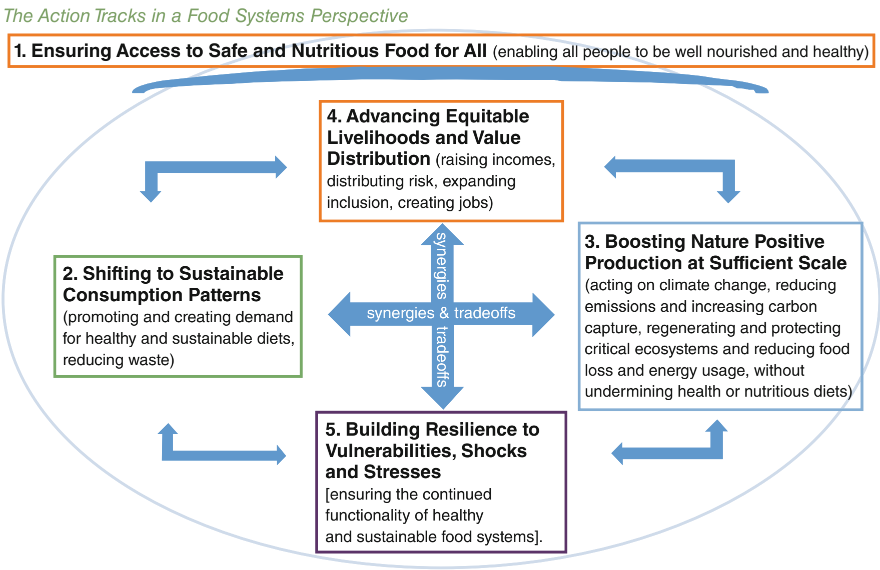


Fig. 1 Action Tracks of the UN food systems summit in a normative systems perspective. (Von Braun et al. 2021)

activities, including socio-economic and environmental outcomes (HLPE 2020). Ensuring access to safe and nutritious food for all underlies the other Summit Action Tracks (Fig. 1).

2 What Is a Safe and Nutritious Diet?

A safe and nutritious diet is a healthy diet that "is human health-promoting and disease-preventing. It provides adequacy (without an excess of nutrients) and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances" (Neufeld et al. 2021). A nutritious food "provides beneficial nutrients (e.g., protein, vitamins, minerals, essential amino acids, essential fatty acids, dietary fibre) and minimises potentially harmful elements (e.g. anti-nutrients, quantities of sodium, saturated fats, sugars)" (Neufeld et al. 2021, drawing on GAIN (2017), Drewnowski (2005) and Katz et al. (2011)). Safe food promotes health and is free of foodborne diseases caused by microorganisms, including bacteria, virus, prionics, parasites and chemicals, as well as foodborne zoonoses transferred from animals to humans and other associated risks in the food chain (WHO 2013).

Malnutrition includes undernourishment, micronutrient deficiencies and overweight (including obesity). Malnutrition increases susceptibility to foodborne diseases, creating a vicious cycle for health, reducing productivity and compromising development. The COVID-19 pandemic is expected to increase the risk of all forms of malnutrition (Headey et al. 2020).

Recent reports draw attention to the affordability of a healthy diet (FAO et al. 2020; Masters et al. 2018). The pandemic has exposed long-standing inequalities in our food and health systems that affect access to safe and nutritious food, as well as income that enables this access (Laborde et al. 2020). Shocks (including health shocks such as COVID-19 that increase the need for a nutritious diet) make healthy diets less accessible and affordable.

While the definitions of an adequate diet and safe food are established and widely accepted, there is debate in the literature about what constitutes a sustainable diet. Each proposed diet has trade-offs in terms of affordability, climate and environmental impacts. These trade-offs are discussed in the sections that follow.

3 We Are Not on Track to Meet International Targets for Ensuring Safe and Nutritious Food for All By 2030

Despite some progress in reducing the rate of extreme poverty, with only 10 years to go to 2030, the world is not on track to meet nutrition-related targets. Table 1 presents a summary of the international targets related to ensuring safe and nutritious food for all. While the proportion of the population that is undernourished, stunting, of low birth weight and displaying anaemia among women of reproductive age has declined, the reductions are not sufficient to meet the global targets. The experience of food insecurity (FIES, a survey that comprises eight questions regarding people's access to adequate food) as measured by FAO et al. (2020) has increased somewhat. Moreover, the numbers of overweight children and adults is rising.

No country is exempt from the scourge of malnutrition. Undernutrition coexists with overweight, obesity and other diet-related non-communicable diseases (NCDs), even in poor countries. UNICEF et al. (2020) report that 37% of overweight children reside in low and middle-income countries. Likewise, fragile and extremely fragile countries are disproportionally burdened by high levels of all three forms of malnutrition compared to less-fragile countries (GNR 2020).

While some progress has been made in certain countries and in some regions, the 2020 Global Nutrition report shows that no country is 'on course' to meet all of WHO's global nutrition targets (GNR 2020). Although the health and behavioural actions required to reduce all forms of malnutrition are well documented (Lancet report, various WHO guidelines), as are the benefits (Hoddinott, etc.), progress has been far too slow. Inequalities in society and the food system make affordable and healthy diFets inaccessible to the most vulnerable populations. There is an urgent need to transform food systems so as to deliver on nutrition outcomes. Unless nutrition-specific (direct) and nutrition-sensitive (indirect) interventions are implemented at scale and in a sustainable way (see Box 1) with complementary services (such as the regular deworming of children), the impact will be suboptimal (Ruel et al. 2018). In addition, urgent action is necessary to minimise the impact of the COVID-19 pandemic on children's nutrition (Headey et al. 2020).

Table 1 Taking stock

	Element	International target/s	Baseline year	Baseline estimate	Latest assessment year	Latest global estimates (with population estimates where available)	Change to date (global)
Nutrition	Hunger (Proportion of the population that is undernourished, PoU)[a]	SDG2: By 2030, end hunger and ensure access for all people, in particular, the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food year-round	2004–2006	12.5% (FAO et al. 2020)	2017–2019	PoU = 8.8% (690 Million) (FAO et al. 2020)	Down 3.7%
	Prevalence of food insecurity (Food Insecurity Experience Scale, FIES) measured as the number of people living in households where at least one adult has been found to be food insecure (FAO et al. 2020)[a,b,c]		2014–2016	Severe – 8.1% Moderate – 22.7% (FAO et al. 2020)	2017–2019	Moderate FIES = 25%, or two billion, including 9% with severe food insecurity (FAO et al. 2020)	Severe: up 0.9% Moderate: up 2.3%
	Wasting (being underweight for one's height)[d,f]	WHO target: Reduce and maintain childhood wasting at less than 5% by 2025 and less than 3% by 2030 (WHO and UNICEF 2017)	2012	8%	2019	6.9% (moderate and severe), or 47 million children (UNICEF et al. 2020)	Down 1.1%

	Stunting (being short for one's age)[d,e,f]	WHO target: 40% reduction in the number of children under 5 years of age who are stunted by 2025 and 50% by 2030 from 2016 (WHO and UNICEF 2017)	2012	24.6% (UNICEF et al. 2020)	2019	21.3% (moderate and severe), or 149 million children under 5 years of age (UNICEF et al. 2020)	Down 3.3%
	Overweight children (children <5 years with a Body Mass Index (BMI) over 30 – calculated as weight/height^2)[d,e,f]	WHO 2025 target: No increase in child overweight (WHO and UNICEF 2017)	2012	4.9%	2019	5.3%, or 38.3 million under 5 years of age are overweight (FAO et al. 2020)	Up 0.7%
	Obesity (Adults with a BMI over 30)	WHO 2025 target: Halt the rise in levels (WHO and UNICEF 2017)	2012	11.8%	2016	13.1%, or 677.6 million obese adults (GNR 2020)	Up 1.3%
	Low birthweight (less than 2500 g)[f]	WHO 2025/2030 target: 30% reduction in low birth weight (WHO and UNICEF 2017)	2012	15%	2015	14.6% (FAO et al. 2020)	Down 0.4%
	Anaemia (iron deficiency)	WHO 2025/2030 target: 50% reduction of anaemia (iron deficiency) in women of reproductive age (WHO and UNICEF 2017)	2012	30.3%	2016	2016 32.8% (FAO et al. 2020)	Up 1.5%

(continued)

Table 1 (continued)

	Element	International target/s	Baseline year	Baseline estimate	Latest assessment year	Latest global estimates (with population estimates where available)	Change to date (global)
Food safety	Foodborne disease burden	None established	2010	Unsafe food caused 600 million cases of foodborne diseases and 420,000 deaths, equivalent to 33 million years of healthy lives lost, WHO Foodborne Disease Burden Epidemiology Reference Group (FERG 2007–2015)	Not applicable (N/A)	N/A – only baseline available	Unknown – only data for 2010 published
Poverty and inequality	Poverty	SDG1: By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.90 a day (World Bank 2018)	2015	10%, or 734 million (World Bank 2018)	2019	8.2% (UN 2021)	Down 1.8%

	Affordability	None	2019	% of population that cannot afford an energy-sufficient diet = 4.6% (FAO et al. 2020)	–	N/A – only baseline available	Unknown – this is a new indicator, without historical data
				% of population that cannot afford a nutrient-adequate diet = 23.3% (FAO et al. 2020)			
				% of population that cannot afford a healthy diet = 38.3% or three billion (FAO et al. 2020)			

[a]Regional estimates were included when more than 50% of the population was covered. To reduce the margin of error, estimates are presented as 3-year averages (FAO et al. 2020)
[b]FAO estimates of the number of people living in households where at least one adult has been found to be food insecure (FAO et al. 2020)
[c]Country-level results are presented only for those countries for which estimates are based on official national data or as provisional estimates, based on FAO data collected through the GallupR World Poll, for countries whose relevant national authorities expressed no objection to their publication (FAO et al. 2020)
[d]For regional estimates, values correspond to the model predicted estimate for 2019. For countries, the latest data available from 2014 to 2019 are used (FAO et al. 2020)
[e]For regional estimates, values correspond to the model predicted estimate for 2012. For countries, the latest data available from 2005 to 2012 are used (FAO et al. 2020)
[f]Wasting, stunting and overweight under 5 years of age and low birthweight regional aggregates exclude Japan (FAO et al. 2020)

Box 1: Sustainable Food Systems

"Sustainable food systems are: productive and prosperous (to ensure the availability of sufficient food); equitable and inclusive (to ensure access for all people to food and to livelihoods within that system); empowering and respectful (to ensure agency for all people and groups, including those who are most vulnerable and marginalized to make choices and exercise voice in shaping that system); resilient (to ensure stability in the face of shocks and crises); regenerative (to ensure sustainability in all its dimensions); and healthy and nutritious (to ensure nutrient uptake and utilization)" (HLPE 2020).

WFP has predicted that the number of people facing acute food insecurity in low and middle-income countries will nearly double to 265 million by the end of 2020 (WFP 2020). Children are disproportionately affected, with likely intergenerational consequences for child growth and development. The pandemic's impact could have life-long implications for education, chronic disease risks and overall human capital formation (Martorell 2017).

Approximately 600 million people fall ill through the consumption of contaminated food each year, with considerable differences among sub-regions; with the highest burden observed in Africa (WHO 2020). More than 420,000 die every year, equating to the loss of 33 million Disability-Adjusted Life Years (WHO 2015a). Foodborne diseases disproportionately affect children, accounting for 40% of the foodborne disease burden. The consumption of unsafe foods costs low- and middle-income countries at least US$ 110 billion in lost productivity and medical expenses annually (Jaffee et al. 2019). With a large proportion of emerging human infectious diseases originating from animal sources (zoonotic diseases), there is also an increasing need to consider both animal and human health as a 'One Health' issue.

Devleesschauwer et al. (2018) report that food safety is a marginalised policy objective, especially in developing countries. The scale of foodborne outbreaks has become more extensive and has affected more countries since 2004 (INFOSAN 2019), representing a constant threat to public health and an impediment to socio-economic development. However, updated data is not available regarding progress on reducing the incidence of foodborne diseases, presenting a major obstacle to adequately addressing food safety concerns (Devleesschauwer et al. 2018).

A recent innovation is the assessment of the adequacy, affordability and access to healthy diets included in the 2020 State of Food Security and Nutrition in the World (SOFI) report (see affordability, Table 1). If continually updated, this indicator could become a comprehensive proxy for monitoring progress on ensuring safe, nutritious food for all.

4 Interconnected Food System Drivers That Affect the Access to Safe and Nutritious Food for All

Several interconnected socio-economic and biophysical food system drivers affect access to safe and nutritious food. Nutrition is both a health and food system concern. While some drivers of food systems are global (e.g., trade liberalisation, climate change), others are regional, national and sub-national (e.g., conflicts). At the same time, many are differentiated across geographies (e.g., poverty, demography, technologies, land degradation). Below, we provide a brief overview of the main drivers, depicted in Fig. 2. At the centre of the diagram is the food system, spurred by socio-economic, supply chain and climate change and land-use drivers (depicted by the segmented circle). The drivers and the food system are influenced by globalisation and the global COVID-19 pandemic. In certain contexts, the drivers and the food system are also affected by conflict and fragility.

4.1 Socio-Economic Drivers

There is a vast array of socio-economic drivers that increase global food demand, including population growth (Gerten et al. 2020), the westernisation of diets, increased food waste and overweight (including obesity) (Hasegawa et al. 2018), increased demand for animal-sourced foods in diets leading to increased demand of feed from arable crops (Mottet et al. 2017), and rapid urbanisation (van Vliet et al. 2017). These trends could cause a doubling of food demand by 2050 and will require

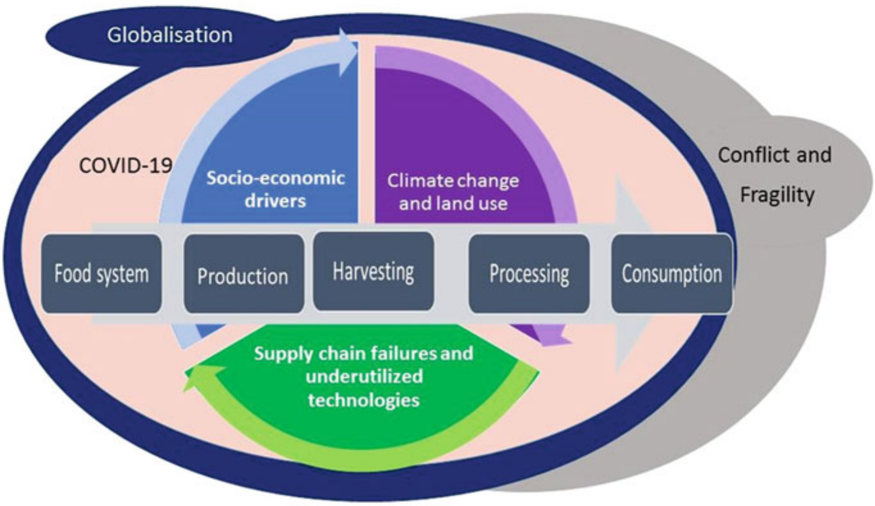


Fig. 2 Food system context and drivers related to Action Track 1

a mean global increase of crop yields by over 30% from 2015 for a range of scenarios without climate change (FAO 2018), a value lower than those in previous projections that assumed rapid economic growth (Alexandratos and Bruinsma 2012).

Globalisation Lockdowns caused by the COVID-19 pandemic of zoonotic origin have disrupted the production, transportation, and sale of nutritious, fresh and affordable foods, forcing millions of families to rely on nutrient-poor alternatives (Fore et al. 2020). International food trade can increase the diversity of diets and has established a global standard food supply, which is relatively species-rich regarding measured crops at the national level, but species-poor globally (Khoury et al. 2014). Globalised food trade can also contribute to unsustainable water use (Rosa et al. 2019) and land degradation (IPCC 2019). The availability of cheap, high-energy, fatty and sugary foods, the high price of nutritious fresh foods and the demand for more 'westernised' and often obesogenic foods increase the incidence of nutrition-related NCDs (Chaudhary et al. 2018). Nevertheless, globalised supply chains support the wide distribution of food, reducing shortages in import-dependent regions (Janssens et al. 2020), improving seasonal availability and often reducing food loss through technological advances in processing, packaging and storage (Zilberman et al. 2019).

Demography and Urbanisation Although population growth has slowed globally, the population in the 47 least developed countries (mostly in Africa and Asia) is projected to double between 2019 and 2050. By 2030, the number of youths in Africa will have increased by 42% from 2015. Nevertheless, in 2018, for the first time in history, the proportion of older persons (above 65) outnumbered that of children under five, a trend that is predicted to continue (UNDESA 2019). A growing proportion of older people will put a strain on the health system and change nutritional needs and dietary preferences. Aging is accompanied by multiple physiological changes that affect diets and nutrition. This may include a lower sense of taste and/or smell; reduced appetite; poor oral health and dental problems; lower gastric acid secretion that may affect the absorption of minerals and vitamins; and loss of vision and hearing and reduced mobility that may limit mobility and affect elderly people's ability to shop for food and prepare meals (WHO 2015b). Moreover, by 2050, 68% of the global population could be urban, shifting the proportion of producers to consumers, changing consumption patterns (demand), driving land take and putting extra pressure on soil resources (Barthel et al. 2019; van Vliet et al. 2017).

Poverty and Inequality Poverty traps millions in poor nutrition, depriving them of their potential. The prevalence of both undernutrition and overweight adults is directly linked with relative food prices (Headey and Alderman 2019). Healthy diets cost roughly 60% and 400% more than nutrient-adequate and energy-sufficient diets, respectively (FAO et al. 2020). More than 1.5 billion people cannot afford a nutrient-adequate diet and over three billion cannot afford even the cheapest of healthy diets (FAO 2011). Food system disruptions caused by COVID-19 measures have aggravated this situation (Headey et al. 2020). The out-of-pocket costs on health care spent by the poorest billion due to NCDs and injuries may be high, accounting for 60–70% of the public health care costs in low-income and lower-middle-income countries (Zuccala and Horton 2020). In total, it has been estimated by the World Bank that under- and malnourishment costs 3% of global GDP, and overweight and obesity another 2% (Jaffee et al. 2019).

Women play a key role in multiple components of food systems and in decisions over food choices. Nonetheless, inequalities and barriers related to access to farming opportunities and services such as extension, credit, digital platforms for knowledge and market access constrain their participation relative to men (Quisumbing et al. 2011). Inequalities and barriers also affect the nutrition and health of minorities and off-farm and food system workers (including migrants and undocumented workers), which is a barrier to food system and societal transformation (CFS 2020).

Conflict and Fragility Conflict can be both a cause and an outcome of food insecurity. Increased competition for natural resources leads to conflict and political fragility, exacerbated by the failure of traditional conflict resolution mechanisms to adapt to the new governance system of communities (FAO, IFAD, UNICEF, WFP, WHO 2017). Government and political institutions (municipalities, legal systems and political party structures) have not adapted to the social fabric they presently govern, constraining development and also affecting development and the delivery of humanitarian aid.

While widespread famine has largely been eradicated, the nature of food crises has changed in recent times. The Food Security Information Network (FSIN 2020) reports that, in 2019, about 135 million people were affected by crisis levels of acute food insecurity, reflecting an increase of 11 million people from the previous year (FSIN 2020). While these crises are largely driven by conflict and economic downturns, they have a severe effect on the ability of people to access food. The provision of food transfers in emergency situations may alter the food preferences of communities, leading to changes in production and consumption post-conflict.

The largest numbers of acutely food-insecure people are in Africa, where extreme weather events in the continent's Horn and its southern region have led to widespread hunger. In many parts of the world, armed conflicts, intercommunal violence and other localised tensions create insecurity (FSIN 2020). Adverse climate events and stresses compound violence, displacement and disrupted agriculture and trade. Often, those affected by crises flee to neighbouring countries, putting additional stress on the international humanitarian response system and on the food systems of the host countries. Women and girls are disproportionately affected by crises. Populations in crisis are disproportionally vulnerable to the impact of the COVID-19 pandemic and have little capacity to cope with the health and socio-economic aspects of the shock (FSIN 2020). WFP predicts that the number of people in LMICs facing acute food insecurity will nearly double to 265 million by the end of 2020

(WFP 2020). Moreover, fragile and extremely fragile countries are disproportionally burdened by high levels of malnutrition compared to non-fragile countries (GNR 2020).

4.2 Supply Chain Failures and Under-Utilised Technologies Affecting the Supply of Food

The focus of food supply has shifted over the past few decades from ‘feeding the world’ to ‘nourishing the world’, but technological advancements still lag behind, and many supply-side factors and failures affect the ability of the food system to sustainably (see Box 1) ensure access to safe and nutritious food for all. In many developing countries (especially in Africa), supply chain failures and the under-utilisation of technology are major constraints on the ability of the transformation of food systems to achieve this access. More than half of the calories consumed by humans are provided by three major cereal crops (rice, maize, and wheat) with a high-calorie output, and current research investments are positively correlated with the energy output of crops, with a number of crop species (e.g., sweet potato, potato, wheat, broad bean, and lentil) remaining under-researched relative to their contribution to healthy human nutrition (Manners and van Etten 2018). Orphan crops that are usually well adapted to low-input agricultural conditions have received little attention from researchers (Tadele 2019). There is a growing recognition that the development of perennial versions of important grain crops and grasses could expand options for ensuring food and ecosystem security (Glover et al. 2020). Viable high biomass perennial grain crops could be further developed in agroecosystems that regenerate soils and capture other important ecosystem functions (Crews and Cattani 2018). In the same way, this lack of research applies to some fruit and vegetable crops and local livestock breeds, especially for small ruminants, as well as fish.

Closing yield gaps on underperforming lands and increasing cropping efficiency would have considerable potential to meet an increasing food demand (Foley et al. 2011). One main reason why yield gaps exist is that farmers do not have sufficient economic incentives to adopt yield-enhancing seeds or cropping techniques, including mechanisation, precision and digital agriculture. Moreover, a lack of access to extension services, to formal credit and cooperative membership, often limits technology adoption, which is associated with positive household welfare effects (Wossen et al. 2017). While efficiency and substitution are steps towards sustainable intensification, system redesign may be essential for agro-ecological intensification through, e.g., integrated pest management, conservation agriculture, integrated crop and biodiversity, pasture and forage, trees, irrigation management and small or patch systems (Pretty et al. 2018).

Currently, 25–30% of total food produced is lost or wasted (IPCC 2019), equating to about one-quarter of land, water, and fertiliser used for crop production (Shafiee-Jood and Cai 2016). Food losses and food waste occur throughout the food chain.

They constrain food system sustainability due to their adverse effects on food security, natural resources, environment, climate and human health (e.g., toxic emissions from incineration) (Xue et al. 2017).

Plant biotechnologies are mostly used for fibre and animal feed, less often for food, because of regulatory constraints and intellectual property rights barriers (Barrows et al. 2014). New and innovative technologies such as biotechnologies, precision agriculture and digital agriculture, alternative protein sources, underutilised food sources and the use of biomass for bioenergy and green chemicals need to be harnessed to improve food systems (reviewed below). However, such advances can also drive negative food system changes. For example, biofuel production based on grains from food crops can drive up staple food prices and increase competition for land, exacerbating inequalities.

4.3 Climate Change, Land-Use Change and Natural Resource Degradation

Climate change, including increases in the frequency and intensity of extremes, has adversely impacted food security, affecting the yields of some crops (e.g., maize and wheat) and the pastoral systems in low latitude regions (IPCC 2019). Climate change may aggravate food system problems in countries with delicate food security balances and relatively high levels of vulnerability to climate change due to the large-scale use of scarce resources (water, land, etc.) for feed and food production for exports, particularly in the case of mono cropping. Diets and cropping patterns may change as climate factors constrain the production of traditionally grown crops.

With increasing warming, the frequency, intensity and duration of heatwaves, droughts and extreme rainfall events are projected to increase in most world regions, increasingly threatening the stability of food supplies (IPCC 2019). For example, Gaupp et al. (2020) found an estimated 86% probability of losses across the world's maize breadbaskets with warming of 4 °C, compared to 7% probability for 2 °C warming under business-as-usual conditions and without considering crop adaptation to climate change. Likewise, in a business-as-usual scenario, Alae-Carew et al.'s (2020) review of predicted changes in environmental exposures has reported likely reductions in yields of non-staple vegetables and legumes. Where adaptation possibilities are limited, this may substantially change their global availability, affordability and consumption in the mid- to long term (Alae-Carew et al. 2020; Scheelbeek et al. 2018). The nutritional quality of crops may also be affected by rising atmospheric CO_2 levels through reduced proteins and micronutrient contents (IPCC 2019). Labour productivity is also likely to reduce with increasing temperatures (Watts et al. 2021).

The global food system (from farm inputs to consumers) emits about 30% of global anthropogenic greenhouse gases (GHG), contributes to 80% of tropical deforestation and is a main driver of land degradation and desertification, water scarcity and biodiversity decline (IPCC 2019). About one-quarter of the Earth's ice-free land area is subject to human-induced degradation and about 500 million people live within areas undergoing desertification (IPCC 2019). By 2050, land degradation and climate change could lead to a reduction of global crop yields by about 10%, with strong negative impacts in India, China and sub-Saharan Africa resulting in the displacement of up to 700 million people (Cherlet et al. 2018). Around two billion people live within watersheds exposed to water scarcity, a number that could double by 2050 (Gosling and Arnell 2016). Future agricultural productivity in the tropics is also at risk from a deforestation-induced increase in mean temperature and the associated heat extremes, as well as from a decline in rainfall (Lawrence and Vandecar 2015). Over half of the tropical forests worldwide have been destroyed since the 1960s, affecting the lives of one billion poor people whose livelihoods depend on forests and set to equal a mass extinction event should tropical deforestation continue unabated (Alroy 2017).

5 Transforming Food Systems Is Key to Safe and Nutritious Food for All

Business-as-usual is not an option with the future of food and nutrition security in jeopardy. Changing the path of our future will demand a structural transformation (transitioning from low productivity and labour-intensive economic activities to higher productivity, sustainable and skill-intensive activities) of food systems. This will require changes in the allocation of resources, and research attention to factors beyond production will be necessary in order to transition to more sustainable patterns of production and consumption (CFS 2020). More concerted effort is needed to coordinate activities, monitor progress more closely and extract greater accountability from all players across the food system. Priority should be given to the establishment of functional problem-solving institutions that address the core challenges facing each of the various components of the global food systems.

A global social compact (an implicit agreement among the members of a society to cooperate for social benefits) is needed to manage the demand and consumption drivers and harness science, technology and innovation for the purpose of improving the sustainable production of enough food to ensure access to affordable, safe and nutritious foods for all (Fig. 3). The sections below identify some of the levers for change.

5.1 Coordination, Monitoring and Accountability

The ambition of the CFS is to be "the most inclusive international and intergovernmental platform for all stakeholders to work together in a coordinated way to ensure food security and nutrition for all" (CFS 2021). Moreover, UN agencies and their

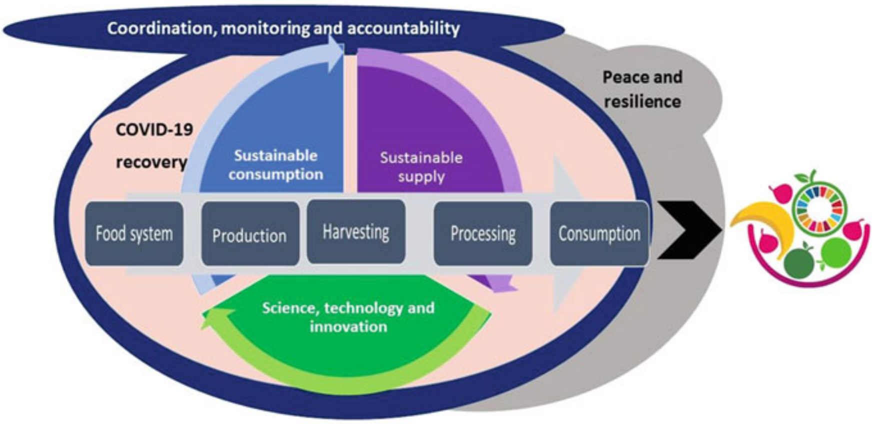


Fig. 3 Food system transformations and solutions related to Action Track 1

partners have converged through various mechanisms for food security coordination (e.g., FSIN, the Global Network Against Food Crises, expanding the SOFI collaborators, the CFS Global Strategic Framework, etc.). Strengthening global governance and accountability regarding safe and nutritious food for all and sustainable food systems is key to meeting the challenges ahead and will require the cross-sectoral integration of policies. Nonetheless, agriculture, development and trade policies that affect access to food, as well as other dimensions of food systems, are often dealt with in separate for a (De Schutter 2013). Therefore, improved coordination, monitoring and accountability across the food system and among all stakeholders is necessary, including knowledge-sharing, capacity-building, better measurement, updated data, better modelling for foresight, scenarios and case studies and access to documented success stories. Food systems bring together elements from various sectors of society: agriculture, consumer affairs, food processing, health, trade, water and sanitation, women's and child welfare, etc., challenging the sectoral organisation found in most countries.

If we are to transform food systems to ensure safe and nutritious food for all from a model of sustainability, a concerted effort is needed to develop a global compact – a non-binding agreement to encourage the transformation of food systems – and appropriate accountability of all stakeholders to monitor agreed-upon transformation targets. Integrated, science-based policies (health and nutrition, food and agriculture, climate and environment) would allow for reinforcing accountability at both national and international scales.

Advances in information technology and data science play an important role in enabling the rapid assessment of situations, monitoring and decision-making and adaptive learning. An integrated global food system model is needed, as existing models (see Valin et al. 2014; Khanna and Zilberman 2012) do not have consistent global coverage and are not designed to assess the impacts of all of the elements of food systems. Strengthening national policy scenarios and foresight is also necessary (Schmidt-Traub et al. 2019). Moreover, improved indicators of food systems (see FAO et al. 2020) are required (see Sukhdev 2018; Chaudhary et al. 2018, for examples) that could provide more holistic measures capturing the four elements addressed by Action Track 1, namely, safety, nutrition, inequality and sustainability.

Rigorous global monitoring systems require global collaboration, updated information, and investment with significant returns. The monitoring of underlying systemic risks (perhaps using artificial intelligence or machine learning), as well as food system indicators, is essential to identify threats/pressure at an earlier stage. A task force charged with global monitoring and data collection opportunities about agri-food systems could provide a clearinghouse for the multiple (often duplicated) data held by UN agencies and public and private organisations. While some effort has been made to coordinate international actions to address crises, access to food requires targeted interventions for the most vulnerable. Two-way real-time and artificial intelligence applications for collecting information of systemic risks and food systems and disseminating information to various stakeholders and beneficiaries are needed in last-mile and crises situations and in regions disproportionately affected by the COVID-19 pandemic food system disruptions. This could include driving supply-side demand through food banks, social grants, subsidised meals, vouchers and other food assistance (including through e-commerce systems) (WFP 2017).

5.2 Influencing Food Demand and Dietary Changes

There are several ways to reduce demand on the global food system in both the short and long term and make nutritious foods more available and affordable (see Herrero et al. 2021). Some of these may be achieved by accelerating demographic transitions, increasing incomes, reducing food losses and waste and changing diets.

Household food waste is proliferating in emerging economies and is likely to increase without deliberate efforts to curb it (Barrera and Hertel 2020). Halving food losses and waste is a target of SDG 12 that could help feed more people, benefit climate and the environment and conserve water (Kummu et al. 2012; Searchinger et al. 2018; IPCC 2019). This requires changes along supply chains (agricultural production, food processing, distribution/retail, restaurant food service, institutional food service, and households) through improved logistics and processing technologies, economic incentives, regulatory approaches and education campaigns (Barrera and Hertel 2020). The amount of food waste/loss varies greatly from region to region, and therefore context-specific interventions are crucial (Hodson et al. 2021).

Private investment is needed to develop food processing, refrigeration, storage, warehousing, and retail markets to reduce food waste. Vertical integration of food chains can shorten said chains to the benefit of smallholder farmers, while trade can expand market opportunities. Compared to a business-as-usual scenario, a combined scenario targeting undernourishment while also reducing over-consumption and food waste would reduce food demand by 9% in 2050 (Hasegawa et al. 2018).

Because of the strong associations between female education, fertility and infant mortality, alternative education scenarios alone (assuming similar education-specific fertility and mortality levels) lead to a difference of more than one billion people in the world population sizes projected for 2050 (Lutz and Samir 2011; Samir and Lutz 2017), and could therefore reduce the rise in food demand.

Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, complemented by animal-sourced food produced in resilient, sustainable and low-GHG emission systems present major opportunities for the adaptation and mitigation of climate change while generating significant co-benefits in terms of human health (Springmann et al. 2018; IPCC 2019; Jarmul et al. 2020). 'Healthy sustainable diets' can be defined by optimisation procedures (Donati et al. 2016). However, most diets have trade-offs among nutritional values, affordability and environmental issues (Headey and Alderman 2019).

Populations with a high prevalence of undernutrition and micronutrient deficiencies (Fanzo 2019) benefit from increasing the consumption of animal-sourced products due to the bioavailability of key micro-nutrients (Perignon et al. 2017). Many highly nutritious foods may simply be unaffordable to poorer populations and displaced by cheap, nutrient-poor foods. Moreover, a balance is necessary between meeting the demand for diversified, nutritious and affordable food and minimising the time and energy needed to prepare meals.

Policies can create incentives for change. Urgent public policy action is needed to create incentives for creating healthy, sustainable food systems and delivering safe, nutritious and affordable foods for all. Policy options could be used to manage food demand, shift consumption patterns, reduce the environmental footprint of food systems and ensure equity across the food system. A wide range of well-established and relatively inexpensive policy options and interventions are available for improving nutrition at the individual level (Bukhman et al. 2020; Hawkes et al. 2019; Bhutta et al. 2008). Policies that enable healthy food environments (such as sugar taxes, educational food labelling, salt reduction, the prohibition of trans-fats and a reduction in the use of high-fructose corn syrup) are core to improving food environments and limiting the burden of NCDs. Increasing the diversity of food sources in public procurement, health insurance, financial incentives and awareness-raising campaigns can potentially influence food demand, reduce healthcare costs, contribute to reducing GHG emissions and enhance adaptive capacity.

Increased income can drive food demand, especially in terms of diversification away from staple crops to more diverse and nutrient-dense foods (diary, fruit, meat, nuts and vegetables). Likewise, income from social protection programmes can drive changes in dietary composition and quality (Alderman 2016). The evidence reviewed in this paper indicates that subsidies on fortified foods can have positive nutritional effects, and in-kind transfers may limit food deficits during periods of currency or price volatility. The affordability of healthy diets can be improved with the distribution of biofortified food in government schemes, cash transfers and nutrition programmes. However, price subsidies and in-kind assistance have complex interactions in regard to markets and purchasing decisions, with both negative implications and benefits (Alderman 2016).

5.3 Shifting to More Sustainable Consumption and Production Within Planetary Boundaries

Nutrition outcomes in developing countries are affected by agriculture in several ways: as a source of food for household consumption and of income, through the role of food prices and agricultural policies, through the role of women's employment in agriculture for nutrition, child care and child feeding and their own nutritional and health status (Gillespie and van den Bold 2017).

There are more than 570 million farms worldwide, most of which are small and family-operated. Between 1960 and the turn of the century, the average farm size decreased in most lower- to middle-income countries, whereas it increased in most high-income countries (Lowder et al. 2016). The diversity of agricultural production diminishes as farm size increases (Herrero et al. 2017). Hence, as farm size increases, the production of diverse nutrients and viable, multifunctional, sustainable landscapes requires efforts to maintain production diversity, which may lead to increased dietary diversity (Pellegrini and Tasciotti 2014). Targeted policies that focus on the farmer may incentivise positive changes in landscapes, production diversity and dietary diversity.

In turn, diversification in the food system (e.g., implementation of agro-ecological production systems, broad-based genetic resources, combined with balanced diets) can enhance adaptation to increased climate variability under climate change (IPCC 2019). Diversified agro-ecological systems can play a role in meeting health and nutrition goals while also reducing environment-related health risks caused by conventional agriculture through water and air pollution, and more specifically, by pesticides, antibiotics and inorganic fertilisers (Frison and Clément 2020). Compared to conventional agriculture, organic agriculture generally has a positive effect on a range of environmental factors, including above and below-ground biodiversity, soil carbon stocks and soil quality and conservation, but it has weaknesses in terms of lower productivity and reduced yield stability (Knapp and van der Heijden 2018).

Sustainable land management can bridge yield gaps and avoid deforestation while providing climate change adaptation and mitigation and land degradation co-benefits in croplands and pastures (Smith et al. 2020). This can be achieved through increased organic carbon in soil (Soussana et al. 2019), agroforestry, erosion and fire control, improved irrigation water and fertiliser management, and heat- and drought-tolerant plants (Smith et al. 2020). For livestock, sustainable options include better grazing land management, improved manure management, higher-quality feed, and use of breeds and genetic improvement (Herrero et al. 2016). Under stringent global climate change mitigation policy, risks to food security would be increased (Hasegawa et al. 2018) through competition among those seeking land use for, respectively, food production, bioenergy and afforestation, be it driven by local or foreign investment in land (Cotula et al. 2014). Nevertheless, increasing and valuing soil carbon sequestration on agricultural land would allow for the reduction of these negative impacts by approximately two-thirds (Frank et al. 2017). The large-scale deployment of bioenergy options such as afforestation, energy crops, carbon capture and storage has adverse effects on food security, but small scale projects with best practices may deliver co-benefits (Smith et al. 2020).

Increased demand for fish and seafood has threatened fisheries and the sustainability of ocean resources. Limited attention has been given to fish as a key element in food security and nutrition (HLPE 2014). The aquaculture industry has emerged and increasingly fills the seafood supply gap to meet growing demand. Overfishing and relatively high waste (often due to catching under-sized fish) pose environmental and biodiversity challenges, threatening the long-term sustainability of fishery resources (HLPE 2014). Additional challenges in production facilities such as marine feed supply, antibiotic use and waste recycling need to be overcome to further develop aquaculture (Belton et al. 2020). The impacts of activities such as oil drilling, energy installations, coastal development and the construction of ports and other coastal infrastructures, dams and water flow management (especially for inland fisheries) affect aquatic productivity. The impact of these activities on the habitats that sustain resources (e.g., erosion and pollution) and the livelihoods of fishing communities – such as the denial of access to fishing grounds or displacement from coastal settlements – need to be carefully balanced with the growing demand for resources (HLPE 2014).

Ensuring that food prices reflect real costs, including major externalities caused by climate change, land and water resource degradation and biodiversity loss, is necessary in order to address artificial price distortions, reduce food waste, internalise the costs of externalities (including the public health impacts) and, at the same time, ensure decent incomes and wages for farmers and food system workers. However, a true calculation of food costs would, on average, increase food prices. Food assistance policies that do not distort market and labour incentives can meet emergency food needs and improve access to food. Trade can help to improve food availability, diversify diets and smooth price volatility (MacDonald et al. 2015).

5.4 Harnessing Science and Innovation and Managing Risks

Structural transformation to a more sustainable food system can bring about efficient and more rapid productivity growth through investment in research and development over the long term (Fuglie et al. 2020). Science should increasingly inform solutions and generate knowledge that is actionable for transforming food systems and achieving safe and nutritious food for all (Arnott et al. 2020). Since policy agendas are largely set at national and local scales, the translation of global-scale scientific assessments into actionable knowledge at national and local scales is needed.

New and emerging technologies appropriate for health, climate change adaptation and mitigation, and disaster preparedness could be game-changers for overcoming challenges and building system resilience. Nonetheless, their development should be guided by an assessment of their socio-economic, ethical and environmental impacts. Evidence-based assessment is needed of the risks and benefits associated with new technologies. Research is also needed to understand the diffusion modes of traditional knowledge and social innovations for supporting the conservation of common goods in more participatory, collaborative, inclusive and equitable ways.

Advances in science and technology such as genome editing (Khatodia et al. 2016), precision agriculture and digital agriculture (Basso and Antle 2020), agro-ecology (Caquet et al. 2020), vertical farming, alternative protein sources (e.g., algae, insects), active packaging and blockchain technologies (Kamilaris et al. 2019), artificial intelligence and big data analysis (Wolfert et al. 2017) and whole-genome sequencing in food safety (Deng et al. 2016) have the potential to meet a number of food system challenges. However, adapting these technologies to local conditions, making them accessible to farmers and retaining much of the gain among consumers and rural communities is challenging, especially for developing economies, smallholder farmers and small businesses. Therefore, investments in science-based, participatory processes for mapping out realistic and equitable options are needed (Basso and Antle 2020).

The importance of agriculture in producing non-food products (biofuels, chemicals, biomaterials) and in supporting ecosystem services is increasingly recognised within the context of the bioeconomy, which targets an increased reliance on renewable resources to address climate change (Zilberman 2014). A circular bioeconomy envisions developments in industrial biotechnologies to generate co-products, by-products and waste recycling, thereby generating an overall increased input efficiency of agricultural systems that produce bio-based products in diversified agro-ecological landscapes (Therond et al. 2017; Maina et al. 2017).

Global and regional data-sharing systems (including machine learning) based on the FAIR (findable, accessible, interoperable and reusable data) principles (Mons et al. 2017) can advance food system knowledge and enhance the accountability of all stakeholders within food systems. The use of open-source platforms for data- and code-sharing should be encouraged to stimulate global learning.

Table 1 shows the fragmented nature of data related to this Action Track, with global reports focussing on single elements. National nutrition assessments are costly and infrequently conducted, constraining the monitoring of progress and the impact of interventions at scale. Even where the indicators have been included in the SDG indicator set, current data on foodborne diseases, some malnutrition indicators (such as wasting), poverty and inequality data are not updated or are missing comparative baselines. Very few sex-disaggregated indicators are available, constraining analysis and the tracking of progress towards gender equality. The upcoming *Countdown on Food System Transformation* mechanism may support the effort to bring together various indicators in a systematic framework for monitoring and evaluation.

Increasingly, risk assessment tools will be needed to drive food safety policy and standards and optimise surveillance, detection and early warning systems of zoonotic diseases for both the formal and informal sectors (Di Marco et al. 2020) and crop diseases (Mohanty et al. 2016). Modernising our food safety and biosecurity risk management systems is an integral part of the food system transformation required to meet food and nutrition security needs. This will require a science- and risk-based approach for production of safe food within a food systems approach.

6 Concluding Messages

Action to address safety, malnutrition, poverty and inequality, as well as climate and environmental issues, through food system transformation will undoubtedly bring large health, social, economic, ecological and development co-benefits and savings for public expenditure while supporting several interrelated SDGs. A range of priority actions to speed up progress towards international targets and scale up the solutions proposed in Sect. 5 can be taken in the short-term, based on existing knowledge, while supporting longer, more sustainable responses with significant co-benefits. Future actions will have to be iterative, coherent, adaptive and flexible to maximise co-benefits and minimise trade-offs. Many recommended policy changes and interventions have win-win potential for food security, health and the environment. However, other choices will have adverse or unintended impacts on the interconnected drivers affecting food systems and their outcomes.

Adopting a whole-system approach in policy, research and monitoring and evaluation is crucial for managing trade-off and externalities from farm-level to national scales and across multiple sectors and agencies. Ultimately, context matters, and comprehensive national action plans are crucial for setting out actions suited to the particular economic, agricultural, social and dietary preferences of the particular nation. Careful consideration of the trade-offs and co-benefits of any actions will be necessary at different levels (sub-national, national, regional and global). Likewise, there may be ‘winners’ and ‘losers’ in each action adopted to transform to more sustainable food systems. The losses and gains will vary depending on the context, but could include a loss of income and livelihoods across the food system, such as would happen with a reduction in the production and consumption of animal-sourced foods or the implementation of seasonal banning of fishing to allow for the regeneration of marine resources. Such shifts could lead to the marginalisation and stigmatisation of people in the food system who have not yet been considered as vulnerable or marginalised.

Including all stakeholders in discussions, policy-making and evaluation processes is essential for the inclusive transformation of food systems at all levels. Strengthening collaboration among research, the private sector and policy-makers is pivotal in creating food environments and guiding consumers’ choices in practical and implementable ways. The elaboration and implantation of the National Food

Systems Plans will be essential instruments for bringing the relevant public sectors and diverse stakeholders together.

Adaptive learning and new knowledge must be shared globally in order to accelerate our capacities to meet existing and future challenges. Substantial public, private and international investment is necessary to foster progress towards the targets and recover from the setbacks of the COVID-19 pandemic. Improved international cooperation and coordination of the food system is necessary, including the establishment of a thorough monitoring, evaluation and early warning system with comprehensive indicators, transparency and commitments from all stakeholders. For example, bringing all of the indicators in Table 1 into one annual food system monitoring report would facilitate cooperation among UN agencies. Creating a food system compass could be based on bottom-up pathways developed at the national scale to reach food systems targets supporting an ensemble of global-scale and integrative food system models. Establishing such a system will require capacity development for comprehensive foresight, scenario and predictive modelling to better understand uncertainties, trade-offs and impacts of various change pathways. More research is needed to identify the most adequate, affordable, healthy and sustainable diets across different contexts. More frequently collected nutrition and poverty data are necessary to provide more data points for monitoring change and progress. Innovative indicators such as the affordability of adequate, nutritious and healthy diets are vital for bringing the three elements of safety, nutrition and inequality together.

The costs of acting and not acting on the key drivers of diet and food system change and the impact of these changes and shifts are required for effective decision-making. For example, the cost of nutrition interventions is relatively low per unit compared to the long-term losses in human potential and incomes for poorer people. The cost of NCDs to the health system is significantly higher per unit than that of scalable interventions. Rapid reductions in anthropogenic GHG emissions across all sectors can reduce the negative impacts of climate change on food systems in the long term (similar to land and water restoration).

Research and technology advances are essential for solving critical constraints and offering many opportunities to improve productivity and food safety and reduce food losses and waste, as well as GHG emissions. Capacity-building, property rights, technology development, transfer and deployment and enabling financial mechanisms across the food system can support livelihoods and increase incomes. Greater cooperation regarding trade could overcome constraints and barriers.

Safe and nutritious food for all requires a transformation of food systems, changing both supply and demand of food in differentiated ways across world regions: bridging yield gaps and improving livestock feed conversion, largely through agro-ecological practices and agroforestry, deploying soil carbon sequestration and agricultural greenhouse gas abatement at scale, reducing food loss and waste, as well as addressing over-nourishment and changing the diets of wealthy populations. Global food system sustainability also requires halting the expansion of agriculture into fragile ecosystems while restoring degraded forests, fisheries, rangelands, peatlands and wetlands.

Acknowledgements Helpful comments on an earlier draft by five external peer reviewers and by colleagues in the Scientific Group are gratefully acknowledged.

References

Alae-Carew C, Nicoleau S, Bird FA, Hawkins P, Tuomisto HL, Haines A, Dangour A, Scheelbeek FP (2020) The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. Environ Res Lett 15:023002

Alderman H (2016) Leveraging social protection programs for improved nutrition: summary of evidence prepared for the global forum on nutrition-sensitive social protection programs, 2015. World Bank, Washington, DC

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations, Rome

Alroy J (2017) Effects of habitat disturbance on tropical forest biodiversity. Proc Natl Acad Sci 114(23):6056–6061

Arnott JC, Mach KJ, Wong-Parodi G (2020) Editorial overview: the science of actionable knowledge. Curr Opin Environ Sustain 42:A1–A5

Barrera, E. L., Hertel, T. (2020). Global food waste across the income spectrum: Implications for food prices, production and resource use. Food Policy 98C:101874.

Barrows G, Sexton S, Zilberman D (2014) Agricultural biotechnology: the promise and prospects of genetically modified crops. J Econ Perspect 28(1):99–120.

Barthel S, Isendahl C, Vis BN, Drescher A, Evans DL, van Timmeren A (2019) Global urbanization and food production in direct competition for land: leverage places to mitigate impacts on SDG2 and on the earth system. Anthropocene Rev 6(1–2):71–97

Basso B, Antle J (2020) Digital agriculture to design sustainable agricultural systems. Nat Sustain 3(4):254–256

Belton B, Reardon T, Zilberman D (2020) Sustainable commoditization of seafood. Nat Sustain 3: 677–684. https://doi.org/10.1038/s41893-020-0540-7

Bhutta A, Ahmed T, Black RE, Cousens S, Dewey K, Giugliani E et al (2008) What works? Interventions for maternal and child undernutrition and survival. Lancet 371(9610):p417–p440. https://doi.org/10.1016/S0140-6736(07)61693-6

Bukhman G, Mocumbi AO, Atun R et al for the Lancet NCDI Poverty Commission Study Group (2020) The lancet NCDI poverty commission: bridging a gap in universal health coverage for the poorest billion. Lancet 396(10256):991–1044. https://doi.org/10.1016/S0140-6736(20)31907-3

Caquet T, Gascuel C, Tixier-Boichard M (2020) Agroecology: research for the transition of agri-food systems and territories. Quae, Versailles, 96 pp. ISBN: 9782759232949

Chaudhary A, Gustafson D, Mathys A (2018) Multi-indicator sustainability assessment of global food systems. Nat Commun 9(1):1–13

Cherlet M, Hutchinson C, Reynolds J, Hill J, Sommer S, von Maltitz G (eds) (2018) World Atlas of desertification. Publication Office of the European Union, Luxembourg

Committee on World Food Security (CFS). (2020) CFS voluntary guidelines on Food Systems for Nutrition (VGFSyN). Draft for negotiations. CFS, Rome. http://www.fao.org/fileadmin/templates/cfs/Docs1920/Nutrition_Food_System/CFS_Voluntary_Guidelines_Food_Systems_Nutrition_Draft_for_Negotiations_16Mar.pdf

Committee on World Food Security (CFS) (2021) About the CFS. CFS, Rome. http://www.fao.org/cfs/home/about/en/. Accessed online 14 Mar 2021

Cotula L, Oya C, Codjoe EA, Eid A, Kakraba-Ampeh M, Keeley J, Asare RO (2014) Testing claims about large land deals in Africa: findings from a multi-country study. J Dev Stud 50(7):903–925

Crews TE, Cattani DJ (2018) Strategies, advances, and challenges in breeding perennial grain crops. Sustainability 10(7):1–7
De Schutter O (2013) The reform of the committee on world food security: the quest for coherence in global governance. Centre de philosophie du droit (CRIDHO), working paper 2013/8. Université catholique de Louvain, Louvain-la-Neuve
Deng X, den Bakker HC, Hendriksen RS (2016) Genomic epidemiology: whole-genome-sequencing–powered surveillance and outbreak investigation of foodborne bacterial pathogens. Annu Rev Food Sci Technol 7:353–374
Devleesschauwer B, Haagsma JA, Mangen MJJ, Lake RJ, Havelaar AH (2018) The global burden of foodborne disease. In: Roberts T (ed) Food safety economics, Food microbiology and food safety. Springer, Cham. https://doi.org/10.1007/978-3-319-92138-9_7
Di Marco M, Baker ML, Daszak P, De Barro P, Eskew EA, Godde CM et al (2020) Opinion: sustainable development must account for pandemic risk. Proc Natl Acad Sci 117(8):3888–3892
Donati M, Menozzi D, Zighetti C, Rosi A, Zinetti A, Scazzina F (2016) Towards a sustainable diet combining economic, environmental and nutritional objectives. Appetite 106:48–57
Drewnowski A (2005) Concept of a nutritious food: toward a nutrient density score. Am J Clin Nutr 82:721–732
Fanzo J (2019) Healthy and sustainable diets and food systems: the key to achieving sustainable development goal 2? Food Ethics 4:159–174
FAO (2011) Global food losses and food waste: extent, causes and prevention. FAO, Rome
FAO (2018) The future of food and agriculture – alternative pathways to 2050. FAO, Rome
FAO, IFAD, UNICEF, WFP, WHO (2017) The state of food security and nutrition in the world 2017. FAO, Rome
FAO, IFAD, UNICEF, WFP, WHO (2020) The State of Food Security and Nutrition in the World 2020. FAO, Rome
Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M et al (2011) Solutions for a cultivated planet. Nature 478(7369):337–342
Fore H, Dongyu Q, Beasley D, Ghebreyesus T (2020) Child malnutrition and COVID-19: the time to act is now. Lancet 396(10250):517–518
Frank S, Havlík P, Soussana JF, Levesque A, Valin H, Wollenberg E et al (2017) Reducing greenhouse gas emissions in agriculture without compromising food security. Environ Res Lett 12(10):105004
Frison E, Clément C (2020) The potential of diversified agroecological systems to deliver healthy outcomes: making the link between agriculture, food systems & health. Food Policy 96C:101851
FSIN (Food Security Information Network) (2020) 2020 global report on food crises: joint analysis for better decisions. FSIN, Rome
Fuglie K, Gautam M, Goyal A, Maloney WF (2020) Harvesting prosperity: technology and productivity growth in agriculture. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/32350
GAIN (Global Alliance for Improved Nutrition) (2017) What constitutes a nutritious and safe food? GAIN, Geneva. Available from: https://www.gainhealth.org/sites/default/files/publications/documents/gain-nutritious-food-definition.pdf
Gaupp F, Hall J, Hochrainer-Stigler S, Dadson S (2020) Changing risks of simultaneous global breadbasket failure. Nat Clim Chang 10(1):54–57
Gerten D, Heck V, Jägermeyr J, Bodirsky BL, Fetzer I, Jalava M et al (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat Sustain 3(3):200–208
Gillespie S, van den Bold M (2017) Agriculture, food systems, and nutrition: meeting the challenge. Global Chall 1(3):1600002
Glover JD, Reganold JP, Bell LW, Borevitz J, Brummer EC, Buckler ES, Cox CM et al (2020) Increased food and ecosystem security via perennial grains. Science 328(5986):1638–1639
GNR (Global Nutrition Report) (2020) 2020 global nutrition report: action on equity to end malnutrition. Development Initiatives, Bristol

Gosling SN, Arnell NW (2016) A global assessment of the impact of climate change on water scarcity. Clim Chang 134(3):371–385
Hasegawa T, Fujimori S, Havlík P, Valin H, Bodirsky BL, Doelman JC et al (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang 8(8):699–703
Hawkes C, Ruel MT, Salm L, Sinclaire B, Branca F (2019) Double-duty actions: seizing programme and policy opportunities to address malnutrition in all its forms. Lancet 395(10218):142–155. https://doi.org/10.1016/S0140-6736(19)32506-1
Headey D, Alderman H (2019) The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. J Nutr 149(11):2022–2033
Headey D, Heidkamp R, Osendorp S, Ruel M, Scott N, Flory A et al (2020) Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. Lancet 396:519–521
Herrero M, Henderson B, Havlík P, Thornton PK, Conant RT, Smith P, Wirsenius S, Hristov AN, Gerber P, Gill M (2016) Greenhouse gas mitigation potentials in the livestock sector. Nat Clim Chang 6(5):452–461
Herrero M, Thornton PK, Power B, Bogard JR, Remans R, Fritz S et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):e33–e42
Herrero M, Hugas M, Lele U, Wira M, Torero M (2021) Shift to healthy and sustainable consumption patterns. A paper from the scientific group of the UN food systems summit. UN, New York
HLPE (2014) Sustainable fisheries and aquaculture for food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome
HLPE (2020) Food security and nutrition: building a global narrative towards 2030. HLPE, Rome
Hodson E, Niggli U, Kaoru K, Lal R, Sadoff C (2021) Boost nature positive production at sufficient scale – a paper on action track 3. A paper from the Scientific Group of the UN Food Systems Summit. UN, New York
INFOSAN (2019) INFOSAN activity report 2018–2019. World Health Organization and Food and Agriculture Organization of the United Nations; 2020. Geneva. https://www.who.int/publications/i/item/9789240006928
IPCC (2019) Climate change and land, an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC. www.ipcc.ch/report/srcc
Jaffee S, Henson S, Unnevehr L, Grace D, Cassou E (2019) The safe food imperative: accelerating progress in low- and middle-income countries. International Bank for Reconstruction and Development and the World Bank, Washington, DC. Accessed 4 Feb 2020. https://openknowledge.worldbank.org/handle/10986/30568
Janssens C, Havlík P, Krisztin T, Baker J, Frank S, Hasegawa T et al (2020) Global hunger and climate change adaptation through international trade. Nat Clim Chang 10:829–835
Jarmul S, Dangour AD, Green R, Liew Z, Haines A, Scheelbeek P (2020) Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets'. Environ Res Lett 15(2020):123014
Kamilaris A, Fonts A, Prenafeta-Boldύ FX (2019) The rise of blockchain technology in agriculture and food supply chains. Trends Food Sci Technol 91:640–652
Katz DL, Doughty K, Njike V, Treu JA, Reynolds J, Walker J, Smith E, Katz C (2011) A cost comparison of more and less nutritious food choices in US supermarkets. Public Health Nutr 14(9):1693–1699
Khanna M, Zilberman D (2012) Modeling the land-use and greenhouse-gas implications of biofuels. Clim Change Econ 3(03):1250016
Khatodia S, Bhatotia K, Passricha N, Khurana SMP, Tuteja N (2016) The CRISPR/Cas genome-editing tool: application in improvement of crops. Front Plant Sci 7:506

Khoury CK, Bjorkman AD, Dempewolf H, Ramirez-Villegas J, Guarino L, Jarvis A et al (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci 111(11):4001–4006

Knapp S, van der Heijden MG (2018) A global meta-analysis of yield stability in organic and conservation agriculture. Nat Commun 9(1):1–9

Kummu M, de Moel H, Porkka M, Siebert S, Varis O, Ward PJ (2012) Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci Total Environ 438:477–489

Laborde D, Martin W, Swinnen J, Vos R (2020) COVID-19 risks to global food security. Science 369(6503):500–502

Lawrence D, Vandecar K (2015) Effects of tropical deforestation on climate and agriculture. Nat Clim Chang 5(1):27–36

Lowder SK, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev 87:16–29

Lutz W, Samir KC (2011) Global human capital: integrating education and population. Science 333(6042):587–592

MacDonald GK, Brauman KA, Sun S, Carlson KM, Cassidy ES, Gerber JS, West PC (2015) Rethinking agricultural trade relationships in an era of globalization. BioScience 65(3): 275–289. https://doi.org/10.1093/biosci/biu225

Maina S, Kachrimanidou V, Koutinas A (2017) A roadmap towards a circular and sustainable bioeconomy through waste valorization. Curr Opin Green Sustain Chem 8:18–23

Manners R, van Etten J (2018) Are agricultural researchers working on the right crops to enable food and nutrition security under future climates? Glob Environ Chang 53:182–194

Martorell R (2017) Improved nutrition in the first 1000 days and adult human capital and health. Am J Hum Biol 29. https://doi.org/10.1002/ajhb.22952

Masters WA, Bai Y, Herforth A, Sarpong DB, Mishili F, Kinabo J, Coates JC (2018) Measuring the affordability of nutritious diets in Africa: price indexes for diet diversity and the cost of nutrient adequacy. Am J Agric Econ 100(5):1285–1301. https://doi.org/10.1093/ajae/aay059

Mohanty SP, Hughes DP, Salathé M (2016) Using deep learning for image-based plant disease detection. Front Plant Sci 7:1419

Mons B, Neylon C, Velterop J, Dumontier M, da Silva Santos LOB, Wilkinson MD (2017) Cloudy, increasingly FAIR: revisiting the FAIR data guiding principles for the European Open Science Cloud. Inf Serv Use 37(1):49–56

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C, Gerber P (2017) Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob Food Sec 14:1–8

Neufeld L, Hendriks SL, Hugas M (2021) Healthy diet: a definition for the United Nations Food systems summit 2021. A paper from the scientific group of the UN food systems summit. UN, New York

Pellegrini L, Tasciotti L (2014) Crop diversification, dietary diversity and agricultural income: empirical evidence from eight developing countries. Can J Dev Stud 35(2):211–227

Perignon M, Vieux F, Soler L, Masset G, Darmon N (2017) Improving diet sustainability through evolution of food choices: review of epidemiological studies on the environmental impact of diets. Nutr Rev 75(1):2–17

Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HC et al (2018) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1(8): 441–446

Quisumbing A, Meinzen-Dick R, Behrman J, Basset J (2011) Gender and the global food-price crisis. Dev Pract 21(4–5):488–492

Rosa L, Chiarelli DD, Tu C, Rulli MC, D'Odorico P (2019) Global unsustainable virtual water flows in agricultural trade. Environ Res Lett 14(11):114001

Ruel MT, Quisumbing AR, Balagamwala M (2018) Nutrition-sensitive agriculture: what have we learned so far? Glob Food Sec 17:128–153

Samir KC, Lutz W (2017) The human core of the shared socio-economic pathways: population scenarios by age, sex and level of education for all countries to 2100. Glob Environ Chang 42: 181–192

Scheelbeek P, Bird FA, Tuomisto HL, Green R, Harris FB, Joy E, Chalabi Z, Allen E, Haines A, Dangour AD (2018) Effect of environmental changes on vegetable and legume yields and nutritional quality. Proc Natl Acad Sci U S A 115(26):6804–6809. https://doi.org/10.1073/pnas.1800442115

Schmidt-Traub G, Obersteiner M, Mosnier A (2019) Fix the broken food system in three steps. Naturecom (comment) 569(7755):181–183

Searchinger T, Waite R, Hanson C, Ranganathan J (2018) Creating a sustainable food future: a menu of solutions to feed nearly 10 billion people by 2050: a synthesis report. World Bank, Washington, DC

Shafiee-Jood M, Cai X (2016) Reducing food loss and waste to enhance food security and environmental sustainability. Environ Sci Technol 50(16):8432–8443. https://doi.org/10.1021/acs.est.6b01993

Smith P, Calvin K, Nkem J, Campbell D, Cherubini F, Grassi G et al (2020) Which practices codeliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Glob Chang Biol 26(3):1532–1575

Soussana JF, Lutfalla S, Ehrhardt F, Rosenstock T, Lamanna C, Havlík P et al (2019) Matching policy and science: rationale for the '4 per 1000-soils for food security and climate' initiative. Soil Tillage Res 188:3–15

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L et al (2018) Smarter metrics will help fix our food system. Nature 558(7708):7–8

Sukhdev P (2018) Smarter metrics will help fix our food system. Nature 558(7708):7–8. https://doi.org/10.1038/d41586-018-05328-1

Tadele Z (2019) Orphan crops: their importance and the urgency of improvement. Planta 250:677–694

Therond O, Duru M, Roger-Estrade J, Richard G (2017) A new analytical framework of farming system and agriculture model diversities. A review. Agron Sustain Dev 37(3):21

UN United Nations (2021) Sustainable development goal 1: end poverty in all its forms everywhere. https://www.un.org/sustainabledevelopment/poverty/. Accessed 6 Mar 2021

UNDESA United Nations, Department of Economic and Social Affairs, Population Division (2019) World population prospects 2019: highlights (ST/ESA/SER.A/423)

UNICEF, WHO, the World Bank (2020) Levels and trends in child malnutrition: UNICEF/WHO/World Bank Group joint child malnutrition estimates. UNICEF/WHO/The World Bank, Geneva/Washington, DC

Valin H, Sands RD, Van der Mensbrugghe D, Nelson GC, Ahammad H, Blanc E et al (2014) The future of food demand: understanding differences in global economic models. Agric Econ 45(1): 51–67

van Vliet J, Eitelberg DA, Verburg PH (2017) A global analysis of land take in cropland areas and production displacement from urbanisation. Glob Environ Chang 43:107–115

Von Braun J, Afsana K, Fresco L, Hassan M, Torero M (2021) Food systems – definition, concept and application for the UN food systems summit. A paper from the scientific group of the UN food systems summit. UN, New York

Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Beagley J, Belesova K et al (2021) The 2020 report of the lancet countdown on health and climate change: responding to converging crises. Lancet 397(10269):129–170

WFP (2017) World food assistance report 2017: taking stock and looking ahead. WFP, Rome

WFP (2020) COVID-19 will double number of people facing food crises unless swift action is taken. Retrieved from https://www.wfp.org/news/covid-19-will-doublenumber-people-facing-food-crises-unless-swift-action-taken

WHO (2013) Advancing food safety initiatives: strategic plan for food safety including foodborne zoonoses 2013–2022. World Health Organization, Geneva. https://apps.who.int/iris/bitstream/handle/10665/101542/9789241506281_eng.pdf;jsessionid=2CA0920F1CE46F365F5C65D9664C0A94?sequence=1

WHO (2015a) WHO estimates of the global burden of foodborne diseases: foodborne disease burden. WHO, Geneva
WHO (2015b) World report on aging and health. WHO, Geneva
WHO (2020) Dietary recommendations: nutritional requirements; establishing human nutrient requirements for worldwide application. WHO, Geneva. https://www.who.int/nutrition/topics/nutrecomm/en/
WHO, UNICEF (2017) The extension of the 2025 maternal, infant and young child nutrition targets to 2030. Discussion paper. WHO/UNICEF, Geneva/New York
Wolfert S, Ge L, Verdouw C, Bogaardt MJ (2017) Big data in smart farming–a review. Agric Syst 153:69–80
World Bank (2018) Poverty and shared prosperity 2018: piecing together the poverty puzzle. World Bank, Washington, DC
World Food Programme (2020) COVID-19 will double number of people facing food crises unless swift action is taken. https://www.wfp.org/news/covid-19-will-double-number-people-facing-food-crises-unless-swift-action-taken
Wossen T, Abdoulaye T, Alene A, Haile MG, Feleke S, Olanrewaju A, Manyong V (2017) Impacts of extension access and cooperative membership on technology adoption and household welfare. J Rural Stud 54:223–233
Xue L, Liu G, Parfitt J et al (2017) Missing food, missing data? A critical review of global food losses and food waste data. Environ Sci Technol 51(12):6618–6633. https://doi.org/10.1021/acs.est.7b00401
Zilberman D (2014) Fellows address: the economics of sustainable development. Am J Agric Econ 96(2):385–396
Zilberman D, Lu L, Reardon T (2019) Innovation-induced food supply chain design. Food Policy 83:289–297
Zuccala E, Horton R (2020) Reframing the NCD agenda: a matter of justice and equity. Lancet 396(10256):939–940. https://doi.org/10.1016/S0140-6736(20)31910-3

A Shift to Healthy and Sustainable Consumption Patterns

Mario Herrero, Marta Hugas, Uma Lele, Aman Wirakartakusumah, and Maximo Torero

1 Introduction

There is global convergence on the need to transform food systems so that they deliver nourishment and health for humanity while contributing to reducing the environmental pressures on our ecosystems. Transforming food systems involves five action tracks: AT1) access to safe and nutritious food, AT2) sustainable consumption, AT3) nature-positive production, AT4) equitable livelihood, and AT5) resilience to shocks and stress. As discussed in Action Track 1, we are not on track to meet international targets related to healthy diets. Currently, 690 million people are chronically malnourished, and two billion individuals suffer micronutrient deficiencies. Over-consumption, notably of unhealthy dietary items, is rising rapidly. Two billion people are overweight or obese, with many suffering chronic diseases driven by poor dietary health (Development Initiatives, 2020; Global Panel on Agriculture and Food Systems for Nutrition 2020). Food, which enjoys the most proximate relationship to our physical health, is failing us. Globally, poor-quality diets are

M. Herrero (✉)
Department of Global Development and Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, USA
e-mail: mh2258@cornell.edu

M. Hugas
European Food Safety Authority (EFSA), Madrid, Spain

U. Lele
International Association of Agricultural Economists (IAAE), Delhi, India

A. Wirakartakusumah
Department of Food Science and Technology and SEAFAST Center, Bogor Agricultural University (IPB), International Union of Food Science and Technology, Jakarta, Indonesia

M. Torero
Food and Agriculture Organization of the United Nations (FAO), Lima, Peru

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_5

linked to 11 million deaths per year (Afshin et al. 2019; Global Panel on Agriculture and Food Systems for Nutrition 2020).

As discussed in Action Track 1, we are failing the planet by enabling the food system to be the single largest driver of multiple environmental pressures. Food production accounts for 80% of land conversion and biodiversity loss, including the collapse of major marine fisheries and freshwater ecosystems (Campbell et al. 2017; IPCC 2019) and high levels of contamination of freshwater and marine ecosystems (Mateo-Sagasta et al. 2017); it is responsible for 70% of freshwater withdrawals (Campbell et al. 2017), with major river systems such as the Colorado River in the USA no longer reaching their deltas; and it contributes approximately 30% of global greenhouse gas emissions (IPCC 2019). Action Track 2 recognises that current food usage patterns, often characterised by high levels of food loss and waste, significant prevalence of the consumption of energy-rich diets, and the production of natural resource-intensive foods, need to be transformed in order to protect both people and the planet. At the same time, context is very important. The challenges and opportunities associated with a nutrient transition will vary for different contexts and countries and will need to be evaluated and solved with an array of different solutions appropriate to their local conditions, culture and values. Awareness-raising, regulatory and behaviour change interventions in food environments, food education, strengthened urban-rural linkages, reformulation, improved product design, packaging and portion sizing, investments in food system innovations, public-private partnerships, public procurement, and separate collection that enables the reutilisation of food waste can all contribute to this transition. Local and national policy-makers and private sector actors of all sizes have a key role in both responding to and shaping the market opportunities created by changing consumer demands.

2 Building the Evidence for Healthy Diets

A healthy diet is health-promoting and disease-preventing. It provides adequacy, without excess, of nutrients and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (**Healthy diet: A definition for the United Nations Food Systems Summit 2021**). It must supply adequate calories for energy balance and include a wide variety of high-quality and safe foods across a diversity of food groups to provide the various macronutrients, micronutrients and other food components needed to lead an active, healthy and enjoyable life.

Consumer demand, availability, affordability and accessibility are important drivers of dietary patterns. It is essential that these four aspects are considered simultaneously when pursuing dietary shifts (Global Panel on Agriculture and Food Systems for Nutrition 2020). There is great diversity in the food and culinary traditions that, together, can form healthy diets, which vary widely across countries and cultures according to traditions, preferences and local food supplies. Food-based dietary guidelines translate these common principles into nationally or regionally relevant recommendations that consider these differences, as well as context-specific diet-related health challenges. National food-based dietary guidelines provide context-specific advice and principles on healthy diets and lifestyles, which are rooted in sound evidence and respond to a country's public health and nutrition priorities, food production and consumption patterns, socio-cultural influences, food composition data, and accessibility, among other factors.[1] Most food-based dietary guidelines recommend consuming a wide variety of food groups and diverse foods within food groups, plentiful fruits and vegetables, the inclusion of starchy staples, animal-source foods and legumes, and the limiting of excessive fat, salt and sugars (Herforth et al. 2019; Springmann et al. 2020). However, there can be wide variation in inclusion of and recommendations for other foods. Only 17% of food-based dietary guidelines make specific recommendations about quantities of meat/egg/poultry/animal-sourced food to consume (20% make specific recommendations about fish), and only three countries (Finland, Sweden and Greece) make specific quantitative recommendations to limit red meat (Herforth et al. 2019). Only around one-quarter of food-based dietary guidelines recommend limiting consumption of ultra-processed foods, yet this is emerging as one of the most significant dietary challenges around the world.

Adherence with national food-based dietary guidelines and recommendations around the world is low. However, accurate data on actual consumption and its determinants is limiting, particularly for low- and low-middle-income countries (Lele et al. 2021). Recent estimates of consumption found that the foods available did not meet a single recommendation laid out in national food-based dietary guidelines in 28% of countries, and the vast majority of countries (88%) met no more than two out of twelve dietary recommendations (Springmann et al. 2020). Dietary intake surveys show vast regional and national differences in consumption of the major food groups (Afshin et al. 2019). No regions globally have an average intake of fruits, whole grains, or nuts and seeds in line with recommendations, and only central Asia meets the recommendations for vegetables. In contrast, the global average intake (and several regional averages) of red meat, processed meat and sugar-sweetened beverages exceeds recommended limits. Australasia and Latin America had the highest levels of red meat consumption, with high-income North America, high-income Asia Pacific and western Europe consuming the highest amount of processed meat (Afshin et al. 2019). In general, consumption of nutritious foods has been increasing over time, albeit, likewise, the consumption of foods high in fat, sugar, and salt, in a trend that is particularly evident as country incomes rise (Imamura et al. 2015). Of particular concern is the growing importance of highly processed foods and sugar-sweetened beverages in diets across the world. Sales of highly processed foods and sugar-sweetened beverages are about ten-fold higher in high-income compared to lower middle-income countries. However, sales growth is evident across all regions, the fastest occurring in middle-income countries (Baker et al. 2020).

[1] http://www.fao.org/nutrition/education/food-dietary-guidelines/home/en/

Micronutrient dietary needs require consideration, especially for women of reproductive age, pregnant and lactating women, and children and adolescents. The odds of death in childbirth double with anaemia (Daru et al. 2018), a condition often caused by nutrient deficiency and affecting almost 470 million women of reproductive age and more than 1.6 billion people globally (WHO 2008). Iron deficiency is estimated to cause 591,000 perinatal deaths and 115,000 maternal deaths per year (Stoltzfus et al. 2004), whereas undernutrition is an underlying cause of 45% of all deaths of children under the age of 5.

Animal-sourced foods can provide high-quality amino acid profile and micronutrient bioavailability. A recent study showed improved linear growth in children receiving animal-sourced foods vs cereal-based diets or no intervention (Eaton et al. 2019). Daily egg provision to young children has also shown increased linear growth compared to control (Iannotti et al. 2017). These changes in growth can be equated to larger economic gains across nations, continents, and globally. A review of the association between stunting and adult economic potential found that a 1 cm increase in stature is associated with a 4% increase in wages for men and a 6% increase in wages for women (McGovern et al. 2017). The Cost of Hunger in Africa series has quantified the social and economic impact of hunger and malnutrition in 21 African countries and concluded that (a) 8–44% of all child mortality is associated with undernutrition, (b) between 1% and 18% of all school repetitions are associated with stunting, (c) stunted children achieve 0.2–3.6 years less in school education, (d) child mortality associated with undernutrition has reduced national workforces by 1–13.7%, and (e) 40–67% of the working age population suffered from stunting as children (The Cost of Hunger in Africa series | World Food Programme 2021). Furthermore, hunger and undernutrition have cost countries between 2% and 17% of their GDP (The Cost of Hunger in Africa series | World Food Programme 2021).

Fish and fish products can be a key component of a healthy diet, given their nutrient-dense profile, including protein, omega-3 fatty acid and other micronutrients. In addition to the underconsumption of fruits, whole grains, nuts and seeds, as noted earlier, seafood is also generally eaten below recommended intake levels. With the exception of high-income Asia Pacific, seafood omega-3 fatty acid consumption is lower than the optimal levels in all 21 global burden-of-disease regions. The recently-released 2020–2025 Dietary Guidelines for Americans also notes that only 10% of Americans eat the recommended amount of seafood – two servings – each week.

3 Building the Evidence on Healthy Diets from Sustainable Food Systems

Foremost, we need evidence on actual food consumption to consider shifts to dietary patterns that promote all dimensions of individuals' health and well-being; *have low levels of environmental pressure and impact*; are accessible, safe and equitable; and are culturally acceptable (FAO and WHO 2019). Considering current environmental challenges, transitioning to food systems that can enhance natural ecosystems, rather than simply sustaining them, may be desirable.

The conceptual transition from healthy diets to healthy diets from sustainable food systems has been mediated by recent studies linking food availability patterns, and projections, to non-communicable disease health consequences, and the environmental impacts of food production (Tilman and Clark 2014; Springmann et al. 2018a; Willett et al. 2019). A broad range of food availability patterns have been tested as alternatives to current patterns, including Mediterranean, vegetarian, vegan, pescatarian, low animal products and many other variants (Aleksandrowicz et al. 2016; IPCC 2019). The most recent set of studies is embodied in the work of the *EAT-Lancet Commission on healthy diets from sustainable food systems* (Willett et al. 2019). Healthy diets, based on food groups, were designed from a large body of evidence from nutrition observational studies. This helped to establish ranges of inclusion of different types of foods. It is important to note that these dietary recommendations diverge from most food-based dietary guidelines, and often have lower ranges of inclusion of animal-sourced foods, which have been the topic of significant debate, and therefore not widely accepted. The authors then used six environmental dimensions of importance to planetary health and earth system processes (greenhouse gas emissions, cropland use, water use, nitrogen and phosphorus use and biodiversity), using the planetary boundaries concept (Rockström et al. 2009), as boundary conditions for achieving a healthy diet from a sustainable food system. The environmental limits of food described by the EAT-Lancet Commission define a safe environmental space for food to help guide sustainable food consumption patterns.

Willett et al. (2019) found that flexitarian diets that allow for diversity in consumption options, including moderate meat consumption, would significantly reduce environmental impacts compared to baseline scenarios reflecting current consumption patterns. Flexitarian diets include the following characteristics:

(a) high in diverse plant-based foods.
(b) high in the consumption of whole grains, legumes, nuts, vegetables and fruits.
(c) low in the consumption of animal-sourced foods (but requiring increases in fish consumption).
(d) low in fats, sugars and discretionary/ultra-processed foods.

These diets can avert 10.8–11.6 million deaths per year from non-communicable diseases, a reduction of 19–24% from the baseline (consistent with the Global Burden of Disease studies). From an environmental perspective, transitions towards flexitarian patterns could primarily contribute to reducing greenhouse gas emissions, as a reduction in animal-sourced foods also reduces land use and the numbers of animals utilised, along with their associated emissions. However, increases in fruits, nuts and vegetables require more land, water and fertilisers, and therefore increases in productivity of cereals and legumes to bridge yield gaps by close to 75%, and reductions in waste of 50% would be needed to achieve these diets within all sustainability constraints. These dynamics are consistent across many studies exploring dietary variants (Aleksandrowicz et al. 2016; Jarmul et al. 2020). However, the environmental footprint of foods is strongly dependent on where and how foods are produced, leaving significant room for innovation and improvement. Moreover, the adoption of any of the four alternative healthy diet patterns (flexitarian, pescatarian, vegetarian and vegan) could potentially contribute to significant reductions of the social cost of greenhouse gas emissions, ranging from USD 0.8 to 1.3 trillion (50–74%) (FAO et al. 2020).

However, a limitation of plant-based diets is that they may not fulfil micronutrient needs, especially of those most vulnerable, such as women of reproductive age, pregnant and lactating women, and children and adolescents. In contexts in which diverse options for fortified cereals, grains, and foods are abundant, these outcomes demonstrate great potential for improving health and environmental indices, because risk of undernutrition can be mitigated by the diversity of options in the food environment. In particular, biofortification of staple foods can lead to the higher accessibility of micronutrients, particularly for the poor and vulnerable. However, in contexts in which such diversity of high-quality, fortified products is not abundant, the health risk of anaemia and iron deficiency due to a lack of vitamins and minerals is significant (as outlined above). The recommendations to move to more plant-based diets are complicated by the high quality of animal-sourced foods in terms of their amino acid profile and micronutrient bioavailability and the evidence that the addition of such foods to plant-based diets of many populations could have large individual and societal benefits. Thus, when economic and socio-cultural sustainability are considered, as well as the complex landscape of diverse nutrition situations globally, healthy diets that take sustainability into consideration will look different in diverse contexts around the world.

Transitions towards healthy diets, let alone sustainable consumption, are critical contributors to achieving climate stability and halting the rampant loss of biodiversity. Combined actions on securing habitat for biodiversity, improving production practices, and encouraging better consumption would allow for halting biodiversity loss and bending the curve towards restoration by 2030 (Leclere et al. 2020).

There is also a financial case for shifting to healthy diets from sustainable food systems. There are hidden costs in our dietary patterns and the food systems supporting them, two of the most important of which are the health- and climate-related costs that the world incurs (FAO et al. 2020). If current food consumption trends continue, diet-related health costs linked to non-communicable diseases and their rates of mortality are projected to exceed USD 1.3 trillion per year by 2030. On the other hand, shifting to healthy diets that include sustainability considerations would lead to an estimated reduction of up to 97% in direct and indirect health costs. The diet-related social cost of greenhouse gas emissions associated with current dietary patterns is projected to exceed USD 1.7 trillion per year by 2030. The adoption of healthy diets that include sustainability considerations would reduce the social cost of greenhouse gas emissions by an estimated 41–74% in 2030 (FAO et al. 2020).

Many studies (Springmann et al. 2018a; Swinburn et al. 2019; Willett et al. 2019; Global Panel on Agriculture and Food Systems for Nutrition 2020; HLPE 2020) that discuss redirecting consumption recognise the need for different consumer behavioural shifts in different locations and contexts. For example, in low-income countries, achieving a healthy diet from sustainable food systems would require increasing the consumption of most nutrient-rich food groups, including animal-sourced foods, vegetables, pulses and fruits, while reducing some starches, oils and discretionary foods (Willett et al. 2019). In contrast, in many high-income countries, achieving the same balance would require reducing the consumption of animal-sourced foods, sugars and discretionary/processed foods, while still increasing the consumption of healthy plant-based ingredients. For many countries, the transition will be complex and the changes difficult to implement. The Global Nutrition Report 2020 demonstrated that, of the 143 countries with comparable data, 124 have double or triple the burden, meaning that micronutrient deficiency is still prevalent in many developed countries demonstrating high levels of overweight/obesity (Development Initiatives 2020). It would be required that these actions play out simultaneously in different population cohorts within these countries to achieve the desired benefits (Willett et al. 2019; Development Initiatives 2020; HLPE 2020), while a smaller number of countries (e.g., Japan) would have smaller adjustments to make.

A global shift towards healthy diets from sustainable food systems will require significant transformations in food systems, and there is no one-size-fits-all solution for countries. Assessing context-specific barriers, managing short-term and long-term trade-offs and exploiting synergies will be critical. In countries where the food system also drives the rural economy, care must be taken to mitigate the potential negative impacts on incomes and livelihoods as food systems transform to deliver affordable healthy diets (FAO et al. 2020). Artificial intelligence may be able to assist in the transition to healthy diets from sustainable food systems. Examples of its application are in the management and automation of crop and livestock production systems and the development of demand-driven supply chains. However, trade-offs and ethical considerations that arise from the use of artificial intelligence need to be carefully managed (Camaréna 2020).

Fish and fish products have one of the most eco-efficient production profiles of all animal proteins. Ocean animals are more efficient than terrestrial systems in producing protein; their impact on climate change and land use is, in general, much lower than that of terrestrial animal proteins. One vital way to improve consumption of nutrient-rich and sustainable seafood is through aquaculture, the world’s fastest growing food sector. According to the Global Panel on Agriculture and Food Systems for Nutrition (2021), “Aquaculture has real potential to accelerate economic growth, provide employment opportunities, improve food security, and deliver an environmentally sustainable source of good nutrition for millions of people, especially in low- and middle-income countries”. The Ocean Panel also documented that the volume of food production from the ocean could be considerably increased. Under optimistic projections, the ocean could produce up to six times more food than it does today, and it could do so with a low environmental footprint.

4 Transitioning to Healthy Diets from Sustainable Food Systems

The evidence is abundantly clear that, without shifts in consumption patterns towards health and sustainability, we will fail to achieve multiple Sustainable Development Goals (SDGs), the Paris Climate Agreement, or the post-2020 biodiversity goals, and we will lose the opportunity to reposition food in such a way to improve health and regenerate the environment. Achieving these transitions and managing the trade-offs and synergies will require additional attention to many facets of food systems, including:

Food Environments The consumption of healthy diets from sustainable food sources is dependent on sustainably produced healthy dietary items being available, affordable and accessible in different outlets. Whether they are in open markets in low- and middle-income countries, in supermarkets or in corner shops across the globe, or available through bartering and sharing, the provisioning of nutritious food at affordable prices is a critical element for achieving transitions towards sustainable consumption (Downs et al. 2009; Swinburn et al. 2019; FAO et al. 2020). These physical environments need to be developed so as to suit culture and tradition in different locations. Additionally, regulated advertisement and product placement will be essential for addressing positive behavioural changes (Swinburn et al. 2019). To increase consumption of healthy diets, the cost of nutritious foods must be affordable for all, although farmers must also be compensated for the real cost of growing food. The cost drivers of these diets can be found throughout the food supply chain, within the food environment, and in the political economy that shapes trade, public expenditure and investment policies (Swinburn et al. 2019; FAO et al. 2020).

Tackling these cost drivers will require large transformations in food systems at the producer, consumer, political economy, and food environment levels. Trade policies, mainly protectionary trade measures and input subsidy programmes, tend to protect and incentivise the domestic production of staple foods, such as rice and maize, often to the detriment of nutritious foods, like fruits and vegetables. International trade could certainly improve food system resilience by spreading the risk of disruption in supply where it is not fully reliant on domestic production and/or trading with neighbouring countries. However, substantial imports from climate-vulnerable countries by climate-resilient trade partners could lead to a number of interlinked problems, including a 'nutrient drain' of healthy dietary items away from production countries to countries with a much more diverse supply of foods, disrupting supply to importing countries when yields in production countries are affected by environmental influences (Scheelbeek et al. 2020). Non-tariff trade measures can help improve food safety, quality standards and the nutritional value of food, but they can also drive up the costs of trade, and hence food prices, negatively affecting the affordability of healthy diets (FAO et al. 2020). Nutrition-sensitive social protection policies, such as cash transfers, may assist the purchasing power and affordability of healthy diets of the most vulnerable populations.

Policies that more generally foster behavioural change towards healthy diets will also be needed. A critical challenge is the tremendous perishability of fruits and vegetables, particularly in tropical climates (Mason-D'Croz et al. 2019), where refrigeration, food processing and sustainable packaging may be critical contributions in creating environmental and public health value. In both urban and rural areas, the lack of physical access to food markets, especially to fresh fruit and vegetable markets, represents a formidable barrier to accessing a healthy diet, especially for the poor. Finally, empowering all people, and especially the poor and vulnerable, with sufficient physical and human capital resources, assets and incomes is the necessary precondition to improving access to healthy diets. This will enable the making of choices, regarding what to produce and consume, leaving no one hungry or malnourished, while allowing them to consume healthy and nutritious food and preserving ecosystems, biodiversity and natural resources. However, making progress and achieving this objective entails dealing with all trade-offs, negative externalities and benefits emerging from policies and combinations of policies presented previously.

Addressing Food Safety Issues Across Value Chains Food safety is positioned at the intersection of agri-food systems and health, thus there are very strong interconnections of bi-directional links among food safety, livelihoods, gender equity and nutrition disciplines (Grace et al. 2018).

Food safety across the value chains must be ensured along all stages until consumption. Responsibilities lie with all actors, from producers to processors, retailers and consumers. Consumer behaviour in households regarding the storing (temperature) and handling of foods (cross-contamination) impacts strongly on the onset of food-borne intoxications. In the European Union, surveillance data indicate that most of the strong-evidence outbreaks in 2018 took place in a domestic setting (EFSA and ECDC 2019). The safety of food is a matter of growing concern, especially after the global estimation of the burden of food-borne disease comparable to that of HIV/AIDS, malaria and tuberculosis together, with low- and middle-income countries bearing 98% of the global burden (WHO 2015). Most of the known health burden comes from biological hazards (virus, bacteria, protozoa and worms), which cause acute intoxication that is easier to detect and control. Chronic effects due to chemicals (natural or processed contaminants, pesticide residues, etc.) are more difficult to be traced and quantified as to their actual impact on the disease burden. The *Global Burden of Foodborne Diseases report* (WHO 2015) quantified the burden of disease from aflatoxin, cassava cyanide and dioxins, and other studies have estimated the burden for four food-borne metals (arsenic, cadmium, lead and methylmercury), which is substantial (Gibb et al. 2019). Since temperature and humidity are important parameters for the growth of fungi, climate change is anticipated to have an impact on the presence of mycotoxins in foods.

The riskiest foods for biological hazards are livestock products, followed by fish, fresh vegetables and fruit (Grace et al. 2018). In addition to the disease burden, food-borne diseases in low- and middle-income countries also have a great impact on economic costs and market access (Unnevehr and Ronchi 2014). In recent years, the possible impact of microplastics and nanoplastics on health via food has gained a lot of attention, with multiple studies identifying the occurrence of micro and nanoplastic particles found in food commodities such as water, filtering molluscs and fish (Lusher et al. 2017; Toussaint et al. 2019; van Raamsdonk et al. 2020). Currently, there is considerable effort to standardise the methods of analysis and identify the health impact from dietary exposure.

Food scares happen from time to time, with the subsequent food incidents (real or perceived) causing a sudden disruption to the food supply chain and food consumption patterns with a high societal impact. In these situations, providing real-time information to consumers is very important so as to maintain confidence in the food supply. Contaminant-based food scares relating to the use of antibiotics, hormones and pesticides have occurred in a number of food and drink sectors and appear to be of more concern to consumers compared to hygiene standards and food poisoning (Miles et al. 2004). Explicit investigations into the aforementioned food scares and their cumulative impact on food purchase behaviour could help to further our understanding of consumer responses to food scares (Knowles et al. 2007).

There are many promising approaches to managing food safety in low- and middle-income countries, but few have demonstrated an impact at scale. Food safety management systems are designed to prevent, reduce or eliminate hazards along the food chain, which includes primary production (farms), processors, retail distribution centres, supermarkets, and retail food outlets (Ricci et al. 2017). Food safety control at primary production is achieved using good general hygiene practices. Food business operators should implement and maintain permanent procedures based on the Hazard Analysis and Critical Control Points principles (WHO and FAO 2006), which are effective in controlling most of the hazards during food production. Small-scale retail producers might have difficulties in Hazard Analysis and Critical Control Points due to the complexity of some systems and a lack of both resources to implement and access to information and appropriate education. Transitions to circular food systems, local food systems, or short circuit systems are often slowed or hampered by current food safety regulations. Ensuring food safety, while enabling small-holder farmers or craft food companies to operate in local contexts, will be critical to facilitating the transition to more sustainable food systems and greater availability of healthy diets while supporting local economies.

To avoid confusion caused by multiple different national standards, the Food and Agriculture Organization of the United Nations and the World Health Organization established the Codex Alimentarius Commission to address safety and the nutritional quality of foods and develop international standards to promote trade among countries (Codex Alimentarius Commission 2007). The Codex Alimentarius establishes standards for maximum levels of food additives, maximum limits for contaminants and toxins, maximum residue limits for pesticides and veterinary drugs and gives indications for limits of microbiological hazards in a given food commodity. At the national level, government food safety systems monitor compliance with official standards through food inspections. While metrics are considered key to monitoring and improving performance, they can also have unintended consequences, including focusing efforts on the thing to be measured rather than the ultimate goal of improving the thing being measured, stifling innovation through standardisation, costs that increase in disproportion to benefits attained, incentivising perverse behaviour to game metrics and reduced attention to things that are not measured (Bardach and Cabana 2009), the balance and potential of large multinationals vs. small and medium-sized enterprises, short vs. long value chains, and low- and middle-income countries.

Even in higher income countries, small and medium-sized firms find it difficult to comply with complex and technocratic rules, measures and metrics that are characteristic of best practice food safety management systems and risk-based approaches: these methods are hardly applicable in low- and middle-income countries. The same applies for traceability, which only appears to be attainable in niche, high-value markets in low- and middle-income countries (Grace et al. 2018).

Local Producers and Value Chains, Income and Land Inequality For many consumers, especially in low- and middle-income countries, local production is the main supplier of nutritious food (fruits, vegetables, pulses) and the primary provider of economic activity. Small and medium-sized farms produce critical nutrient diversity in rural areas (Herrero et al. 2017), and hence the transition to sustainable consumption requires support and value chain creation for linking food system actors (HLPE 2020).

As with any change, some people will be disadvantaged by the transition to healthy diets from sustainable food systems. It is important to provide support and transition options for potential losers impacted by the required changes to food systems (Herrero et al. 2020).

Many cities are playing more active roles in the development of city region food systems, notably recognising that environmental damage in areas within close proximity to cities impacts a large number of people, and that greater collaborations between cities and peri-urban spaces offers important opportunities for tackling environmental challenges while increasing the availability of healthy diets, and supporting stronger rural economies (e.g., the Paris Food System Strategy (Mairie de Paris 2015)). Vertical farming could provide opportunities for increasing food production in urban areas (Al-Kodmany 2018).

The Role of Trade in Open and Closed Economies Trade is an essential instrument in the food system, but it is not always geared towards sustainable consumption. While trade can act as an insurance policy to local disruptions, it can also increase exposure to disruptions in external markets. This is evident in many low- and middle-income countries where trade in cheaper, ultra-processed food with long shelf lives competes with healthy dietary items. In many regions around the world (i.e., the Pacific, South America), this is likely a contributing factor to the high prevalence of obesity and increases in non-communicable diseases (Swinburn et al. 2019). However, trade also eases the leveraging of comparative advantages, which can allow production to be located where it is more efficient (Frank et al. 2018; IPCC 2019). This has been a key feature of scenarios for achieving greenhouse gas mitigation targets (IPCC 2019). However, when facing varied levels of regulation and power dynamics, trade can facilitate the outsourcing of environmental impacts of the food system to more vulnerable countries and individuals. Export-oriented value chains often are dominated by larger producers, who can concentrate market and political power as dominant producers and suppliers of food, as well as sources of employment and revenue to governments (Swinburn et al. 2019). These aspects are intertwined with the political economy of food and need to be accounted for.

It is also important to consider the impacts of the rising number of barriers to international trade on the affordability of nutritious foods (including non-tariff measures put in place to ensure food safety), as restrictive trade policies tend to raise the cost of food, which can be particularly harmful to net food-importing countries (FAO et al. 2020). Protectionary trade measures such as import tariffs and subsidy programmes make it more profitable for farmers to produce rice or corn than fruits and vegetables. According to data from Tufts University, removing trade protection across Central America would reduce the cost of nutritious diets by as much as 9% on average (FAO et al. 2020). The efficiency of internal trade and marketing mechanisms is also important, as these are key to reducing the cost of food for consumers and avoiding disincentives to the local production of nutritious foods.

The Political Economy of Food Swinburn et al. (2019) demonstrated that the current food system has large power imbalances and conflicts of interest when large commercial interests in food manufacturing and trade exist. While some large food companies are interested in opportunities to increase their environmental sustainability, financial interests often prevail over sustainability concerns. Swinburn et al. (2019) articulates that changes in the regulatory environment and new incentives, combined with global efforts on sustainable trade, will be required to create the necessary accountability and shifts towards healthy diets.

Modifying Behavioural Changes Most studies exploring the transitions towards healthy diets from sustainable food systems have focused on the technical feasibility of the diets and their production elements. Transition pathways and the levers for eliciting the required behavioural changes in consumption have received less attention (Garnett 2016; HLPE 2020).

Educating consumers to make healthy choices can modify behaviour in some cases. Educational campaigns in high-income countries have increased awareness and have also achieved some modest gains in fruit and vegetable consumption. However, most have not realised the target levels for consumption over the longer term (Brambila-Macias et al. 2011; Thomson and Ravia 2011; Rekhy and McConchie 2014). Certain people are more receptive to education on healthy diets than others. Providing nutritional information was found to change the behaviour of consumers already interested in nutrition, but was unable to influence consumers with low interest in nutrition (Lone et al. 2009). Conversely, marketing incentives for healthy diets have been found to be more effective for people who have less healthy eating habits (Chan et al. 2017). Educational activities are more effective when used in conjunction with environmental modifications, such as increasing the availability and accessibility of healthy dietary items (Van Cauwenberghe et al. 2010).

Altering food availability options can enhance healthy diets. A review of studies found that the strategic placement of fruit and vegetables could moderately increase fruit and/or vegetable choice, sales or servings (Broers et al. 2017). However, individual studies show mixed results. Furthermore, the provision of financial incentives to make healthy diets more affordable has been shown to increase consumption of fruits and vegetables (Olsho et al. 2016).

Taxes and front-of-pack information labels have been used with success to moderate the purchase of unhealthy dietary items, as well as influence reformulation of unhealthy products (Colchero et al. 2017; Roache and Gostin 2017; Taillie et al. 2020). Although the magnitude of effect ranges, there is evidence that fiscal measures such as taxes on unhealthy dietary items improve diets (Andreyeva et al. 2010; Brambila-Macias et al. 2011; Eyles et al. 2012; Niebylski et al. 2015). A sugar-sweetened beverage tax has reduced consumption of such drinks in the study cohorts in Berkeley, USA (Lee et al. 2019) and Mexico (Sánchez-Romero et al. 2020). A review on the effect of subsidies for healthy dietary items and taxation on unhealthy dietary items found evidence that taxation and subsidy intervention influenced dietary behaviours to a moderate degree. The study suggests that food taxes and subsidies should be a minimum of 10 to 15% and should both be implemented to improve success and effect (Niebylski et al. 2015).

Reducing Food Loss and Waste and Embracing Circularity As discussed in Action Tracks 1 and 3, a critical component of rebalancing food systems is reducing food loss and waste. Food loss and waste currently accounts for significant losses of food availability around the world, and current estimates are, for food loss, 14% (FAO 2019) and, for food waste, 17% (United Nations Environment Programme 2021) of total production, depending on the type of commodity. In low- and middle-income countries, these losses occur mostly at the pre-consumer stage due to harvest and storage losses, while in OECD countries, they are more significant at the consumption stage (for example, sell-by dates). Circular food systems have been suggested as a mechanism for reutilising these biomass streams (Jurgilevich et al. 2016). For example, it has been estimated that circular livestock could produce 7–23 g of protein per capita/day while decoupling livestock from land use systems (Van Zanten et al. 2018). Microbial protein production in fermentation processes or through alternative foods (i.e., insects, algae) are considered part of these solutions (Parodi et al. 2018; Pikaar et al. 2018).

5 The Key Trade-Offs and Synergies

Food systems in low-, middle- and high-income countries are changing rapidly. Increasingly characterised by a high degree of vertical integration and high concentration, transitions in food systems are being driven by new technologies that are changing production processes, distribution systems, marketing strategies, and the food products that people eat (Stordalen and Fan 2018; Herrero et al. 2020).

In terms of synergies, the arguments for aligned action on healthy diets from sustainable food systems are attractive from multiple standpoints. The possibility of engaging in triple-win actions linking health, consumption and the environment presents a real opportunity to achieve numerous global commitments simultaneously, which could be desirable from a policy perspective. These include planned emissions reductions (United Nations 2015; IPCC 2019; Leclere et al. 2020), reductions in non-communicable diseases and malnutrition in all its forms, and achievement of SDG goals and targets (SDGs 1, 2, 3, 6, 8, 12–16). These multi-sectoral opportunities will require increased concerted action and alignment at the global and national levels. While these synergies could potentially lead to human and planetary well-being, their achievement could also yield significant trade-offs that will require resolution (Herrero et al. 2021). Some of these are related to the following dimensions:

Multiple Environmental Trade-Offs Changing consumption patterns can have impacts on the environmental footprints of the food system. Over a decade ago, Stehfest et al. (2009) demonstrated that reductions in the demand for animal-sourced foods could lead to reduced greenhouse gas emissions. These effects were mediated through reductions in methane production and carbon dioxide due to the use of less land and fewer animals for achieving consumption targets. More recently, studies integrating many environmental indicators (Springmann et al. 2018b; Van Zanten et al. 2018; Willett et al. 2019) confirmed those findings, but due to the compositions of the healthy diets with higher amounts of coarse grains, fruits, vegetables and nuts, the environmental impact of these diets remains high. The impacts on different locations are markedly different due to different limiting constraints (i.e., water scarcity). It is only when consumption is modified, waste is reduced, and productivity increased that improvements across all environmental metrics are obtained.

Trade-Offs with Affordability and Availability A key trade-off of pursuing healthy diets from sustainable food systems is the increase in the costs of the diets in many countries, as a result of increasing the demand for nutrient-rich foods. A significant portion of the people living in extreme poverty are the two billion who struggle to access sufficient foods and suffer acute caloric and nutrient deficiencies. Even the cheapest healthy diet costs 60% more than diets that only meet the requirements for essential nutrients. Examples like the EAT-Lancet diet are not affordable for an estimated 1.5 billion people (Hirvonen et al. 2020, Table 1) and almost double the cost of the nutrient adequate diet; it is five times as much as diets that meet only the dietary energy needs through a starchy staple (FAO et al. 2020). This is of concern, as the high cost and unaffordability of healthy diets is associated with increasing food insecurity and different forms of malnutrition, including child stunting and adult obesity. The unaffordability of healthy diets is due to their high cost relative to people's incomes. Healthy diets are unaffordable for more than 3 billion poor people in low-, middle- and high-income countries, and more than 1.5 billion people cannot even afford a diet that only meets required levels of essential nutrients (FAO et al. 2020; Global Panel on Agriculture and Food Systems for Nutrition 2020). The cost of a healthy diet is much higher than the international poverty line, established at

Table 1 Number and share of people with daily income below the cost of the EAT-Lancet reference diet, by country income levels and major regions (Hirvonen et al. 2020)

	Number of countries	Population (in millions)	Share (%)
Global	141	1579·02	23·8%
By country income level			
High income	38	9·00	0·8%
Upper-middle income	37	254·07	10·8%
Lower-middle income	40	1005·89	37·1%
Low income	26	310·06	62·2%
By geographical region			
East Asia and Pacific	13	319·88	15·0%
Europe and central Asia	45	14·86	1·7%
Latin America and Caribbean	19	62·84	11·6%
Middle East and North Africa	11	48·40	19·4%
North America	2	3·95	1·2%
South Asia	7	627·31	38·4%
Sub-Saharan Africa	44	501·77	57·2%

We used the World Bank's PovcalNet system to calculate the share of people in each country whose daily consumption or income was less than the estimated cost of the EAT-*Lancet* reference diet.

USD 1.90 purchasing power parity per day. At a global level, on average, a healthy diet is not affordable, with the cost representing 119% of mean food expenditures per capita per day. Where hunger and food insecurity are greater, the cost of a healthy diet even exceeds average national food expenditures. The cost of a healthy diet exceeds average food expenditures in most countries in the Global South. 57% or more of the population throughout sub-Saharan Africa and Southern Asia cannot afford a healthy diet (FAO et al. 2020).

Part of the reason why many of the components of healthy diets are expensive follow the basic economics of supply and demand. In many cases, production of key dietary components does not meet the required demand, even at the global level, and therefore their prices are high. Mason-D'Croz et al. (2019) recently demonstrated this for fruits and vegetables, a key component of healthy diets. The study concluded that even under optimistic socioeconomic scenarios, future supply will be insufficient to achieve recommended levels in many countries. Even where supply exists (i.e., India), internal barriers like poorly developed markets mean that increased incomes do not necessarily result in increased consumption of healthy diets (Fraval et al. 2019).

Low market access can be a large barrier to achieving a healthy diet. A 'food desert' refers to areas with poor access to a retail outlet with fresh produce, where cheap, ultra-processed, and unhealthy dietary items can predominate. While food deserts are often associated with economically disadvantaged communities in high-income countries (Walker et al. 2010; Ghosh-Dastidar et al. 2014), they also affect poor urban communities in low- and middle-income countries, particularly newly urban communities (Battersby and Crush 2014). Food deserts can also occur in areas that lack refrigeration, or have harsh environmental conditions or poor storage conditions, far from towns, where highly processed foods can be stored easily (i.e., the Pacific). Vertical farming may provide opportunities for food production in urban areas, where available land for farming is limited and expensive. Currently, economic feasibility, codes, regulations, and a lack of expertise are major obstacles to implementing vertical farming (Al-Kodmany 2018).

Trade-Offs with Pandemics and Zoonosis In contexts in which animal-sourced food consumption is higher than recommended, shifting towards greater plant consumption would also have the added benefit of preserving ecological systems and wildlife and avoiding the spillover of zoonotic agents (mainly viruses) from wildlife to humans. In contexts in which animal-sourced food consumption is critical for maintaining appropriate intake of essential nutrients, it is vitally important to scale up a ONE HEALTH approach that enables environmental, animal, and human health (Wood et al. 2012; Gale and Breed 2013) while avoiding causing a public health threat. In recent years, there have been several examples of such spillovers (Ebola, SARS, MERS and COVID-19) with dramatic economic and public health consequences and the potential to cause global pandemics (see Box 1). A consequence of the COVID-19 pandemic is the disruption of global, or concentrated, value chain production in terms of affordability and food availability; inversely, many local value chains have seen increases in production and market shares.

The global burden of disease from food consumption is very different across the globe (WHO 2015), and it is, in large part, produced by zoonotic infections. Today, the largest food source attributions in food-borne intoxications are from food of animal origin in the developed world. Antimicrobial resistance contributes significantly to the burden of disease across the globe and constitutes a threat to public health.

Box 1: The impact of COVID19 on Food Systems

Food

The new type of respiratory tract disorder COVID-19 is based on an infection with the new type of coronavirus (SARS-CoV-2). The main target organs of coronaviruses in humans are the respiratory tract organs. The scientific data collected so far suggests that the virus is transmitted mainly via small respiratory droplets through sneezing, coughing, or when people interact with each other in close proximity, as may happen in slaughterhouses and meat-processing plants, where environmental conditions seem more

(continued)

Box 1 (continued)
favourable than in other places to the propagation of the virus. In fact, there have been COVID-19-related outbreaks at some slaughterhouses and meat-processing plants worldwide, which has led to risk management measures to contain the propagation of the virus from occupational exposure among workers and related communities. Up to now, there is no evidence that food, including meat, is a source or transmission route of SARS-CoV-2. Meat, like any other food, might theoretically be contaminated by SARS-CoV-2. This could happen with food in the same way that it could happen with any other animated or non-animated surface. For example, food might be exposed to the virus through contamination by an infected person during food manipulation and preparation. This does not mean however that the food ingested would cause infection for the consumer. As indicated above, there is so far no evidence of transmission of this virus through ingestion of any type of food. Several food safety agencies and organisations worldwide have concluded that there is no evidence of food-borne transmission of the virus.

Pandemics and value chains
COVID19 is an example of the importance of ONE HEALTH approach as it is a zoonosis (disease transmitted from animals to humans). It is well known that damaging ecological systems might lead to spillovers of zoonotic agents (mainly viruses such as Ebola, SARS, MERS) outside their original environment with dramatic economic and public health consequences and the potential to cause global pandemics. A consequence of the COVID-19 pandemic is the disruption of global, or concentrated value chain production in terms of affordability and food availability; inversely, many local value chains have seen increases in production and market shares.

Waste
In response to COVID-19, hospitals, healthcare facilities and individuals are producing more waste than usual, including masks, gloves, gowns, other protective equipment and single-use plastics that could be infected with the virus. Infected medical waste could lead to public health risks, as well as environmental risks add to land, riverine and marine pollution.

Political Economy Trade-Offs Broad awareness of the positive or negative consequences of food system changes from nutritional, health, environmental and livelihood perspectives among key policy-makers is key to policy changes that facilitate a transition to healthy diets from sustainable food systems. Increased biodiverse agricultural production can result in increased employment and income, leading to growing demand for (healthy) food, provided that there is strong consumer awareness regarding diets and their consequences, and provided that there are few competing demands on incomes, especially of the poor.

The political impediments to achieving healthy and sustainable diets are numerous. Maintaining the status quo benefits the current actors of the food system, hence the inertia for change (Béné et al. 2020; Fanzo et al. 2020; Herrero et al. 2020). Additionally, many public policies are not geared towards creating sustainable food systems, such as a lack of research and investment in nutritious foods at the expense of cereals or the creation of food environments that promote nutritious foods. The current system rewards economic efficiency rather than sustainability and the production of nutrition foods (Béné et al. 2020). Therefore, farmers have little incentive to change production practices. At the same time, large private companies exercise disproportionate control over the food agenda, and this is not necessarily aligned with a health and sustainability agenda needed to transform the food systems.

Technology will be important, but even with the best intentions, assurance that equitable and fair distribution of its availability and impacts are taken into account when designing transition pathways remains elusive (Herrero et al. 2021). Critical dialogues and transparency in designing these transition pathways must be developed with a broad range of stakeholders, and with mutual respect for values and motivations (Herrero et al. 2021).

6 Solutions and Actions

Solutions for enabling the shift towards more sustainable consumption need to be defined around cross-cutting levers connecting policy reform, coordinated investment, accessible financing, innovation, traditional knowledge, governance, data and evidence, and empowerment (Béné et al. 2020). It is important to identify and learn from the success stories of individuals and groups that have shifted to healthy diets from sustainable food systems and use these examples to clearly inform policy-makers, practitioners and the public. Figure 1, from the Global Panel on Agriculture and Food Systems for Nutrition (2020), synthesises the range of critical actions necessary to effectively create transition towards healthy and sustainable diets. We develop this list further into a broader set of actions for implementation in different contexts, which are presented below, following the categories of actions in Béné et al. (2020).

Economic and Structural Costs Off-set the economic and structural costs associated with the transition to more healthy and sustainable diets.

- Develop policies and investments across food supply chains (food storage, road infrastructure, food preservation capacity, etc.) that are critical to cutting losses and enhancing efficiencies so as to reduce the cost of nutritious food (FAO et al. 2020).
- Provide support and transition options for potential losers impacted by the required changes to land use, food production practices, storage and processing technologies, food environment, distribution and food waste.

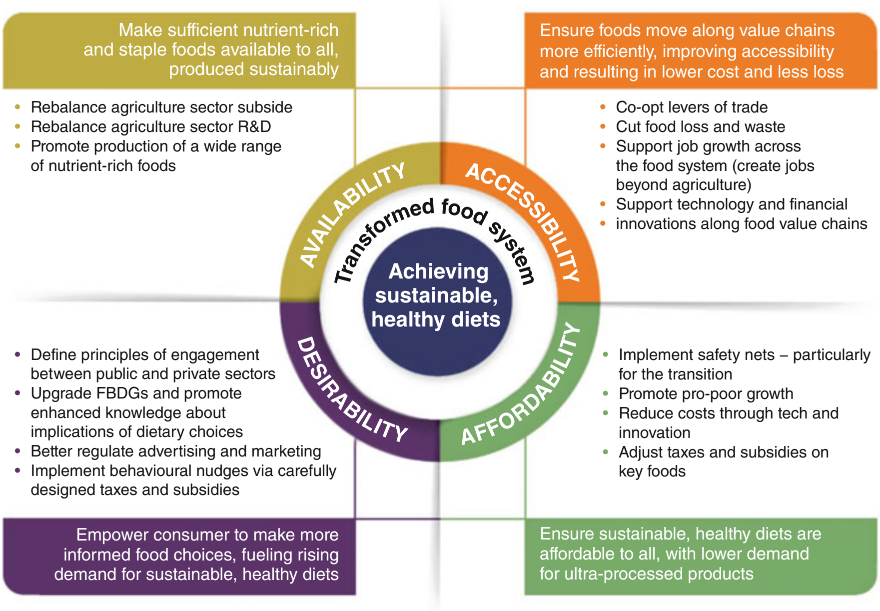


Fig. 1 Priority policy actions to transition food systems towards sustainable, healthy diets. (Global Panel on Agriculture and Food Systems for Nutrition 2020)

- Direct funding towards a healthy and sustainable food system, e.g., repurpose funding from monoculture crops, or foods that, when overproduced, are detrimental to health and the environment (e.g., sugar and its derivatives).
- Facilitate easier access to loans from financial institutions, or lands from municipalities, notably for young farmers, both men and women.
- Pilot and scale behaviour change interventions that are effective in reducing consumer food waste and increasing the adoption of healthy and sustainable diets.
- Invest in innovative food-related infrastructure and logistical systems that will improve the efficiency of food supply chains, particularly for urban consumers.
- In low and lower middle-income countries, facilitate increased consumption of nutrition foods by encouraging those with access to land to grow more such foods themselves or by exchange within the local communities.
- Encourage the creation of rural food markets in cities based on the production and sale of indigenous and sustainably produced foods grown by local farmers.
- Break existing policy silos so as to facilitate food system transformations, providing support for a major policy drive to enhance the cultivation of indigenous food systems. Many native foods have biological components that can contribute to nutritionally-rich and healthy diets. Priority actions should be taken to promote research into these native foods worldwide.

Challenge the Current Political Economy

- Encourage large food system actors to transition to the provision of healthy diets through incentives that are matched with penalisation or taxes for overproduction of unhealthy dietary items, or the use of degradative production practices.
- Develop trade policies and input subsidy programmes that can change incentives towards nutritious foods like fruits and vegetables. This also implies improvement of food safety to reduce non-tariff trade measures so as to increase the availability of healthy diets.
- Promote social and environmental aspects of corporate performance to be equal to financial performance.
- Develop regulatory measures such as taxes and front-of-pack information labels to limit the sale and production of unhealthy products.
- Change the global regulatory environment, including international trade and investment agreements, to favour healthy diets from sustainable food systems.
- Promote divestment to avoid harm. This includes the exclusion of certain companies from investment portfolios.
- Encourage a culture of corporate responsibility in the food industry to investigate the level of sustainability of products. Encourage social impact investing. This aims to generate a positive social impact from investment decisions, alongside financial return.
- Empower consumers to demand healthy, sustainable products and reject unhealthy products.
- Encourage consumers to demand increased accountability for large food system actors.
- Encourage institutions, for example, schools, health care facilities and government offices, to transition to healthier diets through improved nutrition standards, which flow on to improve the nutritional quality of meals served in those institutions (Gearan and Fox 2020).
- Gear public policies towards creating healthy diets from sustainable food systems.

Influencing Consumer Demand The Global Panel on Agriculture and Food Systems for Nutrition (2020) recommends the following four priority lines of action, while also acknowledging that far better evidence of what works in low- and middle-income countries is required:

- Define principles of engagement between the public and private sectors, leading to the leveraging of expertise and resources and influence of the businesses in the food sector. This recognises the considerable role of firms in driving consumer choices, too often employed in ways that are not conducive to healthy diets from sustainable food systems. A new relationship between public and private actors is needed, so that they can work together on a common agenda.
- Upgrade and improve food-based dietary guidelines and promote enhanced knowledge about the implications of dietary choices. For example, food-based dietary guidelines seldom take account of issues of food system sustainability.

Moreover, policy-makers in many governments need to take account of food-based dietary guidelines in developing policies, both in relation to the food system and in wider areas of government (e.g., relating to infrastructure development, safety nets, etc.).

- Improve regulation of advertising and marketing. This is mentioned in the AT2 paper and discussed further in the Foresight report, which addresses, in particular, the ineffectiveness of businesses self-regulating.
- Implement behavioural nudges via carefully designed taxes and subsidises.

Education and Cultural Norms The role of education will be pivotal in changing consumption patterns at many levels. It can facilitate a cultural shift in consumer perceptions and behaviour.

- Provide education and clarity for consumers about what constitutes a healthy and sustainable diet and educate consumers to make healthy choices, coupled with other incentives to improve success and effect.
- Invest in female, minority and youth leadership and technical and managerial skills, which are key to promoting the more equitable and sustainable participation of women in food supply chains, as producers, processors, business leaders and consumers, using women's self-help groups as an example.
- Alter food availability options to promote healthy diets.
- Invest in large-scale awareness campaigns that connect food consumption patterns with health, the environment and, specifically, climate change outcomes.
- Engage in school education programmes on healthy diets from sustainable food systems to ensure that the next generation has a novel conceptualisation of what the food system can offer.
- Include sustainability-of-consumption learning modules in medical school curricula worldwide.

Equity and Social Justice Manage equity and social justice to provide the greatest benefit to all:

- Identify the current consumption patterns of households.
- Encourage regions to transition to more healthy and sustainable diets in a culturally appropriate manner.
- Systematically use full supply chain traceability to promote internal transparency, as has been shown to work (Bush et al. 2015). This could potentially be a way to promote social justice in the industry and protect people employed in low- and middle-income countries.
- Deploy safety nets to protect the poor against dynamic food system transitions that might render them vulnerable and disenfranchised. This will require international coherence and action (Global Panel on Agriculture and Food Systems for Nutrition 2020).

Governance and Decision Support Tools

- Invest in additional knowledge, skills, data and tools needed to identify, prioritise and manage trade-offs and competing priorities.
- Establish standardisation and clear labelling.
- Develop tools for measuring consumer and retail food waste at the national level, so as to understand the scale of the problem, identify hotspots for targeted action, and track progress towards SDG 12.3.
- Increase adherence to principles of circular economy recycling and the repurposing of food waste until they become the norm.
- Rationalise food-related sustainability standards. Such initiatives, which set standards for sustainable production and often include certification programmes to verify compliance, can be used as tools to drive consumer choice on the one hand and to channel and enhance the nascent demand for more sustainable food systems into market-related investments on the other. However, some regulatory approaches and private sector-led schemes create barriers, primarily because of the costs of compliance and the potential exclusion of actors. Nevertheless, some excellent examples exist within the salmon industry (Global Salmon Institute 2020).

7 Conclusions

A shift towards sustainable consumption patterns is necessary to harmonise global societal and environmental goals and for humanity to prosper sustainably and equitably in the coming years. Transitioning towards healthy diets from sustainable food systems at the country level is essential to achieving this, together with strategies for managing waste reduction and increasing productivity.

The range of constraints preventing this transition include the lack of availability and access to healthy diets, the costs of eating healthily, poor food environments, lack of incentives and standards, food safety, pandemics and, in many cases, a lack of political will. These are not insurmountable. Many strategies exist for circumventing these problems, including awareness-raising, behaviour change interventions in food environments, food education, strengthened urban-rural linkages, improved product design, investments in food system innovations, public-private partnerships, public procurement, and novel strategies for food waste management.

The role of science and innovation will be essential in deploying these interventions at scale and at low costs, and for minimising the potential trade-offs that may arise. Transparent multi-stakeholder dialogues will be key at all stages of planning the appropriate transition pathways towards our desired global goals of healthy diets, healthy ecosystems and prosperity for all.

Acknowledgements Helpful comments on an earlier draft by five external peer reviewers, and by colleagues in the Scientific Group, are gratefully acknowledged.

References

Afshin A et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393(10184):1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Aleksandrowicz L et al (2016) The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLOS ONE 11(11):e0165797. https://doi.org/10.1371/journal.pone.0165797. Edited by A. S. Wiley

Al-Kodmany K (2018) The vertical farm: a review of developments and implications for the vertical city. Buildings 8(2). https://doi.org/10.3390/buildings8020024

Andreyeva T, Long MW, Brownell KD (2010) The impact of food prices on consumption: a systematic review of research on the price elasticity of demand for food. Am J Public Health:216–222. https://doi.org/10.2105/AJPH.2008.151415. American Public Health Association

Baker P et al (2020) Ultra-processed foods and the nutrition transition: global, regional and national trends, food systems transformations and political economy drivers. Obes Rev (February), pp. 1–22. https://doi.org/10.1111/obr.13126

Bardach NS, Cabana MD (2009) The unintended consequences of quality improvement. Curr Opin Pediatr 21(6):777–782. https://doi.org/10.1097/MOP.0b013e3283329937

Battersby J, Crush J (2014) Africa's urban food deserts. Urban Forum 25(2):143–151. https://doi.org/10.1007/s12132-014-9225-5

Béné C et al (2020) Five priorities to operationalize the EAT-Lancet Commission report. Nat Food 1(8):457–459. https://doi.org/10.1038/s43016-020-0136-4

Brambila-Macias J et al (2011) Policy interventions to promote healthy eating: a review of what works, what does not, and what is promising. Food Nutr Bull 32(4):365–375. https://doi.org/10.1177/156482651103200408

Broers VJV et al (2017) A systematic review and meta-analysis of the effectiveness of nudging to increase fruit and vegetable choice. Eur J Public Health 27(5):912–920. https://doi.org/10.1093/eurpub/ckx085

Bush SR et al (2015) Sustainability governance of chains and networks: a review and future outlook. J Clean Prod 107:8–19. https://doi.org/10.1016/j.jclepro.2014.10.019

Camaréna S (2020) Artificial intelligence in the design of the transitions to sustainable food systems. J Clean Prod:122574. https://doi.org/10.1016/j.jclepro.2020.122574. Elsevier Ltd.

Campbell BM et al (2017) Agriculture production as a major driver of the earth system exceeding planetary boundaries. Ecol Soc 22(4). https://doi.org/10.5751/ES-09595-220,408

Chan EK, Kwortnik R, Wansink B (2017) McHealthy. Cornell Hosp Q 58(1):6–22. https://doi.org/10.1177/1938965516668403

Codex Alimentarius Commission (2007) Codex Alimentarius Commission: Procedural Manual. FAO &WHO, Rome. Available at: https://books.google.com.au/books?hl=en&lr=&id=P2zOGjHGoyIC&oi=fnd&pg=PA1&dq=Codex+Alimentarius+Commission+2007&ots=aSg5DRv0sY&sig=R9DcaDIUKJRSI2IKEMno-jiNABg#v=onepage&q=CodexAlimentariusCommission2007&f=false. Accessed 4 Nov 2020

Colchero MA et al (2017) In Mexico, evidence of sustained consumer response two years after implementing a sugar-sweetened beverage tax. Health Aff 36(3):564–571. https://doi.org/10.1377/hlthaff.2016.1231

Daru J et al (2018) Risk of maternal mortality in women with severe anaemia during pregnancy and post partum: a multilevel analysis. Lancet Glob Health 6(5):e548–e554. https://doi.org/10.1016/S2214-109X(18)30078-0

Development Initiatives (2020) Global nutrition report, The global nutrition report's independent expert group. https://doi.org/10.2499/9780896295841.

Downs JS, Loewenstein G, Wisdom J (2009) Strategies for promoting healthier food choices. Am Econ Rev:159–164. https://doi.org/10.1257/aer.99.2.159

Eaton JC et al (2019) Effectiveness of provision of animal-source foods for supporting optimal growth and development in children 6 to 59 months of age. The Cochrane database of systematic reviews 2(2):CD012818. https://doi.org/10.1002/14651858.CD012818.pub2

EFSA and ECDC (2019) The European Union One Health 2018 Zoonoses Report. EFSA J 17(12). https://doi.org/10.2903/j.efsa.2019.5926

Eyles H et al (2012) Food pricing strategies, population diets, and non-communicable disease: a systematic review of simulation studies. PLoS Med 9(12):e1001353. https://doi.org/10.1371/journal.pmed.1001353. Edited by D. Stuckler

Fanzo J et al (2020) A research vision for food systems in the 2020s: defying the status quo. Glob Food Secur 26:100397. https://doi.org/10.1016/j.gfs.2020.100397

FAO (2019) The state of food and agriculture. Rome. https://doi.org/10.4324/9781315764788.

FAO et al (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. Rome. https://doi.org/10.1109/JSTARS.2014.2300145

FAO & WHO (2019) Sustainable healthy diets, sustainable healthy diets. Rome. https://doi.org/10.4060/ca6640en

Frank S et al (2018) Structural change as a key component for agricultural non-CO2 mitigation efforts. Nat Commun 9(1):1–8. https://doi.org/10.1038/s41467-018-03489-1

Fraval S et al (2019) Food access deficiencies in Sub-Saharan Africa: prevalence and implications for agricultural interventions. Front Sustain Food Syst 3(5):104. https://doi.org/10.3389/fsufs.2019.00104

Gale P, Breed AC (2013) Horizon scanning for emergence of new viruses: from constructing complex scenarios to online games. Transbound Emerg Dis 60(5):472–474. https://doi.org/10.1111/j.1865-1682.2012.01356.x

Garnett T (2016) Plating up solutions. Science 353:1202–1204. https://doi.org/10.1017/S1368980016000495

Gearan EC, Fox MK (2020) Updated nutrition standards have significantly improved the nutritional quality of school lunches and breakfasts. J Acad Nutr Diet 120(3):363–370. https://doi.org/10.1016/j.jand.2019.10.022

Ghosh-Dastidar B et al (2014) Distance to store, food prices, and obesity in urban food deserts. Am J Prev Med 47(5):587–595. https://doi.org/10.1016/j.amepre.2014.07.005

Gibb HJ et al (2019) Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury. Environ Res 174(December 2018):188–194. https://doi.org/10.1016/j.envres.2018.12.062

Global Panel on Agriculture and Food Systems for Nutrition (2020) Future food systems: for people, our planet, and prosperity

Global Panel on Agriculture and Food Systems for Nutrition (2021) Harnessing aquaculture for healthy diets. London

Global Salmon Institute (2020) Sustainable salmon farming: the future of food

Grace, D. et al. (2018) Food safety: food safety metrics relevant to low and middle income countries, food safety. London

Herforth A et al (2019) A global review of food-based dietary guidelines. Adv Nutr 10(4):590–605. https://doi.org/10.1093/advances/nmy130

Herrero M et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4

Herrero M et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1(5):266–272. https://doi.org/10.1038/s43016-020-0074-1

Herrero M et al (2021) Articulating the effect of food systems innovation on the Sustainable Development Goals. Lancet Planet Health 5(1):e50–e62. https://doi.org/10.1016/S2542-5196(20)30277-1

Hirvonen K et al (2020) Affordability of the EAT-Lancet reference diet: a global analysis. Lancet Glob Health 8(1):e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

HLPE (2020) Food security and nutrition: building a global narrative towards 2030', Research Guides. Available at: https://research.un.org/en/foodsecurity/key-un-bodies
Iannotti LL et al (2017) Eggs in early complementary feeding and child growth: a randomized controlled trial. Pediatrics 140(1):20163459. https://doi.org/10.1542/peds.2016-3459
Imamura F et al (2015) Dietary quality among men and women in 187 countries in 1990 and 2010: a systematic assessment. Lancet Glob Health 3(3):e132–e142. https://doi.org/10.1016/S2214-109X(14)70381-X
IPCC (2019) IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems: Summary for Policymakers, IPCC Special Report on Climate Change and Land. https://doi.org/10.1002/9781118786352.wbieg0538
Jarmul S et al (2020) Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of "sustainable diets". Environ Res Lett 15(12):123014. https://doi.org/10.1088/1748-9326/abc2f7
Jurgilevich A et al (2016) Transition towards circular economy in the food system. Sustainability 8(1):69. https://doi.org/10.3390/su8010069
Knowles T, Moody R, McEachern MG (2007) European food scares and their impact on EU food policy. Br Food J:43–67. https://doi.org/10.1108/00070700710718507. Emerald Group Publishing Limited
Leclere D et al (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature:1–6. https://doi.org/10.1038/s41586-020-2705-y
Lee MM et al (2019) 'Sugar-sweetened beverage consumption 3 years after the Berkeley, California, sugar-sweetened beverage tax'. Am J Public Health. American Public Health Association Inc., pp. 637–639. https://doi.org/10.2105/AJPH.2019.304971
Lele U, Goswami S, Mekonnen MM (2021) Achieving sustainable healthy food systems: the need for actual food consumption data for measuring food insecurity and its consequences. Econ Polit Wkly LVI(7):40–47
Lone TA et al (2009) Marketing healthy food to the least interested consumers. J Foodserv 20(2):90–99. https://doi.org/10.1111/j.1745-4506.2009.00131.x
Lusher A, Hollman P, Mendoza-Hill J (2017) Microplastics in fisheries and aquaculture: Status of knowledge on their occurrence and implications for aquatic organisms and food safety. Rome
Mairie de Paris (2015) Sustainable Food Plan 2015–2020. Paris.
Mason-D'Croz D et al (2019) Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. Lancet Planet Health 3(7):e318–e329. https://doi.org/10.1016/S2542-5196(19)30095-6
Mateo-Sagasta J, Zadeh SM, Turral H (2017) Water pollution from agriculture: a global review Executive summary
McGovern ME et al (2017) A review of the evidence linking child stunting to economic outcomes. Int J Epidemiol 46(4):1171–1191. https://doi.org/10.1093/ije/dyx017
Miles S et al (2004) Public worry about specific food safety issues. Br Food J 106(1):9–22. https://doi.org/10.1108/00070700410515172
Niebylski ML et al (2015) Healthy food subsidies and unhealthy food taxation: a systematic review of the evidence. Nutrition:787–795. https://doi.org/10.1016/j.nut.2014.12.010. Elsevier Inc
Olsho LE et al (2016) Financial incentives increase fruit and vegetable intake among supplemental nutrition assistance program participants: a randomized controlled trial of the USDA Healthy Incentives Pilot. Am J Clin Nutr 104(2):423–435. https://doi.org/10.3945/ajcn.115.129320
Parodi A et al (2018) The potential of future foods for sustainable and healthy diets. Nat Sustain 1(12):782–789. https://doi.org/10.1038/s41893-018-0189-7
Pikaar I et al (2018) Decoupling livestock from land use through industrial feed production pathways. Environ Sci Technol 52(13):7351–7359. https://doi.org/10.1021/acs.est.8b00216
Rekhy R, McConchie R (2014) Promoting consumption of fruit and vegetables for better health. Have campaigns delivered on the goals? Appetite 79:113–123. https://doi.org/10.1016/j.appet.2014.04.012

Ricci A et al (2017) Hazard analysis approaches for certain small retail establishments in view of the application of their food safety management systems. EFSA J 15(3). https://doi.org/10.2903/j.efsa.2017.4697

Roache SA, Gostin LO (2017) The untapped power of soda taxes: Incentivizing consumers, generating revenue, and altering corporate behavior Int J Health Policy Manag. Kerman University of Medical Sciences, pp 489–493. https://doi.org/10.15171/ijhpm.2017.69

Rockström J et al (2009) A safe operating space for humanity. Nature:472–475. https://doi.org/10.1038/461472a. Nature Publishing Group

Sánchez-Romero LM et al (2020) Association between tax on sugar sweetened beverages and soft drink consumption in adults in Mexico: open cohort longitudinal analysis of Health Workers Cohort Study. BMJ 369. https://doi.org/10.1136/bmj.m1311

Scheelbeek P et al (2020) Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: analyses of multiple UK studies. BMJ Open 10:37554. https://doi.org/10.1136/bmjopen-2020-037554

Springmann M, Wiebe K et al (2018a) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet Health 2(10):e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7

Springmann M, Clark M et al (2018b) Options for keeping the food system within environmental limits. Nature 562(7728):519–525. https://doi.org/10.1038/s41586-018-0594-0

Springmann M et al (2020) The healthiness and sustainability of national and global food based dietary guidelines: modelling study. BMJ 370:2322. https://doi.org/10.1136/bmj.m2322

Stehfest E et al (2009) Climate benefits of changing diet. Clim Chang 95:83–102. https://doi.org/10.1007/s10584-008-9534-6

Stoltzfus RJ, Mullany L, Black RE (2004) Iron deficiency anaemia. In: Comparative quantification of health risks, pp 163–210. https://doi.org/10.1016/0957-5839(94)90009-4

Stordalen G, Fan S (2018) Food security: the global food system under radical change. 2018 Global food policy report, pp 14–19. https://doi.org/10.2499/9780896292970_02.

Swinburn BA et al (2019) The global syndemic of obesity, undernutrition, and climate change: the lancet commission report. Lancet 6736(18):1–56. https://doi.org/10.1016/S0140-6736(18)32822-8

Taillie LS et al (2020) An evaluation of Chile's law of food labeling and advertising on sugar-sweetened beverage purchases from 2015 to 2017: A before-and-after study. PLoS Med 17(2): e1003015. https://doi.org/10.1371/JOURNAL.PMED.1003015

The Cost of Hunger in Africa series | World Food Programme (2021). Available at: https://www.wfp.org/publications/cost-hunger-africa-series. Accessed 24 Mar 2021

Thomson CA, Ravia J (2011) A systematic review of behavioral interventions to promote intake of fruit and vegetables. J Am Diet Assoc 111(10):1523–1535. https://doi.org/10.1016/j.jada.2011.07.013

Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515(7528):518–522. https://doi.org/10.1038/nature13959

Toussaint B et al (2019) Review of micro- and nanoplastic contamination in the food chain. Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment. Taylor and Francis Ltd., pp. 639–673. https://doi.org/10.1080/19440049.2019.1583381

United Nations (2015) Paris Agreement

United Nations Environment Programme (2021) Food waste index report 2021. Nairobi

Unnevehr LJ, Ronchi L (2014) Food safety and developing markets: research findings and research gaps, IFPRI Discussion Paper. Elsevier BV. https://doi.org/10.2139/ssrn.2523530

Van Cauwenberghe E et al (2010) Effectiveness of school-based interventions in Europe to promote healthy nutrition in children and adolescents: systematic review of published and grey literature. Br J Nutr 103(6):781–797. https://doi.org/10.1017/S0007114509993370 van Raamsdonk LWD et al (2020) Current insights into monitoring, bioaccumulation, and potential health effects of microplastics present in the food chain. Foods 9(1):1–28. https://doi.org/10.3390/foods9010072

Van Zanten HHE et al (2018) Defining a land boundary for sustainable livestock consumption. Glob Change Biol 24(9):4185–4194. https://doi.org/10.1111/gcb.14321

Walker RE, Keane CR, Burke JG (2010) Disparities and access to healthy food in the United States: a review of food deserts literature. Health Place 16(5):876–884. https://doi.org/10.1016/j.healthplace.2010.04.013

WHO (2008) Worldwide prevalence of anaemia 1993–2005. Available at: http://whqlibdoc.who.int/publications/2008/9789241596657_eng.pdf

WHO (2015) WHO estimates of the global burden of foodborne disease, foodborne disease burden epidemiology reference group 2007–2015. https://doi.org/10.1007/978-3-642-27769-6_3884-1

WHO & FAO (2006) Food and Agriculture Organization of the United Nations FAO/WHO guidance to governments on the application of HACCP in small and/or less-developed food businesses, WHO & FAO

Willett W et al (2019) Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Wood JLN et al (2012) A framework for the study of zoonotic disease emergence and its drivers: Spillover of bat pathogens as a case study. Philos Trans R Soc B Biol Sci. Royal Society, pp 2881–2892. https://doi.org/10.1098/rstb.2012.0228

Fruits and Vegetables for Healthy Diets: Priorities for Food System Research and Action

Jody Harris, Bart de Steenhuijsen Piters, Stepha McMullin, Babar Bajwa, Ilse de Jager, and Inge D. Brouwer

1 Why Fruits and Vegetables? Why Now?

Fruits and vegetables are vital for healthy diets, and there is broad consensus that a diverse diet containing a range of plant foods (and their associated nutrients, phytonutrients and fibre) is needed for health and wellbeing (FAO 2020). Studies have suggested intake ranges of 300–600 g per day (200–600 g of vegetables and 100–300 g of fruits) to meet different combinations of health and environmental goals (Willett et al. 2019; Loken et al. 2020; Afshin et al. 2019). The World Health Organisation (WHO) recommends that adults eat at least 400 g of fruits and vegetables per day (World Health Organisation 2003), with national food-based dietary guidelines translating these into recommendations to eat multiple portions of a variety of fruits and vegetables each day for health (Herforth et al. 2019).

Despite this clear message, intake of fruits and vegetables remains low for a majority of the global population (Afshin et al. 2019; Kalmpourtzidou et al. 2020). Low fruit and vegetable consumption is among the five main risk factors for poor

J. Harris (✉)
World Vegetable Centre, Bangkok, Thailand
e-mail: Jody.harris@worldveg.org

B. de Steenhuijsen Piters
Wageningen Economic Research, Wageningen, the Netherlands

S. McMullin
World Agroforestry, a partnership of CIFOR-ICRAF, and CGIAR FTA, Nairobi, Kenya

B. Bajwa
CABI, Rawalpindi, Pakistan

I. de Jager
Wageningen University and Research, Wageningen, the Netherlands

I. D. Brouwer
Wageningen University and Research, and CGIAR-A4NH, Wageningen, the Netherlands

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_6

health, with over 2 million deaths and 65 million Disability-Adjusted Life Years (DALYs) attributable to low intake of fruits, and 1.5 million deaths and 34 million DALYs attributable to low intake of vegetables globally each year, particularly in low- and middle-income countries (Afshin et al. 2019). Low consumption is a global problem, affecting high- and low-income countries: only 7% of countries in Africa, 7% in the Americas, and 11% in Europe reach 240 g/day of vegetables on average (Kalmpourtzidou et al. 2020), and only 20% of individuals in low- and middle-income countries reach the recommendation of five servings of fruits and vegetables a day (Frank et al. 2019). The mean global intake of vegetables is estimated to be around 190 g/day, and of fruits, 81 g/day. Studies generally agree that parts of Africa and the Pacific Islands have the lowest fruit and vegetable consumption, and East Asia has the highest vegetable (but not fruit) consumption (Afshin et al. 2019; Kalmpourtzidou et al. 2020; Micha et al. 2015).

Changes in fruit and vegetable consumption are happening against a backdrop of the 'nutrition transition' from traditional foods to processed and ultra-processed foods that are high in energy, fat, sugar and salt, but poor in other essential nutrients (Popkin et al. 2020). This transition also brings opportunities to diversify into healthy diets containing more fresh fruits and vegetables, although, for some populations, there is less opportunity than for others (Global Panel on Agriculture and Food Systems for Nutrition 2016). The available literature does not suggest systematic differences in fruit and vegetable consumption between men and women in many contexts (Frank et al. 2019; Micha et al. 2015), but it does highlight differences in consumption between rural and urban areas (Hall et al. 2009; Ruel et al. 2004; Mayen et al. 2014), and among populations with different levels of education and national income (Frank et al. 2019). These differences illustrate that there is an equity issue across populations in accessing fruits and vegetables (Harris et al. 2021a).

We now have good conceptual models for how food systems work to provide diets (HLPE 2017). These help us to describe the structural and social constraints to fruit and vegetable consumption and research how these play out in different contexts and for different populations. Below, we summarise what we know (and what we need to know) about how to address the issues above through a set of push (production and supply), pull (demand and activism) and policy (legislation and governance) actions. We conclude that there is still a need to better understand the different ways that food systems can make fruits and vegetables available, accessible, affordable and desirable for all people, across places and over time, so as to meet global recommendations, but also that we know enough to accelerate action in support of healthy diets. The year 2021 is the UN International Year of Fruits and Vegetables, embedded in the middle of the Decade of Action on Nutrition. Now is the time to prioritise understanding and addressing these issues to enable fruit- and vegetable-rich food systems that can drive healthy diets for all.

2 Policy Factors: Political Power

The Green Revolution in the latter part of the twentieth century transformed agriculture's ability to produce sufficient calories to feed the world, but the focus on grain crops through funding, research, extension and technology development limited the supply of nutrient-dense fruits and vegetables, both through losses of wild sources with the promotion of monocultures and through policy and structural impediments that crowded out non-staple crops (Pingali 2012). Today, the combined international public research budget for maize, wheat, rice, and starchy tubers is 30 times greater than for vegetables, for instance (Herforth 2020), and these incentives skew many of the technology and infrastructure drivers of food systems. This has fed into national food policies, which are normally focused on the production or import of staple crops (as a source of cheap calories), rather than diet quality through diversity of fresh foods (as a source of other essential nutrients) (McDermott and De Brauw 2020). Following suit, food system data have focused largely on globally-tradable commodities, leading to a dearth of trustworthy and disaggregated data with which to track the production, price, trade or consumption of the diversity of fruits and vegetables (Masters et al. 2018), and global data are biased towards economically-relevant crops, often missing traditional fruits and vegetables and those produced non-commercially (Thar et al. 2020). Research on food systems and diets often treats fruits and vegetables as a single food group, rather than looking at diversity within fruit and vegetable species, or the amounts or variety consumed within the food group (Harris et al. 2021b), further limiting our knowledge on the specifics of issues or actions.

At the same time, large structural changes outside of the food system, such as the globalisation of supply chains and societies, and changing demographics and urbanisation have shaped food regimes to prioritise foods that are non-perishable and globally tradable (Magnan 2012; Lang and Heasman 2015), the very opposite of most fruits and vegetables, whose perishability requires shorter food chains from farm to fork. Modern trade rules improve regulation on the safety of imported fruits and vegetables and may protect domestic production or improve supply of highly-traded commodities, but they also limit the ability of governments to protect the public health policy space and the institutional purchase of fresh foods (Thow et al. 2015) and tend to prioritise staple foods over fruits and vegetables, while out-sourcing the environmental impacts of production to poor countries (FAO 2020). In many contexts, the concentration of inputs, distribution and retail of foods – including fruits and vegetables – in the hands of a few large companies, has shifted food system choices away from the livelihood interests of producers, the health interests of consumers, and the environmental interests of all (Howard 2016).

These broad and sweeping changes have not been without interruption: the COVID-19 pandemic and previous economic shocks and natural disasters have disrupted many aspects of food systems and diets over time (Savary et al. 2020; Block et al. 2004; Darnton-Hill and Cogill 2010). Such disruptions particularly affect fruits and vegetables because of their specific labour, storage and transport requirements (Harris 2020), with at least temporary impacts of different shocks having been documented on the livelihoods of fruit and vegetable producers and on fruit and vegetable prices and consumption (Block et al. 2004; Darnton-Hill and Cogill 2010; Harris et al. 2020; Hirvonen et al. 2020). These shocks have affected the diets and livelihoods of marginalised populations in ways different from those with economic or social power, further exacerbating inequity (Carducci et al. 2021; Kansiime et al. 2021; Goldin and Muggah 2020).

2.1 Opportunities for Research and Action

Each of these big-picture policy and political drivers has created food system 'lock-ins' (Leach et al. 2020), which have tended to steer away from pathways prioritising fruits and vegetables, and away from agronomic and food system paradigms – such as agroecology, a right to food, or food as a commons rather than a commodity (Rosset and Altieri 2017; Vivero-Pol et al. 2018; Patnaik and Oenema 2015) – that might promote a return to more diverse production systems. Policy decisions can start with evidence: we need to know more about how different production and distribution systems, based in different social and political traditions, drive the availability and accessibility of fruits and vegetables in food systems, and how they weather shocks to provide healthy diets sustainably and equitably. However, ultimately, while data and evidence can reveal nuance in the issues and their solutions, food policy decisions are political (and, ideally, ethical) in reality, depending on the priorities and tolerances of the actors involved in making those decisions (Harris 2019). Bringing together people with a stake in food systems to debate and decide policy, explicitly recognising disparities in power among them in contributing to outcome and decisions, is likely to lead to the most context-specific and equitable policy in practice when done well (Chaudhury et al. 2013; Barzola et al. 2019; Blay-Palmer et al. 2018).

A starting point for addressing the lack of fruits and vegetables in food system policy is 'reverse thinking', putting the dietary outcomes we want from food systems upfront in responsive food policy-making and legislation, and working towards incentivising systems that create these (McDermott and De Brauw 2020). A difficulty in achieving this vision is that different actor coalitions frame food system issues and priorities differently according to their interests and beliefs, so that there is no single narrative to work towards (Harris 2019; Béné et al. 2019), and coherent diet and food system policy will require policy sectors to work together in non-traditional ways (Thow et al. 2018). There is, therefore, a need to better understand how public and private decision-makers make food system choices and how other food system actors influence these, as well as the implications for fruits and vegetables across food systems.

Public investment in agriculture is shown to impact the growth of production through the private sector, but different types of investment produce different results for different foods in different contexts (Mogues et al. 2012), so we need to know more about how specific investments, such as in breeding, production subsidies, and extension support, play out in food environments for different fruits and vegetables. Acknowledging the imbalance of power among food system actors, illustrated by disparities between budgets of processed food producers (Baker et al. 2020) and public investment in healthy foods such as fruits and vegetables (Herforth 2020), is necessary in order to make transparent and health-positive policy, regulation and investment. Public policy shaping food environments – such as mandating vegetables in institutional meals (schools, workplaces, hospitals), setting incentives for healthy retail, and regulating food system actors (Knai et al. 2006; Micha et al. 2018; Vandevijvere et al. 2019) – is seen to improve intakes in some contexts. Similarly, land rights are a key issue for sustainable food access and production (Sunderland and Vasquez 2020), and we need to know more about how these issues affect fruits and vegetables. For all of these analyses, better data and contextual knowledge on diverse fruits and vegetables in different systems is needed, particularly in low- and middle-income countries, to inform businesses, policy-makers, practitioners, workers and activists in making decisions within food systems.

3 Push Factors: Production and Post-Harvest Power

By the data we have, global fruit and vegetable production is insufficient to meet the WHO dietary recommendations, and has been since global records began: in 1965, sufficient fruits and vegetables (≥400 g/day) were available for 17% of the global population, increasing to 55% in 2015 (Mason-D'Croz et al. 2019). Supply varies widely between contexts: in Africa, only 13% of countries have an adequate aggregate vegetable supply, while in Asia, 61% do (Kalmpourtzidou et al. 2020). This is despite the fact that fruits and vegetables are valuable: the annual farmgate value of global fruit and vegetable production is nearly $1 trillion and exceeds the farmgate value of all food grains combined (US$ 837 billion) (Schreinemachers et al. 2018). Most fruits and vegetables (about 92%) are not internationally traded, but the international trade in fruits and vegetables was still valued at US$ 138 billion in 2018.

Fruit and vegetable production needs to increase, particularly in regions with low consumption, together with accompanying measures to prevent losses, to provide enough for healthy diets (Mason-D'Croz et al. 2019). Scaling production is not straightforward, as fruits and vegetables have specific attributes – in terms of seasonal and agro-climatic differences, labour and input needs, knowledge and expertise, and storage and distribution – that mean there are particular trade-offs to consider. While we can, in theory, produce healthy diets within planetary boundaries (Willett et al. 2019), achieving national food-based dietary guidelines has been found to be incompatible with climate and environmental targets in a majority of the 85 countries studied (Springmann et al. 2020), and producing more fruits and vegetables may require more land, water and chemical inputs than producing staple foods in some contexts (Aleksandrowicz et al. 2016), with one-third of all greenhouse gas emissions being produced by the food system (Crippa et al. 2021). Various studies show widespread misuse of agricultural chemicals, particularly on high-value vegetables, creating hazards for farm workers, consumers and the environment (Schreinemachers et al. 2020a). Foodborne diseases caused by biological contamination of food are also an important threat to public health, particularly in low- and middle-income countries, and fruits and vegetables are among the riskiest foods for biological hazards (Grace 2015).

Seed or planting stock is a key input in fruit and vegetable production, although it is a contested area: some see the introduction of (often proprietary) improved varieties of fruits and vegetables as necessary to transform the fruit and vegetable sector to one with increased volumes of regularly available quality products (Schreinemachers et al. 2018; Dawson et al. 2019; Schreinemachers et al. 2021; Lillesø et al. 2018). Others stress the importance of local or cultural seed-saving and exchange of planting material for conserving farmers' independence, agricultural diversity and food sovereignty (Howard 2016; Phillips 2016), and debates about the primacy of breeders' rights or farmers' rights are ongoing (Gupta and Negi 2019; Salazar et al. 2007; Dias 2011). Beyond inputs, labour requirements in fruit and vegetable production are considerably higher than in cereal production, with labour costs making up more than 50% of production costs, depending on the food grown, related to more skilled and intensive field operations (Weinberger and Lumpkin 2007; Herrero et al. 2017). This is a positive for food system worker incomes, but extension services are often geared towards staple crops, with little support for fruit and vegetable producers, limiting formal training opportunities (Pingali 2015). Beyond the farm, post-farmgate midstream employment in developing regions constitutes roughly 20% of rural employment (Dolislager et al. 2020; Reardon et al. 2014). It is assumed that many smallholders also engage in midstream fruit and vegetable chain operations, such as trade and processing, but fruit and vegetable value chains have not been a focus of this work, so more knowledge is needed in this area.

Of food produced for human consumption, around one-third by volume or one-quarter by calories is either lost (before retail) or wasted (after purchase) (HLPE 2014). Highly perishable fruits and vegetables have the highest rates of loss and waste, usually within the range of 40–50% (Global Panel 2018; FAO 2019). Local production is therefore central, and in many contexts, ultra-local home-based fruit and vegetable production and wild plant gathering are important strategies (Schreinemachers et al. 2015; Bharucha and Pretty 2010), as are 'under-utilised' species and many traditional fruits and vegetables that are often left out of data, policy and extension (Raihana et al. 2015; Hunter et al. 2019). Fruits and vegetables are particularly seasonal, which can be an advantage in diverse systems where different foods become available at different times, or a challenge where there are gluts and shortages that lead to price changes over the course of the year (Gilbert et al. 2017; McMullin et al. 2019).

3.1 Opportunities for Research and Action

Clearly, greater availability of a variety of fruits and vegetables is needed for everyone to meet recommendations. This can be achieved through increased production, although there are trade-offs between environmental sustainability and providing for diets: sustainable intensification using a wide range of approaches according to the social, political and agro-ecological contexts to improve yields or protect against climate changes without environmental degradation has been suggested (Schreinemachers et al. 2018; Godfray and Garnett 2014), although further understanding of the implications of different approaches to fruit and vegetable production is needed. Organic agriculture meets goals for a range of environmental factors, including reduced chemical contamination of diets, but it has weaknesses in terms of lower productivity and reduced yield stability (Knapp and van der Heijden 2018), and the subsidisation of chemical inputs makes it appear less profitable. Supporting the availability of planting material through formal (breeding and seed companies) and informal (seed-saving and sharing networks) channels is important (Schreinemachers et al. 2018).

The economic value of fruits and vegetables is a strong incentive for their production, but much of this value is captured by large global firms rather than smallholders, despite over 80% of fruit and vegetables being grown on smallholder family farms (<20 ha) in LMICs (Herrero et al. 2017). The smallholder nature of many fruit and vegetable producers and traders provides challenges and opportunities for vegetable supply (Reardon and Timmer 2014), and the complexity of systems of traders and the heterogeneity of smallholders and their support needs (particularly peri-urban vegetable producers or women, who may not be engaged in formal extension systems (FAO 2021; Fischer et al. 2017)) means that agricultural policy very often does not adequately support the twin goals of healthy food production and livelihood development (Gassner et al. 2019). Aggregation or contract farming is commonly used to reduce transaction costs and risk, and to sell to modern channels such as supermarkets, where demand for fruits and vegetables is growing (Reardon et al. 2012; Holtland 2017), although the impacts of commercialisation on the diets of commercial farmers themselves are mixed (Carletto et al. 2017). Farmer extension needs to be strengthened (Schreinemachers et al. 2018), and we need more documented understanding of how informal sectors and formal small and medium enterprises involved in fruit and vegetable processing, distribution and retail can deliver more on desired food system outcomes. These need further research to understand how they play out in fruit and vegetable systems.

Better availability can also be achieved by addressing food loss and waste: in low-income countries, through addressing on-farm pests and diseases, pre-maturity harvesting due to climate shocks or seasonal gluts, and inappropriate post-harvest handling, transport and storage, and in middle-/high-income countries, by addressing quality grading standards set by retailers (Global Panel 2018). Packaging of perishable fruits and vegetables can limit losses (Wohner et al. 2019), but also contributes to environmental pollution and greenhouse gas emissions (Crippa et al. 2021;

Yates et al. 2021). More understanding is needed of the production, processing and distribution options and trade-offs, and of food loss and waste, specifically for fruits and vegetables in different contexts.

The physical availability of food varies, depending on functioning supply chains, whether short or long. Food deserts and swamps associated with poorer diets occur where there is a lack of available fresh foods for local purchase, and exist particularly in poorer urban areas (Ghosh-Dastidar et al. 2014). Physical access is a key driver of purchase (and, by extension, consumption), with a lack of fresh food outlets making consumption of fresh produce harder (Beaulac et al. 2009), and, conversely, living close to vegetable vendors making vegetable purchase more likely (Ambikapathi et al. 2021), suggesting that local access options are important in shaping diets.

4 Pull Factors: People Power

While availability of, and physical access to, sufficient fruits and vegetables is an important prerequisite, there are other factors at the socio-economic and personal levels that also impact their role in diets. Reviews of research suggest that, in low-income countries, similar determinants play a role in food choices as in high-income countries, at the individual level (income, employment, education level, food knowledge, lifestyle, time), in the social environment (family and peer influence, cultural factors), and in the physical environment (food expenditure, lifestyle) (Gissing et al. 2017).

Food prices interact with incomes to determine whether households can afford the components of a healthy diet, and fruits and vegetables, along with animal-source foods, are the most expensive element of a healthy diet, comprising, by many metrics (Maillot et al. 2007; Headey and Alderman 2019), around 40% of the cost of a healthy diet (Herforth et al. 2020), although these costs tend to vary with the season (Gilbert et al. 2017). Fruits and vegetables are unaffordable for many, with 3 billion people unable to afford diverse, healthy diets (Herforth et al. 2020). Fruits and vegetables appear more affordable when comparing prices per micronutrient, according to which they are likely to be a relatively low-cost source of varied vitamins, minerals, and phytonutrients (Drewnowski 2013), but this is not how most families choose their food.

Beyond a certain income level, affordability is not a driving factor for everyone everywhere: while an increase of fruit and vegetable consumption by income across geographical regions is confirmed in many studies, indicating that a low income is a barrier to fruit and vegetable consumption for some (Frank et al. 2019; Miller et al. 2016), there is only a weak association between incomes and fruit and vegetable consumption, showing that, on average (across 52 countries), 82% of the poorest quintile consume an insufficient amount of fruits and vegetables and 73% of the wealthiest quintile do the same (Hall et al. 2009). As incomes rise, the consumption of meat, dairy and ultra-processed foods rises much faster than that of vegetables; additionally, the purchase of vegetables in some contexts changes little across income groups, and hence vegetable consumption is relatively inelastic to income past a certain level (Ruel et al. 2004), although a greater amount of fruit may be consumed at higher incomes. With little change in the consumption of vegetables across income groups in some contexts (Morris and Haddad 2020), affordability is not the largest driver of consumption for all.

Even if vegetables are available, accessible and affordable, most people still do not consume large enough quantities (Hall et al. 2009), particularly if they are not considered an acceptable or desirable food choice, for instance, due to food safety or contamination concerns, taste preferences, or cultural appropriateness (Aggarwal et al. 2016; Ha et al. 2020; Hammelman and Hayes-Conroy 2014). Low desirability of fruits and vegetables is a particular problem among children and adolescents, with data across 73 countries showing that between 10% and 30% of students do not eat any vegetables at all in one-quarter of these countries (FAO, IFAD, UNICEF, WFP, WHO 2019).

4.1 Opportunities for Research and Action

Addressing the affordability of fruits and vegetables is key to creating an environment where all can access a healthy diet, and affordability can come from a combination of lower retail prices (through productivity improvements, reduced post-harvest losses, or increased market efficiency for stable prices) and higher incomes (from inclusive economic growth and social safety nets) (Hirvonen et al. 2019). Cheap food is not necessarily good for healthy diets, fair livelihoods or biodiverse environments, so a focus on raising people up through fair wages is important (Benton et al. 2021). Price subsidies for fruits and vegetables is a policy option that is popular with the public in some contexts (Niebylski et al. 2015), and there is evidence that price incentives to make fruits and vegetables more directly affordable have worked to increase consumption (Swinburn et al. 2019; Olsho et al. 2016). These affordability interventions in contexts where a majority of fruits and vegetables are purchased can be combined with non-purchase interventions such as promoting home and community production or the facilitation of foraging where the context allows (Schreinemachers et al. 2016; Baliki et al. 2019; Powell et al. 2015).

Alongside the ability to afford fruits and vegetables, the challenge is to enhance consumer choice of and preference for these foods. There is clear evidence that focusing on education at all levels is a key component for modifying behavioural changes in general (Alderman and Headey 2017), and nutrition literacy, social norms for healthy eating, and self-efficacy are key components of health-related behavioural change (Eker et al. 2019), although we know less in regard to fruits and vegetables in particular. Nutrition literacy programmes generally target women, who are custodians of household nutrition in many contexts, but there may also be a need for community-targeted messages to change social norms (Van den Bold et al. 2013). Promoting traditional or under-utilised vegetables that are familiar was seen as a key policy option for healthy diets and environmental sustainability among the members of an expert opinion Delphi panel (Pedersen et al. 2020), and the latest generation of food-based dietary guidelines have begun to move in this direction, but these efforts need to better consider cultural acceptability and may require promotional efforts to increase the willingness of consumers to shift their tastes to new or forgotten foods (Davis et al. 2021). Food composition data is lacking for many indigenous species, limiting the opportunity to develop appropriate nutritional messaging and promote wider use (Stadlmayr et al. 2013; Jansen et al. 2020).

Beyond appeals to public health, better understanding is required of consumers' preferences and behaviours with respect to these foods and what kinds of incentives might promote more consumption in different contexts. Strategic placement of fruit and vegetables in retail outlets is found to have a moderately significant effect on increasing fruit or vegetable servings (Broers et al. 2017), and early exposure to fruits and vegetables through schools may shape future preferences for healthier diets (Schreinemachers et al. 2020b). Marketing is a key factor shaping desirability, but is consistently applied for 'hedonic' (processed) rather than 'healthy' (nutrient-dense) foods (Bublitz and Peracchio 2015). On marketing issues, much is known about high-income countries (Thomson and Ravia 2011), but less about low- and middle-income contexts where these approaches (understanding market segments and speaking to issues of desirability, aspiration, emotion and imagination) can be adapted for fruits and vegetables (Deo and Monterrosa 2020).

5 Fruit and Vegetable Food Systems: What Next?

The brief review above has laid out evidence on the key food system issues for fruits and vegetables in healthy diets, and, where available, included evidence on actions to address these. From this summary, it is clear that we know, on a broad scale, the structural limitations to fruits and vegetables: global and national challenges of increasing production and accessing quality growing material shared equitably, local issues of ensuring affordability, addressing perishability and enabling everyone everywhere to access fruits and vegetables, and social issues of valuing vegetables for their role in cuisines and for health. It is also clear that the precise issues and solutions to these vary by population and according to the food system context, and that there are multiple potential routes towards solutions that sometimes clash on ideals. Food system actions to make fruits and vegetables more available, affordable, accessible and desirable through policy, push and pull mechanisms comprise various options working at the macro (global and national), meso (institutional, city and community) and micro (household and individual) levels. Examples of actions from the review above are laid out in the table below.

It is unlikely that these are all of the options available for orienting food systems towards fruit- and vegetable-rich diets, but these are the options that appear in the academic literature, albeit with varying levels of evidence. In addition, there are two important over-arching considerations when considering action options: (1) Acknowledging that power shapes food systems, from the concentration of economic and political power in a few global agri-food businesses to the marginalisation of certain groups in societies from accessing healthy diets, so this needs to be considered in terms of both facilitating inclusive processes for deciding policies and actions and assessing their equity impacts (Howard 2016; Harris and Nisbett 2018); and (2) there will be trade-offs among food system outcomes, so starting with a focus on healthy diets is important, but understanding how food system decisions then impact fair livelihoods and sustainable environments is key (Wiebe and Prager 2021). We do not yet know enough to formulate clear actions that will address these trade-offs, but they need to be acknowledged and openly debated by those making food system decisions.

Examples of Policy, Push and Pull Actions at Different Levels

	Macro (global and national)	Meso (institutional, city and community)	Micro (household and individual)
Policy	R&D investment Right to food legislation Food safety regulation	Zoning and marketing regulation Prioritising fruit and vegetables (F&V) in institutional food procurement plans	Protected foraging rights Land rights
Push	Production subsidies Efficiency through breeding and technology Support for diverse alternative production paradigms Infrastructure development Fair finance access	Quality F&V planting material (formal and informal systems) Pre- and post-harvest practices and packaging Improving market access, shortening food supply chains F&V extension and training Support for fresh food outlets	Home & community gardens
Pull	Price subsidies Social safety nets Food-based dietary guidelines	F&V-rich institutional meals Basic processing for preservation Social marketing campaigns Promotion of traditional F&V F&V product placement in shops and canteens	Nutrition literacy campaigns School gardens and learning for shaping preferences

These actions are likely to be foundational to creating change within food systems towards enabling fruit- and vegetable-rich diets. None of these actions will change diets when implemented alone, but rather packages of actions need to be assembled to address particular limitations for fruit and vegetable consumption. These need to be considered in context, in light of an understanding of food system issues and bottlenecks limiting healthy diets in different places and for different people. It is likely that the best way to start is to bring together diverse groups of people interested in these issues at the different levels, to understand the issues and options from different perspectives and to prioritise together which actions should be undertaken first in their own context. This is not easy, given inherent power disparities among interested parties, but with care and inclusion, a strategy, policy or plan can be crafted to move towards enabling fruit and vegetable-rich food systems.

To guide better action, we need more evidence and understanding. We know a lot about a small fraction of the fruit and vegetable species of which we are aware, and very little about the rest. We know that there are disparities in diets in different contexts, but not how to address the political, social and equity determinants of who gets to eat fruits and vegetables. We know much about the technical production and market aspects of fruits and vegetables, but less about bottlenecks in bringing these to low- and middle-income countries, and we do not know enough about how these things change with context or over time. Work drawing on different academic traditions, including valuing traditional and tacit knowledge, is needed to connect the dots. Food systems that enable fruits and vegetables in healthy diets are not only a technical issue, but bring up very real political, social and ethical questions that societies will have to address, alongside a reliance on evidence. Having these conversations through the lens of equity to address the needs of both winners and losers within changing food systems will be a vital part of the UNFSS process towards enabling fruit and vegetable-rich food systems for healthy diets for all.

References

Afshin A, Sur PJ, Fay KA et al (2019) Health effects of dietary risks in 195 countries, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393(10184): 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Aggarwal A, Rehm CD, Monsivais P, Drewnowski A (2016) Importance of taste, nutrition, cost and convenience in relation to diet quality: evidence of nutrition resilience among US adults using National Health and Nutrition Examination Survey (NHANES) 2007–2010. Prev Med 90:184–192

Alderman H, Headey DD (2017) How important is parental education for child nutrition? World Dev 94:448–464

Aleksandrowicz L, Green R, Joy EJ, Smith P, Haines A (2016) The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLoS One 11(11):e0165797

Ambikapathi R, Shively G, Leyna G et al (2021) Informal food environment is associated with household vegetable purchase patterns and dietary intake in the DECIDE study: empirical evidence from food vendor mapping in peri-urban Dar es Salaam, Tanzania. Glob Food Secur 28:100474

Baker P, Machado P, Santos T et al (2020) Ultra-processed foods and the nutrition transition: global, regional and national trends, food systems transformations and political economy drivers. Obes Rev 21(12):e13126

Baliki G, Brück T, Schreinemachers P, Uddin MN (2019) Long-term behavioural impact of an integrated home garden intervention: evidence from Bangladesh. Food Secur 11:1217–1230. https://doi.org/10.1007/s12571-019-00969-0

Barzola CL, Dentoni D, Allievi F et al (2019) Challenges of youth involvement in sustainable food systems: lessons learned from the case of farmers' value network embeddedness in Ugandan Multi-Stakeholder Platforms. In: Achieving the Sustainable Development Goals through sustainable food systems. Springer, Cham, pp 113–129

Beaulac J, Kristjansson E, Cummins S (2009) A systematic review of food deserts, 1966–2007. Prev Chronic Dis 6(3)

Béné C, Oosterveer P, Lamotte L et al (2019) When food systems meet sustainability – current narratives and implications for actions. World Dev 113:116–130

Benton TG, Bieg C, Harwatt H, Pudasaini R, Wellesley L (2021) Food system impacts on biodiversity loss. Research paper: Energy, Environment and Resources Programme

Bharucha Z, Pretty J (2010) The roles and values of wild foods in agricultural systems. Philos Trans R Soc B Biol Sci 365(1554):2913–2926

Blay-Palmer A, Santini G, Dubbeling M, Renting H, Taguchi M, Giordano T (2018) Validating the city region food system approach: enacting inclusive, transformational city region food systems. Sustainability 10(5):1680

Block SA, Kiess L, Webb P et al (2004) Macro shocks and micro outcomes: child nutrition during Indonesia's crisis. Econ Hum Biol 2(1):21–44

Broers VJ, De Breucker C, Van den Broucke S, Luminet O (2017) A systematic review and meta-analysis of the effectiveness of nudging to increase fruit and vegetable choice. Eur J Public Health 27(5):912–920

Bublitz MG, Peracchio LA (2015) Applying industry practices to promote healthy foods: an exploration of positive marketing outcomes. J Bus Res 68(12):2484–2493

Carducci B, Keats E, Ruel M, Haddad L, Osendarp S, Bhutta Z (2021) Food systems, diets and nutrition in the wake of COVID-19. Nature Food 2(2):68–70

Carletto C, Corral P, Guelfi A (2017) Agricultural commercialization and nutrition revisited: empirical evidence from three African countries. Food Policy 67:106–118

Chaudhury M, Vervoort J, Kristjanson P, Ericksen P, Ainslie A (2013) Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. Reg Environ Chang 13(2):389–398

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello F, Leip A (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food:1–12

Darnton-Hill I, Cogill B (2010) Maternal and young child nutrition adversely affected by external shocks such as increasing global food prices. J Nutr 140(1):162S–169S

Davis KF, Downs S, Gephart JA (2021) Towards food supply chain resilience to environmental shocks. Nature Food 2(1):54–65

Dawson IK, Powell W, Hendre P et al (2019) The role of genetics in mainstreaming the production of new and orphan crops to diversify food systems and support human nutrition. New Phytol 224(1):37–54

Deo A, Monterrosa E (2020) Demand creation at GAIN

Dias JCS (2011) Biodiversity and vegetable breeding in the light of developments in intellectual property rights. Ecosyst Biodivers:389–428

Dolislager M, Reardon T, Arslan A et al (2020) Youth and adult agrifood system employment in developing regions: rural (peri-urban to hinterland) vs. urban. J Dev Stud:1–23

Drewnowski A (2013) New metrics of affordable nutrition: which vegetables provide most nutrients for least cost? J Acad Nutr Diet 113(9):1182–1187

Eker S, Reese G, Obersteiner M (2019) Modelling the drivers of a widespread shift to sustainable diets. Nature Sustain 2(8):725–735

FAO (2019) Moving forward on food loss and waste reduction. The State of Food and Agriculture

FAO (2020). The state of food security and nutrition in the world. Food and Agriculture Organisation

FAO (2021) Fruit and vegetables – your dietary essentials. The International Year of Fruits and Vegetables 2021 – Background paper. http://www.fao.org/3/cb2395en/CB2395EN.pdf

FAO, IFAD, UNICEF, WFP, WHO (2019) The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns, FAO

Fischer G, Gramzow A, Laizer A (2017) Gender, vegetable value chains, income distribution and access to resources: insights from surveys in Tanzania. Eur J Hortic Sci 82(6):319–327

Frank SM, Webster J, McKenzie B et al (2019) Consumption of fruits and vegetables among individuals 15 years and older in 28 low-and middle-income countries. J Nutr 149(7): 1252–1259
Gassner A, Harris D, Mausch K et al (2019) Poverty eradication and food security through agriculture in Africa: rethinking objectives and entry points. Outlook Agric 48(4):309–315
Ghosh-Dastidar B, Cohen D, Hunter G et al (2014) Distance to store, food prices, and obesity in urban food deserts. Am J Prev Med 47(5):587–595. https://doi.org/10.1016/j.amepre.2014.07.005
Gilbert CL, Christiaensen L, Kaminski J (2017) Food price seasonality in Africa: measurement and extent. Food Policy 67:119–132. https://doi.org/10.1016/j.foodpol.2016.09.016
Gissing SC, Pradeilles R, Osei-Kwasi HA, Cohen E, Holdsworth M (2017) Drivers of dietary behaviours in women living in urban Africa: a systematic mapping review. Public Health Nutr 20(12):2104–2113
Global Panel (2018) Preventing nutrient loss and waste across the food system: policy actions for high-quality diets. Policy brief no. 12
Global Panel on Agriculture and Food Systems for Nutrition (2016) Food systems and diets: Facing the challenges of the 21st century. http://www.glopan.org/foresight
Godfray HCJ, Garnett T (2014) Food security and sustainable intensification. Philos Trans R Soc B Biol Sci 369(1639):20120273
Goldin I, Muggah R (2020) COVID-19 is increasing multiple kinds of inequality. Here's what we can do about it
Grace D (2015) Food safety in low and middle income countries. Int J Environ Res Public Health 12(9):10490–10507
Gupta A, Negi P (2019) Protection of 'plant varieties' vs. balancing of rights of breeders and farmers. Int J Rev Res Soc Sci 7(4):741–745
Ha TM, Shakur S, Pham Do KH (2020) Risk perception and its impact on vegetable consumption: a case study from Hanoi, Vietnam. J Clean Prod 271:122793
Hall JN, Moore S, Harper SB, Lynch JW (2009) Global variability in fruit and vegetable consumption. Am J Prev Med 36(5):402–409.e5. https://doi.org/10.1016/j.amepre.2009.01.029
Hammelman C, Hayes-Conroy A (2014) Understanding cultural acceptability for urban food policy. J Plan Literat 30(1):37–48. https://doi.org/10.1177/0885412214555433
Harris J (2019) Coalitions of the willing? Advocacy coalitions and the transfer of nutrition policy to Zambia. Health Policy Plan 34(3):207–215
Harris J (2020) Diets in a time of coronavirus: don't let vegetables fall off the plate. IFPRI Covid-19 blogs blog. April 13, 2020. https://www.ifpri.org/blog/diets-time-coronavirus-dont-let-vegetables-fall-plate
Harris J, Nisbett N (2018) Equity in social and development studies research: what insights for nutrition? SCN News 43
Harris J, Depenbusch L, Pal AA, Nair RM, Ramasamy S (2020) Food system disruption: initial livelihood and dietary effects of COVID-19 on vegetable producers in India. Food Secur 12(4): 841–851
Harris J, Tan W, Mitchell B, Zayed D (2021a) Equity in agriculture-nutrition-health research: a scoping review. Nutr Rev 80:78
Harris J, Tan W, Raneri J, Schreinemachers P, Herforth A (2021b) Vegetables in food systems for healthy diets in low- and middle-income countries: mapping the literature. Food Nutr Bull 43:232
Headey DD, Alderman HH (2019) The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. J Nutr. https://doi.org/10.1093/jn/nxz158
Herforth A (2020) Three billion people cannot afford a healthy diet: What does this mean for the next Green Revolution? Center for Strategic and International Studies commentary blog. September 23, 2020. https://www.csis.org/analysis/three-billion-people-cannot-afford-healthy-diets-what-does-mean-next-green-revolution

Herforth A, Arimond M, Álvarez-Sánchez C, Coates J, Christianson K, Muehlhoff E (2019) A global review of food-based dietary guidelines. Adv Nutr 10(4):590–605

Herforth A, Bai Y, Venkat A, Mahrt K, Ebel A, Masters W (2020) Cost and affordability of healthy diets across and within countries: background paper for The State of Food Security and Nutrition in the World 2020. FAO Agricultural Development Economics Technical Study No. 9, vol 9. Food & Agriculture Organisation

Herrero M, Thornton PK, Power B et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):e33–e42

Hirvonen K, Bai Y, Headey D, Masters WA (2019) Cost and affordability of the EAT-Lancet diet in 159 countries. Lancet

Hirvonen K, Mohammed B, Minten B, Tamru S (2020) Food marketing margins during the COVID-19 pandemic: evidence from vegetables in Ethiopia, vol 150. International Food Policy Research Institute, Washington, DC

HLPE (2014) Food losses and waste in the context of sustainable food systems. High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security

HLPE (2017) Nutrition and food systems

Holtland G (2017) Contract farming in Ethiopia: concept and practice. AgriProFocus

Howard PH (2016) Concentration and power in the food system: who controls what we eat? vol 3. Bloomsbury Publishing, London

Hunter D, Borelli T, Beltrame DM et al (2019) The potential of neglected and underutilized species for improving diets and nutrition. Planta 250(3):709–729

Jansen M, Guariguata MR, Raneri JE et al (2020) Food for thought: the underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. People Nature 2(4): 1006–1020

Kalmpourtzidou A, Eilander A, Talsma EF (2020) Global vegetable intake and supply compared to recommendations: a systematic review. Nutrients 12(6):1558

Kansiime MK, Tambo JA, Mugambi I, Bundi M, Kara A, Owuor C (2021) COVID-19 implications on household income and food security in Kenya and Uganda: findings from a rapid assessment. World Dev 137:105199

Knai C, Pomerleau J, Lock K, McKee M (2006) Getting children to eat more fruit and vegetables: a systematic review. Prev Med 42(2):85–95

Knapp S, van der Heijden MG (2018) A global meta-analysis of yield stability in organic and conservation agriculture. Nat Commun 9(1):1–9

Lang T, Heasman M (2015) Food wars: the global battle for mouths, minds and markets. Routledge, London

Leach M, Nisbett N, Cabral L, Harris J, Hossain N, Thompson J (2020) Food politics and development. World Dev 134:105024

Lillesø J-PB, Harwood C, Derero A et al (2018) Why institutional environments for agroforestry seed systems matter. Dev Policy Rev 36:O89–O112

Loken B, Opperman J, Orr S et al (2020) Bending the curve: the restorative power of planet-based diets. WWF Food Practice

Magnan A (2012) Food regimes. In: The Oxford handbook of food history, pp 370–388

Maillot M, Darmon N, Darmon M, Lafay L, Drewnowski A (2007) Nutrient-dense food groups have high energy costs: an econometric approach to nutrient profiling. J Nutr 137(7): 1815–1820. https://doi.org/10.1093/jn/137.7.1815

Mason-D’Croz D, Bogard JR, Sulser TB et al (2019) Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. Lancet Planet Health 3(7):e318–e329

Masters WA, Bai Y, Herforth A et al (2018) Measuring the affordability of nutritious diets in Africa: price indexes for diet diversity and the cost of nutrient adequacy. Am J Agric Econ 100(5):1285–1301

Mayen A-L, Marques-Vidal P, Paccaud F, Bovet P, Stringhini S (2014) Socioeconomic determinants of dietary patterns in low-and middle-income countries: a systematic review. Am J Clin Nutr 100(6):1520–1531

McDermott J, De Brauw A (2020) National food systems: inclusive transformation for healthier diets. IFPRI book chapters, pp 202054–202065

McMullin S, Njogu K, Wekesa B et al (2019) Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. Food Secur 11(6):1355–1372

Micha R, Khatibzadeh S, Shi P, Andrews KG, Engell RE, Mozaffarian D (2015) Global, regional and national consumption of major food groups in 1990 and 2010: a systematic analysis including 266 country-specific nutrition surveys worldwide. BMJ Open 5(9):e008705

Micha R, Karageorgou D, Bakogianni I et al (2018) Effectiveness of school food environment policies on children's dietary behaviors: a systematic review and meta-analysis. PLoS One 13(3):e0194555

Miller V, Yusuf S, Chow CK et al (2016) Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the Prospective Urban Rural Epidemiology (PURE) study. Lancet Glob Health 4(10):e695–e703. https://doi.org/10.1016/s2214-109x(16)30186-3

Mogues T, Yu B, Fan S, McBride L (2012) The impacts of public investment in and for agriculture: synthesis of the existing evidence

Morris S, Haddad L (2020) Selling to the world's poorest – the potential role of markets in increasing access to nutritious foods. GAIN working paper series 14

Niebylski ML, Redburn KA, Duhaney T, Campbell NR (2015) Healthy food subsidies and unhealthy food taxation: a systematic review of the evidence. Nutrition 31(6):787–795

Olsho LE, Klerman JA, Wilde PE, Bartlett S (2016) Financial incentives increase fruit and vegetable intake among Supplemental Nutrition Assistance Program participants: a randomized controlled trial of the USDA Healthy Incentives Pilot. Am J Clin Nutr 104(2):423–435

Patnaik B, Oenema S (2015) The human right to nutrition security in the post-2015 development agenda. SCN News 41:69–73

Pedersen C, Remans R, Zornetzer H, et al (2020) Game-changing innovations for healthy diets on a healthy planet: Insights from a Delphi Study

Phillips C (2016) Saving more than seeds: practices and politics of seed saving. Routledge, London

Pingali PL (2012) Green revolution: impacts, limits, and the path ahead. Proc Natl Acad Sci 109(31):12302–12308

Pingali P (2015) Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains. Food Secur 7(3):583–591. https://doi.org/10.1007/s12571-015-0461-x

Popkin BM, Corvalan C, Grummer-Strawn LM (2020) Dynamics of the double burden of malnutrition and the changing nutrition reality. Lancet 395(10217):65–74

Powell B, Thilsted SH, Ickowitz A, Termote C, Sunderland T, Herforth A (2015) Improving diets with wild and cultivated biodiversity from across the landscape. Food Secur 7(3):535–554

Raihana AN, Marikkar J, Amin I, Shuhaimi M (2015) A review on food values of selected tropical fruits' seeds. Int J Food Prop 18(11):2380–2392

Reardon T, Timmer CP (2014) Five inter-linked transformations in the Asian agrifood economy: food security implications. Glob Food Secur 3(2):108–117

Reardon T, Chen KZ, Minten B, Adriano L (2012) The quiet revolution in staple food value chains in Asia: enter the dragon, the elephant, and the tiger. Asian Development Bank and International Food Policy Research Institute, Manila

Reardon T, Tschirley D, Dolislager M, Snyder J, Hu C, White S (2014) Urbanization, diet change, and transformation of food supply chains in Asia. Global Centre for Food Systems Innovation

Rosset PM, Altieri MA (2017) Agroecology: science and politics. Practical Action Publishing, Warwickshire

Ruel MT, Nicholas M, Lisa S (2004) Patterns and determinants of fruit and vegetable consumption in sub-Saharan Africa. FAO/WHO workshop on fruits and vegetables for health

Salazar R, Louwaars NP, Visser B (2007) Protecting farmers' new varieties: new approaches to rights on collective innovations in plant genetic resources. World Dev 35(9):1515–1528
Savary S, Akter S, Almekinders C et al (2020) Mapping disruption and resilience mechanisms in food systems. Food Secur 12(4):695–717
Schreinemachers P, Patalagsa MA, Islam MR et al (2015) The effect of women's home gardens on vegetable production and consumption in Bangladesh. Food Secur 7(1):97–107
Schreinemachers P, Patalagsa MA, Uddin N (2016) Impact and cost-effectiveness of women's training in home gardening and nutrition in Bangladesh. J Dev Effect 8(4):473–488. https://doi.org/10.1080/19439342.2016.1231704
Schreinemachers P, Simmons EB, Wopereis MC (2018) Tapping the economic and nutritional power of vegetables. Glob Food Secur 16:36–45
Schreinemachers P, Grovermann C, Praneetvatakul S et al (2020a) How much is too much? Quantifying pesticide overuse in vegetable production in Southeast Asia. J Clean Prod 244: 118738
Schreinemachers P, Baliki G, Shrestha RM et al (2020b) Nudging children toward healthier food choices: an experiment combining school and home gardens. Glob Food Secur 26:100454
Schreinemachers P, Howard J, Turner M et al (2021) Africa's evolving vegetable seed sector: status, policy options and lessons from Asia. Food Secur:1–13
Springmann M, Spajic L, Clark MA et al (2020) The healthiness and sustainability of national and global food based dietary guidelines: modelling study. BMJ 370
Stadlmayr B, Charrondiere UR, Eisenwagen S, Jamnadass R, Kehlenbeck K (2013) Nutrient composition of selected indigenous fruits from sub-Saharan Africa. J Sci Food Agric 93(11): 2627–2636
Sunderland TC, Vasquez W (2020) Forest conservation, rights, and diets: untangling the issues. Front For Glob Change 3:29
Swinburn BA, Kraak VI, Allender S et al (2019) The global syndemic of obesity, undernutrition, and climate change: the Lancet Commission report. Lancet 393(10173):791–846
Thar C-M, Jackson R, Swinburn B, Mhurchu CN (2020) A review of the uses and reliability of food balance sheets in health research. Nutr Rev 78(12):989–1000
Thomson CA, Ravia J (2011) A systematic review of behavioral interventions to promote intake of fruit and vegetables. J Am Diet Assoc 111(10):1523–1535
Thow AM, Snowdon W, Labonté R et al (2015) Will the next generation of preferential trade and investment agreements undermine prevention of noncommunicable diseases? A prospective policy analysis of the Trans Pacific Partnership Agreement. Health Policy 119(1):88–96
Thow AM, Verma G, Soni D et al (2018) How can health, agriculture and economic policy actors work together to enhance the external food environment for fruit and vegetables? A qualitative policy analysis in India. Food Policy 77:143–151
Van den Bold M, Quisumbing AR, Gillespie S (2013) Women's empowerment and nutrition: an evidence review, vol 1294. International Food Policy Research Institute
Vandevijvere S, Barquera S, Caceres G et al (2019) An 11-country study to benchmark the implementation of recommended nutrition policies by national governments using the Healthy Food Environment Policy Index, 2015–2018. Obes Rev 20:57–66
Vivero-Pol JL, Ferrando T, De Schutter O, Mattei U (2018) Routledge handbook of food as a commons. Routledge, London
Weinberger K, Lumpkin TA (2007) Diversification into horticulture and poverty reduction: a research agenda. World Dev 35(8):1464–1480
Wiebe K, Prager S (2021) Commentary on foresight and trade-off analysis for agriculture and food systems. Q Open 1(1):qoaa004

Willett W, Rockstrom J et al (2019) Food in the anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393(10170):447–492. https://doi.org/10.1016/s0140-6736(18)31788-4

Wohner B, Pauer E, Heinrich V, Tacker M (2019) Packaging-related food losses and waste: an overview of drivers and issues. Sustainability 11(1):264

World Health Organisation (2003) Diet, nutrition and the prevention of chronic diseases. WHO technical report series 916

Yates J, Deeney M, Rolker HB, White H, Kalamatianou S, Kadiyala S (2021) A systematic scoping review of environmental, food security and health impacts of food system plastics. Nature Food 2(2):80–87

Modeling Actions for Transforming Agrifood Systems

David Laborde and Maximo Torero

1 Introduction

The 2030 Agenda for Sustainable Development calls for transformational change that aims to achieve economically dynamic, socially inclusive and environmentally sustainable change. The 2030 Agenda has raised awareness of the key role that agrifood system transformation can play as an entry point for accelerating progress to achieve many of the SDGs, but also highlighted the complexity of promoting transformational change. SDG 2 alone draws attention to several related challenges: the need to eliminate hunger and all other forms of malnutrition by ensuring that sufficient quantities of safe, nutritious and affordable food are available to all while also recognizing the importance of raising the productivity and incomes of small producers, and calling for a variety of measures, including investment, trade and market development to promote the inclusive, sustainable development of agriculture and agrifood systems. Yet, the 2030 Agenda also emphasizes the interconnectedness of the SDGs beyond SDG2 and requires that Member States achieve this while creating the growth and employment opportunities needed to eradicate poverty, protect biodiversity and the natural resource environment, and address the growing pressures of climate change.

Addressing the multidimensionality of agrifood systems requires using a multisectoral, dynamic multi-country model to properly capture the various

D. Laborde (✉)
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: d.laborde@cgiar.org

M. Torero
Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_7

trade-offs.[1] Specifically, this model will allow us to grasp the interactions among different food value chains (primary production, processing, distribution), as well as with the rest of the economy. This is important for economic interactions (demand for inputs and outputs, income generation flows) and for environmental aspects: the carbon footprint of food production and consumption depends on the energy system in which it operates. Agrifood systems cannot be studied independently from the wider economic structure, both because these structures condition a number of drivers shaping agrifood systems (income distribution, availability and costs of technologies, inputs) and because agrifood systems represent a major source of employment and income generation for a large number of low- and middle-income economies. Therefore, the transformation of agrifood systems will have macroeconomic implications (employment, income, cost of living, fiscal consequences) and economy-wide trade-offs.

Secondly, this model structure will allow us to consider the dynamic evolutions of agrifood systems and their environment, since policy reform does not occur in a frozen universe. A static analysis could describe current systems. But it is essential to develop a dynamic framework to capture the evolution of the world, particularly in terms of economic growth, inequalities, demographic pressure and climate change. We cannot jump from current systems to a different one in a framework where other conditions remain the same. Even if such an exercise could shape the debate and provide important insights, any practical implications and guidelines for triggering the required transformation—a set of voluntary actions—need to consider future evolutions of the world that agrifood systems could help to shape, but not define. This is important when presenting roadmaps for action and dynamic trade-offs.

Finally, it will allow us to capture the plurality of agrifood systems (with an “s”) at a global level and understand the interactions that occur through the flows of goods, services, capital, people and ideas. The magnitude and speed of globalization have skyrocketed in recent years, but agrifood systems have been largely shaped by international exchanges for more than 6000 years. Regions with a high concentration of population, or volatile weather, have relied on external food producers to guarantee their food security. New crops and technologies have been traded and new products consumed, taking advantage of the diversity of agro-ecological systems at a global level. However, even as production and consumption decisions in one country could affect producers and consumers 10,000 miles away in just a few

[1] Externalities generate trade-offs when people’s welfare is pitted against environmental objectives. Sometimes, trade-offs happen at a large scale, among food, land, water, energy and climate (Bleischwitz et al. 2018 and others). Other times, they emerge from biomass uses and the competition among food consumption, feed for animals and biofuels (Muscat et al. forthcoming). In addition, many different dimensions, such as time, geography, governance and technology, affect the links among the SDGs. Positive interactions, though not discussed here, can be used to build strategies across sectors. Negative interactions are the targets of regulations and policies or the topic of public investment in technologies and solutions. The ultimate goal is to support coherent strategies and policies that neutralize the negative impact of SDG interactions, while achieving food and nutrition security and socioeconomic and environmental sustainability.

weeks, we do not have a homogenous and global, fully integrated food system. We have a web of interconnected (at various degrees) and heterogenous agrifood systems. Our modeling system should capture them. In particular, while prices in different locations interact with one another, we should not imagine that they are cleared in one global market. Beyond the market linkages, the global perspective is essential for non-marketed outcomes. We have to take into account the fact that the transformation of domestic agrifood systems will have external environmental footprints, and that global production and consumption involve trade-offs that require international cooperation.

In addition to the above features, we need to think about the type of model we need. The traditional modeling toolbox has recently been expanded beyond the econometric models and the equilibrium models. At the same time, other instruments (machine learning, evolutionary behavioral models) have been proposed. However, we can narrow down the choice of the instrument easily. Indeed, our goal is not to provide a foresight tool or to forecast the future using econometric models or machine learning models. Both of them heavily rely on reduced forms, and, as such, the traditional Lucas' critique (1976)[2] would be a notable weakness for them. Transformative change requires structural and disaggregated models. We need a modeling framework based on a strong economic theory, which would allow us to compare various "equilibriums"—or the state of the world and agrifood systems under different conditions and policies. For this reason, we need models for which the equilibrium's unicity and stability are theoretically grounded.

For these reasons, we have selected, in this paper, a global, computable general equilibrium model (CGE): the MIRAGRODEP model has the core element of the modeling framework. It is a dynamic, multisectoral, global model that generates unique market equilibria across goods, services and factors of production, in which economic agents (farms, firms, households, governments) are fully described with structural equations, and have clear optimization programs and constraints. Such a model has the virtue of being completely consistent: there is no leakage, "free lunch," or elements outside the system. Agrifood systems would be properly defined within a multisectoral context, and the framework itself would allow for the investigation of different definitions when drawing borders across systems. In addition, while providing a framework within which countries interact while facing individual constraints—through their balance of payments and domestic endowments, including labor and land—we can still operate with imperfectly integrated markets, leading to various price dynamics in different countries.

The MIRAGRODEP model has been developed to capture various social and environmental outcomes so as to track the various trade-offs at stake, going beyond the traditional CGE model. It can also be paired with various models upstream, or downstream, that could provide key inputs (e.g., crop technology, nutrient balance for the soil or human consumption) or downscale or extend the results generated by the CGE model. The MIRAGRODEP framework has been used to study social and

[2]Lucas (1976).

environmental implications of various policies and economic changes. For instance, see Laborde and Martin (2018) for the link between economic growth and rural poverty; Laborde (2011) and Laborde and Valin (2012) for an assessment of biofuel policies; and Laborde et al. (2020a) for GHG accounting of farm policies. The MIRAGRODEP model has also contributed to policy and political processes in various countries.

The modeling initiative proposed in this chapter brings the modeling innovations of the last decade into an integrated framework and builds on existing partnerships to extend its scope. It builds and extends the existing development for the Ceres2030 project,[3] looking at several aspects of SDG2 (hunger, environmental sustainability, poverty, and smallholders' income). In particular, a strong comparative advantage of the MIRAGRODEP CGE is its integration with household data and the use of detailed household information. We will discuss this issue at greater length in the next section, but it is very important to be able to capture household heterogeneity, in terms beyond income-level structure, production opportunities, food consumption patterns and potential locations, in order to properly assess the socio-economic and health implications of agrifood system transformation.

The model is based on a set of macro and sectoral accounts updated for 2017 (GTAP database of social accounting matrix), and where national data can be modified easily. In addition, it has been made compatible with the last release of the latest FAO food balance sheets and the *State of Food Security and Nutrition in the World 2020*s prevalence of undernourishment and cost of healthy diets numbers. It also benefits from a large dataset on farm and trade policies, in particular, from the Ag-Incentives project.[4] It is also compatible with various emissions (farm and non-farm databases) and satellite accounts. The household dataset is largely based on the POVANA database, not only comprising LSMS surveys, but also reconciled with other macroeconomic accounts and data sources. In terms of commodity and sector coverage, the GTAP database covers 67 sectors, of which 21 are food or agri-food products. The MIRAGRODEP dataset has been extended to cover additional products. In particular, some key staples like cassava and key inputs like fertilizers have been disaggregated.

This chapter is organized as follows: after the introduction, Sect. 2 presents the main objectives of the agrifood systems summit that will be targeted through the modeling and how the different objectives will be used to develop the scenarios to be modeled. Section 3 presents an overview of the model, its attributes and limitations, and describes the baseline scenario. Section 4 features the results of all the scenarios modeled and, finally, a section of conclusions is presented.

[3] Laborde et al. (2020b).

[4] http://ag-incentives.org/

2 Addressing the Objectives of the Agri-Food Systems

An agrifood systems approach is centered around people by aiming to achieve food and nutrition security, improve diets and reduce poverty for all. People-centered objectives are embedded in the broad performance of the system with regards to social, economic and environmental sustainability. Goals and targets in the 2030 Agenda that relate to the food system are owned by all stakeholders involved in its management and operations. They are owned by the global development community, which aims to promote sustainable development now and in the future.

The success of the food system approach depends on the actions and conduct of a large number of actors that are engaging with it. Among them, governments and the development community play a key role in coordinating the food system so that the objectives are achieved in a sustainable way.

The four core objectives are:

*Objective 1: End hunger and malnutrition***.** The principal objective of sustainable agrifood systems is to provide food and nutrition for people. While the last few decades have seen progress on this front, it is no longer sufficient to focus only on increased production, calorie consumption and low food prices. Increasing production at any cost has damaged the Earth. Calorie consumption alone does not constitute a healthy diet. Lower food prices can hurt producers and discourage them from investing in technologies to protect the ecosystem.

Objective 2: Achieve high-quality diets for all. Failure to deliver high-quality diets for everyone is holding back SDG progress. Yet, there is no mention of it in any of the SDG targets or indicators. Just ensuring stable access to food is not sufficient. Rather, we must understand the interactions among diets, health and agrifood systems to make progress toward SDG Goals and targets in agriculture, inequality, poverty and sustainable production and consumption.

Objective 3: Achieve 1 and 2 while enabling the sustainable use of biodiversity and ecosystems. Safeguarding land, oceans, freshwater and climate is a precondition for social justice and robust economic development for current and future generations (Arrow et al. 2014). Agrifood systems' operations have to be compatible with ecosystem services. Restricting the use of natural resources and the effects of climate change can limit agricultural productivity. Sustainable agrifood systems need to find ways to address this trade-off. Agroecological farming practices are one way to move in this direction.

Objective 4: Eliminate poverty to the level necessary to achieve 1, 2, and 3. Poverty and hunger are interlinked, and reduction of extreme poverty has a direct impact on the elimination of hunger and all forms of malnutrition. In this sense, under this objective, we want to identify the level of extreme poverty reduction that is needed to achieve all three of the above objectives.

However, all four of these objectives should be seen as different pieces of an overarching objective: Achieve high-quality diets for all, while enabling the sustainable use of biodiversity and ecosystems.

It is quite useful to see that objectives 1–4, as previously defined, are composed of caloric consumption, healthy diets, environmental sustainability and inclusiveness. As shown in Fig. 1 and Table 1, these elements are bricks. They can theoretically be achieved independently. Combined together, and in an incremental way, they form our four objectives. Therefore, we use the model to illustrate each of these bricks and the impacts of achieving this goal on a number of indicators.

However, the implementation of the model requires defining scenarios to achieve these goals. Instruments and interventions are the actual means of achieving our set of objectives. They are policy actions by nature. We propose to use a set of definitions developed by Laborde et al. (2020b): (a) an *Intervention* is a public action aimed at altering the existing state of the world. The action is intended to solve a problem (such as a market failure). It targets a specific population. It is associated with a set of expenditures paid by one (or several) economic agent(s). It has a given

Fig. 1 An integrated vision of the objectives of agrifood systems. (Source: Authors' own elaboration)

Table 1 Breaking down the Objectives

A	Caloric consumption	B	Healthy diets	C	Environmental sustainability	D	Inclusiveness
Objective 1: Ending hunger							
Objective 2: Ending malnutrition							
Objective 3: Sustainable food system							
Objective 4. End poverty & sustainable food system							

Source: Authors' own elaboration

set of direct effects; (b) an *Instrument* is the projection (i.e., translation) of the intervention in the model space.

The combination of various policy instruments is necessary to achieve the various objectives, while balancing trade-offs. This could be seen as an illustration of the famous Tinbergen rule (1952).[5] Scenarios are a combination of objectives (the end) and instruments (the means). This is an important issue, since a structural model could achieve the same goal through different pathways: We can eliminate hunger by implementing a major redistribution of income, massively subsidizing production, or investing massively in agricultural R&D. These different pathways will generate different trade-offs. The model allows us to tailor such a story in an *ad hoc* way (we define the mix of instruments to be used qualitatively and quantitatively). Or the model can be used to define an optimal mix of instruments, taking into account one or several constraints (fiscal optimization, social preferences[6]).

In the current context, and for the initial use of the model, we propose not crafting complex policy mixes, whether exogenous or endogenous, that will reshape incentives within agrifood systems. We will use a simple set of policy instruments to illustrate the core trade-offs. In particular, we will achieve: (a) brick A: ending hunger, with a producer subsidy on staple products. The value is endogenous, determined for each country to reduce its prevalence of undernourishment (PoU) below three percent; (b) brick B: sustainable diets, with a differentiated consumption subsidy by food groups to target a recommended diet pattern by country (relative contribution of various food groups in terms of calorie intake). The total value of subsidies per country will be constrained to zero, meaning that the final vector of subsidies will include positive and negative values (e.g., tax); and (c) brick C: when introducing environmental sustainability, we will implement a carbon tax instrument that could be extrapolated to other sustainability dimensions, like biodiversity and water use, to internalize externalities and target pre-defined constraints (e.g., first of all, a carbon budget for agriculture, based on the Paris NDC plans).

From A to C, the goal is to modify relative prices so as to shift production and consumption patterns. Brick D will introduce another set of instruments, including a progressive tax system (e.g., negative income tax), allowing for household redistribution. This will significantly change the required amount of distortions needed to achieve [A] and [B], since we will directly help poor consumers to expand their food consumption in both quality and quantity without having to alter the market prices. These choices of instruments are obviously quite conservative and far from optimal, but they do not require "new technologies" or strong behavioral shifts in preferences. They are quantifiable outcomes. In addition, we do not change trade policies; trade flows will adjust. In this regard, the different instruments that we propose in order to achieve bricks A and B are not neutral—since a consumption subsidy is "neutral" in

[5] See Tinbergen (1952): https://repub.eur.nl/pub/15884/. Also see Preston (1974) for generalization: https://www.jstor.org/stable/2296399?seq=1

[6] See Laborde et al. (2020a) for discussion.

terms of trade implications, but a production subsidy is not, except if we assume a global homogenous subsidy.

As an illustration, let us consider Country X. Country X has a prevalence of undernourishment above 25% of the population, which is high. It also enjoys a relatively diversified food consumption pattern, but has high levels of greenhouse gas emissions due to a large livestock sector. Country X can pursue a number of pathways to achieve SDGs 1, 2, 3 and 4 (as set out in Fig. 2). On a traditional pathway, Country X would likely have adopted a production-focused approach, aimed at reducing its PoU through increasing the supply of staple foods. This approach encourages a sectoral focus, with an emphasis on technical fixes to increase production. The interventions would be under the mandate of the agriculture ministry or sector-specific agency.

Using a systems-thinking approach, however, Country X would aim to achieve several goals simultaneously by developing a policy package that uses multiple systems to reduce the PoU and greenhouse gas emissions at the same time. This would necessitate the engagement of a number of ministries, including energy, environment and agriculture, and a coordinated policy response, as illustrated in Fig. 2.

In the Appendix, we provide an analytical and formal representation of our method for integrating the various Objectives in our modeling framework.

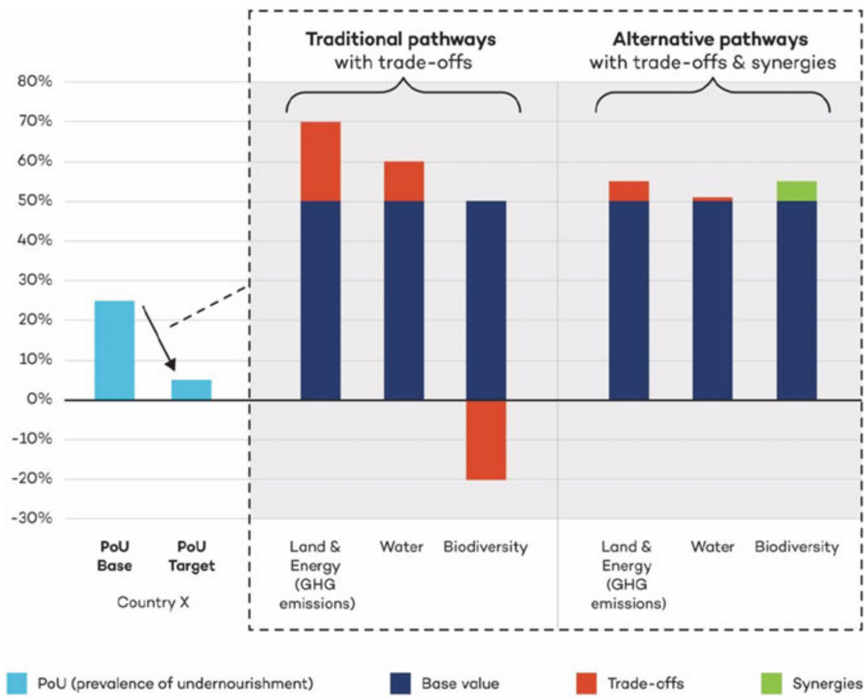


Fig. 2 Illustrating trade-offs: a simple PoU case. (Source: Authors' own elaboration)

3 The Model

3.1 Model Overview

The model used in this paper is the MIRAGRODEP model. This model is an extension of the widely used MIRAGE model of the global economy.[7] The model was developed and improved with the support of the African Growth and Development Policy Modeling Consortium (AGRODEP). It is a multi-region, multi-sector, dynamically recursive CGE model. The model allows for a detailed and consistent representation of the economic and trade relations between countries.[8]

The model assumes perfect competition in each market. In each country, a representative consumer maximizes a CES-LES (Constant Elasticity of Substitution-Linear Expenditure System) utility function subject to an endogenous budget constraint to generate the allocation of expenditures across goods. This functional form replaces the Cobb-Douglas structure of the Stone-Geary function (that is, LES) with a CES structure that retains the ability of the LES system to incorporate different income elasticities of demand, with those for food typically being lower than those for manufactured goods and services. The demand system is calibrated around the income and price elasticities estimated by Muhammad et al. (2017).

Once total consumption of each good has been determined, the origin of the goods consumed is determined by another CES nested structure, following the Armington assumption of imperfect substitutability between imported and domestic products. On the production side, demands for intermediate goods are determined through a Leontief production function that specifies intermediate input demands in fixed proportions to output. Total value added is determined through a CES function of unskilled labor and a composite factor of skilled labor and capital. This specification assumes a lower degree of substitutability between the last two production factors.

In agriculture and mining, production also depends on land and natural resources. Labor markets are differentiated by gender, assuming an imperfect substitution between male and female labor for each category of skills. Unskilled labor is imperfectly mobile between agricultural and non-agricultural sectors, according to a constant elasticity of transformation function. Land is also imperfectly mobile among agricultural sectors. Capital in a given region, whatever its origin (domestic or foreign), is assumed to be obtained by assembling intermediate inputs according to a specific combination. The capital good is the same regardless of the sector. In this version, we assume that all sectors operate under perfect competition, there are no fixed costs, and price equals marginal cost.

The model dynamic is recursive in nature: capital in year t + 1 is based on the capital of year t, increased by the previous year's investment, and corrected for

[7] Decreux and Valin (2007).

[8] Laborde et al. (2013).

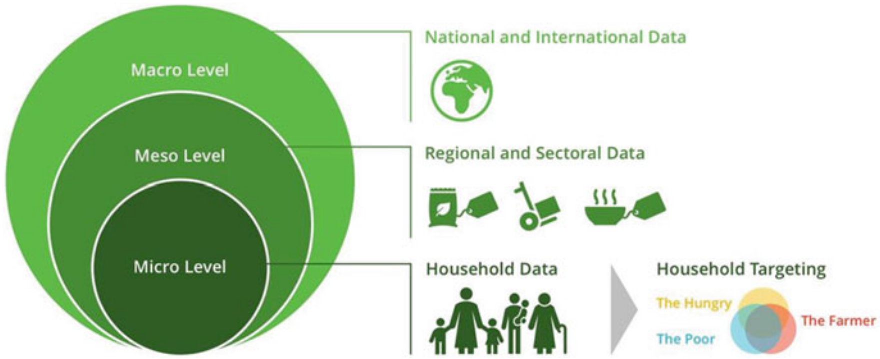


Fig. 3 An integrated modeling framework: the MIRAGRODEP CGE. (Source: Authors' own elaborations)

depreciation. Total factor productivity at the sectoral level and labor supply follow the exogenous trend. The macroeconomic assumptions used for the analysis were designed to be relatively "neutral" to avoid situations in which macroeconomic adjustments such as real exchange rate changes outweigh the impacts of interest, and to allow us to focus on the impacts of agricultural support policies on emissions. These assumptions were: (a) the investment dynamics (savings driven) and the real exchange rates evolve to keep the current account constant relative to national GDP; (b) global savings balance is achieved through a proportional change in the demand of foreign capital by net capital importers; (c) aggregate real public expenditures are kept constant, and a consumption tax is adjusted to keep the government budget balance fixed as a share of GDP and (d) total employment in the economy is constant.

A comprehensive modeling is depicted in stylized ways in Fig. 3. The figure summarizes the scope of the model, showing the added value of having these different layers in an integrated framework.

3.2 *How Do We Couple This Model with Other Models?*

The core contribution of the MIRAGRODEP CGE model is to provide an integrated framework in which economic and biophysical constraints can be implemented and markets will clear in a consistent way. As a matter of fact, markets are the nexus where final decisions on production and consumption are determined. In addition, explicitly representing market equilibria for goods and factors of production is essential in order to capture both the real income impacts and their social implications.

However, the MIRAGRODEP CGE does not aim to answer all relevant questions about agrifood systems. Nor is it meant to be used on its own. It is designed to be integrated with other modeling platforms, either as an element of a knowledge value chain (using inputs from other models or providing inputs to other models) or in a coupled way (the integrated approach). As result, model integration or connectivity should be done with parsimony and under strict scientific principles regarding the compatibility of the approaches, including theoretical underpinnings, the definition of model solutions and data consistency.

We have identified IIASA with the GLOBIOM modeling team as our main research partner. They have global modeling capacity and a global model with a detailed land use component. As such, they provide a strong complementarity to the MIRAGRODEP CGE framework and could downscale MIRAGRODEP results and develop a targeted biodiversity indicator. They could also provide a more detailed description of technology and technology changes, with their GHG implications, in the farm sector. They also have deep experience in addressing climate change issues. It is critical when combining modeling frameworks into a unified analytical platform to guarantee data consistency at the initial stage.

We are exploring other downstream linkages in the fields of health, nutrition, gender and inequalities. While our modeling framework "stops" at the household level, some socio-economic drivers such as food availability parameters at that level could break down the analysis and investigate intra-household challenges.

Regarding upstream linkages, most of the ongoing investigations are focused on biophysical models that could inform the transformation of the production function and the input/output relations, including for non-priced inputs. Similarly, some ecosystem valuation approaches could expand our set of indicators and the illustration of trade-offs. But the investigations are at a very early stage.

3.3 Importance of Including Household-Level Modeling

As discussed, a significant amount of the changes in agrifood systems will have very heterogeneous impacts across households, in terms of income opportunities and consumption space. Therefore, having a proper representation of the household heterogeneity is essential.

The MIRAGRODEP CGE framework proposes two approaches to including household-level analysis (for details, see Laborde et al. 2021b). The choice of the precise method depends on the scale of the exercise (global assessment, or regional- or country-level requirements), data availability and the need to integrate feedback effects. Both approaches rely on our harmonized treatment of existing household surveys, which describe both the expenditures and the revenue account of each household, including the farm production module, when available (POVANA database). The household data is also used to reproduce non-economic indicators, such as the PoU by reconciling household expenditure pattern, food consumption and its caloric equivalence, as well as household energy requirements.

The first approach, which could be implemented in most low- and middle-income countries, is a top-down approach. It is where country-specific macroeconomic variables from the MIRAGRODEP CGE are implemented in our set of harmonized household surveys, which include prices of goods and services, factors of production, remittances and tax instruments, among other things. This approach allows for a systematic assessment of how a systemic change impacts households in terms of poverty (real income) or food consumption. The household-level modeling could include first order impacts alone or second order impacts as well, with production and demand function calibrated for each household, but consistent with the aggregated CGE response in the initial condition. Choosing this approach allows for the use of the GIS tagging available in some surveys to illustrate within-country heterogeneity.

The second approach incorporates a large set of households directly into the CGE model in a fully bottom-up way. Usually, using 75–150 household categories captures most of the relevant heterogeneity in terms of consumption pattern and income generation. This approach is more intensive in terms of computational power and requires additional data reconciliation between macroeconomic accounts and household-level data. But this approach may be needed when distributional issues have strong feedback effects and alter the sectoral or macroeconomic equilibrium. Indeed, even with the calibration used in the first approach, if prices and income changes are significant, the aggregated response of the CGE and sum of individual responses in the household surveys start to diverge, mainly because the economic weights of the various household groups change compared with the initial conditions.

Depending on the use of the modeling framework for the Agrifood Systems Summit (global or regional assessment, or country-level profiles), we propose using the two approaches alternatively. The existing coverage of countries for which we have detailed household data is available online[9] and is frequently updated. For countries that are not covered, we generate representative household distribution at the continental level based on available countries' data and reshape the distribution weights to target demographic and income macroeconomic indicators (e.g., Poverty and GINI for each country). The existing dataset and country coverage could be expanded easily, since the POVANA database is based on systematic templates and protocols that could be used to add new countries or update data for those already covered.

3.4 *What Are We Missing?*

While the modeling framework already covers a number of topics, there are still some limits and missing elements that should be acknowledged.

[9] https://public.tableau.com/profile/laborde6680#!/vizhome/POVANA_Surveys/POVANA

(a) *Competition:* The first element is directly related to how we represent markets. While the choice of imperfectly integrated markets for goods and factors of production is satisfactory, the way we capture imperfect competition remains a major challenge. By default, our model operates in perfect competition. Therefore, the consumer at the end, leading to some optimistic view in terms of inequalities, captures all changes in production costs. The questions of imperfect competition and market power within agrifood systems are critical and could have significant implications for agrifood system transformation's social impacts. While there are modeling options to address this issue, the lack of data, especially on a global basis, remains a key challenge. In addition, considering how various consumers/producers at the household level may face differentiated mark-ups is not a trivial issue. For these reasons, we propose to flag this issue as one to be discussed as a major research question. In the meantime, existing results should be interpreted with caution. Most importantly, since our competition assumption changes the way that markets operate, this issue should not be fixed "outside" the model, with a complementary analysis upstream or downstream; rather, it should be tackled within the model.

(b) *Biophysical Balances and Soil Health:* While the issue of soil health constitutes a key topic for the sustainability of agrifood systems, systematic datasets and actual causal linkages between production systems and evolution of soil health remain scarce. In particular, we should aim to track soil health and nutrient balance, and be able to capture feedback effects through productivity channels within the model, since they will change relative to productivity and prices. However, the complex mechanisms at stake may not need to be implemented in the MIRAGRODEP CGE and could be developed externally. The CGE model will just adjust the input-output coefficient matrix describing farm technologies. It could include dynamic equations about the soil quality productivity as a new form of capital in the farm sectors. At this stage, a potential limitation is the reliance on only one aggregated item for mineral fertilizers. To be sure, the price and supply dynamics of various fertilizers are more complex. For future development, it may be required to break down this sector into sub-products. Similarly, the substitution between manure and mineral fertilizer is not currently integrated, while manure on cultivated soil is still monitored for emissions purposes. This could be addressed, assuming the availability of technical expertise.

(c) *Household Data in Developed Countries:* Due to the history of the modeling framework and the acuteness of food insecurity in developing economies, our household database does not include developed countries. Since the social and health implications in the developed economies should not be neglected, we should aim at addressing this data gap with the right set of partners.

3.5 Key Indicators Generated

The MIRAGRODEP CGE framework, with its satellite account, could generate a huge number of indicators to illustrate the evolution of agrifood systems and some of their trade-offs. Figure 4 provides an overview of such indicators. Some are based on

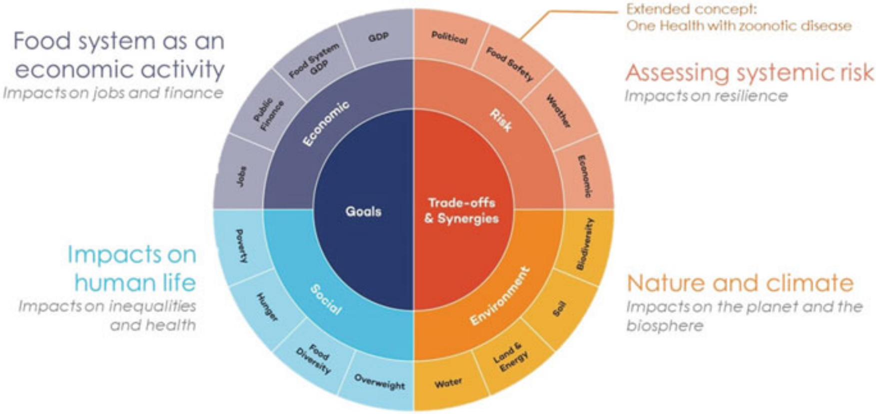


Fig. 4 Quantifying agrifood systems. (Source: Authors' own elaboration)

the detailed household impacts (e.g., poverty, hunger, overweight), others on macroeconomic accounts (e.g., public finance). Still others are linked to sectoral productions (e.g., water use, land, energy).

Some indicators are generated by default with MIRAGRODEP, using a set of fixed coefficients per unit of outputs or inputs (e.g., water requirement per ton of wheat per country), but are aimed at being fine-tuned by linking the MIRAGRODEP outputs (directly or indirectly) to other models. In particular, the biodiversity indicator and spatially explicit land use changes will be generated by IIASA through the GLOBIOM modeling framework. Similarly, we investigate some additional health- and nutrition-related indicators by linking food consumption and income distribution outcomes to specific models, like the LIST models suit.

An important issue not directly linked to the objectives and the core trade-offs is assessment of the risk of the system, in particular, the "systemic" risk when considering the complex interactions and the various profiles of variance/covariance at stake. As a starting point, we propose to use historical events, such as a historical catalog of productivity (weather-related or zoonotic disease), prices (world prices, exchange rate), consumer choices (the "mad cow disease" type of consumer reactions) and other disruptors to see how the system in its initial or modified situation reacts, and how to assess the vulnerability of various populations or components of the system. The Appendix provides an illustrative example.

4 Modeling Results

With this previously detailed modeling framework, six individual interventions are modeled in terms of their impact on agrifood systems, prevalence of undernutrition and ecological effects in terms of GHG emissions, land and energy use, and the use of chemical inputs. Due to synergies and complementarities among these scenarios, the authors also assess them as a package. The sensitivity to the results is also assessed under different governance principles, such as land use policies.[10] The scenarios are listed in Table 2 and organized around three main pillars, as shown in Fig. 5: achievement of a more efficient and more inclusive system, allowing consumers and producers to make better choices. The results of the different scenarios are based on the baseline consistent with the State of Food Security and Nutrition in the World 2020, which, by 2019, reported 690 million undernourished people and the fact that healthy diets were unaffordable for almost three billion people in the world.

A first key result is the confirmation that ending chronic hunger at a 5% level is reachable by 2030 with the right balance of interventions. While no intervention alone, at a realistic scale, could solve the problem, we see in Fig. 6 that key structural interventions to increase the efficiency of agrifood systems, through increased farm productivity and a reduction of food loss and waste, will reduce the number of people in chronic hunger by 314 million in 2030. Beyond hunger, 568 million people will be able to afford healthy diets, as shown in Fig. 7. To target the remaining population, safety nets and well-targeted programs, such as school feeding interventions, will be required. When adding such safety nets into the model by designing them endogenously so as to leave no one behind, it is possible to cover the 2.4 billion remaining people without economic access to healthy diets.

Achieving the end of widespread hunger requires mobilization of significant resources, but the cost is manageable, and represents 8% of the size of food markets.[11] Figure 8 provides the decomposition of this total cost by action (Panel a) and the distribution by group of countries (Panel b). In regard to the actions referred to as "better choices" in Table 2, i.e., consumer incentives and the repurposing of farm subsidies, they do not contribute to the total costs because they have been designed to be income neutral for the government, as well as for the producers (farm subsidies) or consumers (food tax/subsidies) in each country. The cost structure is dominated (45%) by the combined large structural investment in physical, human and knowledge capital of the innovation package that impacts through value chains, national economies and social safety nets (36% of total cost). Of course, these two main items are different in nature, since the latter involves recurrent spending every year and will have to be managed, and financed, by the governments alone.

A critical finding of the analysis is the role of other interventions in minimizing the cost of the safety nets. Indeed, to cover the income gap of the three billion people who – without action - will not be able to afford healthy diets in 2030, countries will have to redistribute 1.4 trillion dollars (constant 2017) annually. By investing in the

[10] Other aspects of the global agrifood systems, such as trade policies, are also analyzed to see how they interact with the main interventions considered.

[11] 2030 spending and food market values, as estimated by the model for guaranteeing full consistency.

Table 2 Scenario definitions

Action domain	Scenario label	Description
More justice	#1 Social Safety Net: Healthy Diets for Everyone	Provide food stamps (income transfer that should be spent on food products) to eliminate the "poverty gap" between the per capita income of each household and the affordability of healthy diets cost line. The cost is initial calibrated on SOFI 2019 and updated based on model dynamics
More justice	#2 School Feeding Program	All children between 6 and 11 years old have access to school feeding programs 200 days a year. Daily per capita ration includes 320 g of fruits, 102 g of grains, 51 g of animal proteins (meat, fish, eggs), 480 g of milk, and 100 g of vegetables
Better choices	#3 Farm Subsidy Repurposing	All farm subsidies (outputs, inputs, others) are redistributed in the form a subsidy to farmer revenue. The rate of support is computed endogenous by the model to maintain farm subsidy budget constant, but a sectoral bias is introduced. Nutritious and low-emissions products are subsidized at twice the average rate, while products with low nutrition value and high emissions are subsidized at half the average rate
Better choices	#4 Consumers' Incentive Reform	Taxation of red meat products in high- and middle-income countries. The level of tax is computed by the model to obtain a reduction of consumption of 15% in high- and upper middle income countries (HIC and UMIC in Europe), and 7.5% in UMIC (exc. Africa). The group of countries have been constructed by computing an index of "excess" consumption by comparing average daily intake with a sustainable and healthy diet reference (i.e. Flexitarian diet in this case, but alternative diets give the same ranking of countries)
More efficiency	#5 Innovation, Technology and Knowledge for Farmers	This package of interventions is aimed at increasing farm level productivity, while reducing environmental footprints. It has three components
		Increased/or Improved **Irrigation** systems. [X]% of each country cropland benefits from new investments by 2030. For regions with high rate of irrigated land (all Asian regions), we consider only an upgrade of existing materials, leading to no change in yield but a reduction in water inefficiency. For other regions, we consider an increase of water use (for irrigation, but with an improved average efficiency) but also a yield increase of [Z]%. With X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 100% for all regions except Africa where Z = 200%. Initial cost of $1000 per ha

(continued)

Table 2 (continued)

Action domain	Scenario label	Description
		Increased **livestock** genetics and better practices for higher productivity [Z%] and lower emissions per unit of output. [X]% of the herd of each country is improved by 2030 With X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 10% for HIC, 25% for MIC and 50% for LIC Initial average cost of $400 per standard Livestock Unit
		Extension services and farmer **training** to increase all farm productivity (total factor productivity, TFP). [X]% of farmers in each country are covered. TFP is increased by [Z]%. In addition, carbon sequestration in soil is increased X = 10% in HIC, 20% in UMIC, 30% in LMIC and 40% in LIC; Z = 10% for HIC, 25% for MIC and 50% for LIC 1 extension agent per 100 farmers in average. Cost is indexed on labor cost across countries and calibrated at $10,000 for UMIC
More efficiency	#6 Reducing Food Waste and Loss	Reduction of 25% in all countries of food waste and food losses, including for left-on-the field. Recurrent cost per unit of food restored
Combined actions	All except Safety Nets	Include actions 2–6. Since the Safety Net is computed to provide enough income to everyone to be able to afford healthy diets, it is important to consolidate all the other actions before this one
Combined actions	All including Safety Nets	All actions, 1–6. While this package will take care of all vulnerable people, showing the consolidated impact on environmental and economic indicators is important (trade-off lens)
Combined actions	Everything with Land Use Regulation	In this consolidated scenario, we do not allow for land use change (fixed amount of agricultural land) by considering a stronger land governance

Source: Authors' own elaboration

various programs, the value of the required safety nets drops by about two thirds (428 billion dollars globally) in 2030. Using safety nets to make sure that everyone can afford healthy diets is required, but, if used alone, they will be far too expensive.

The second panel in Fig. 9 shows the distribution of the spending by region, i.e., where the money needs to be spent and/or invested. Since the needs are unevenly distributed globally, a significant effort in terms of global coordination, and even solidarity, will be required, especially to support the transformation of the agrifood systems of low-income countries.

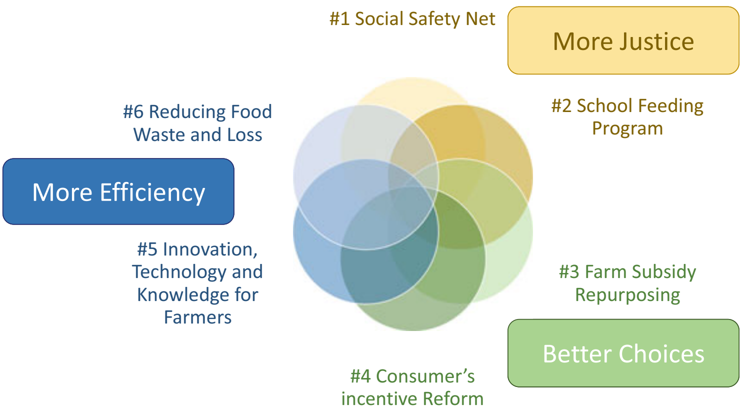


Fig. 5 Policy Action Scenarios. (Source: Authors' own elaboration)

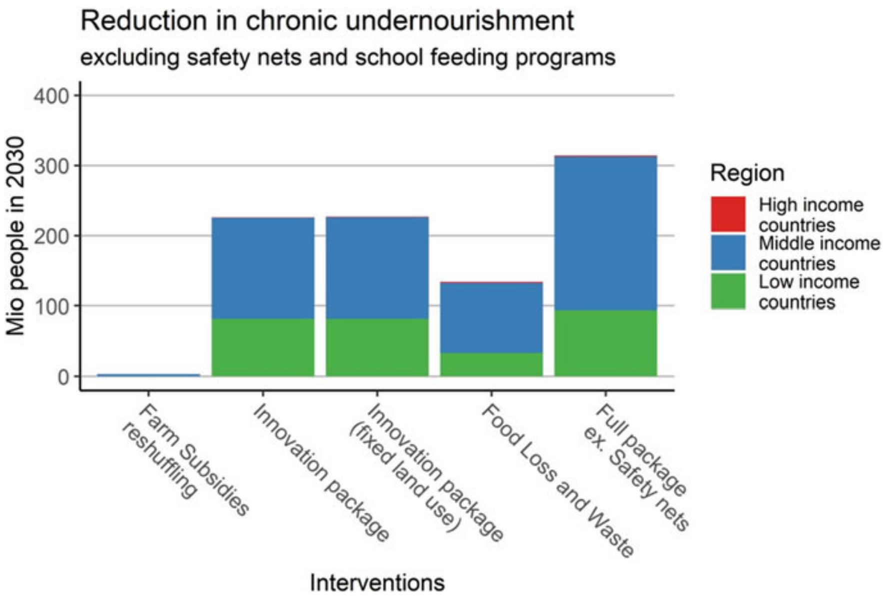


Fig. 6 Number of people (mio) removed from a chronic undernourishment situation in 2030. (Source: Authors' own elaboration)

As previously shown, no single intervention could achieve the end of malnourishment, and synergies are needed to tackle the various source causes of the problem, but also to minimize the total cost of the package. However, their complementarity goes beyond their impacts on household food security and their cost-effectiveness, and therefore we also need to combine them to address heterogeneous environmental trade-offs.

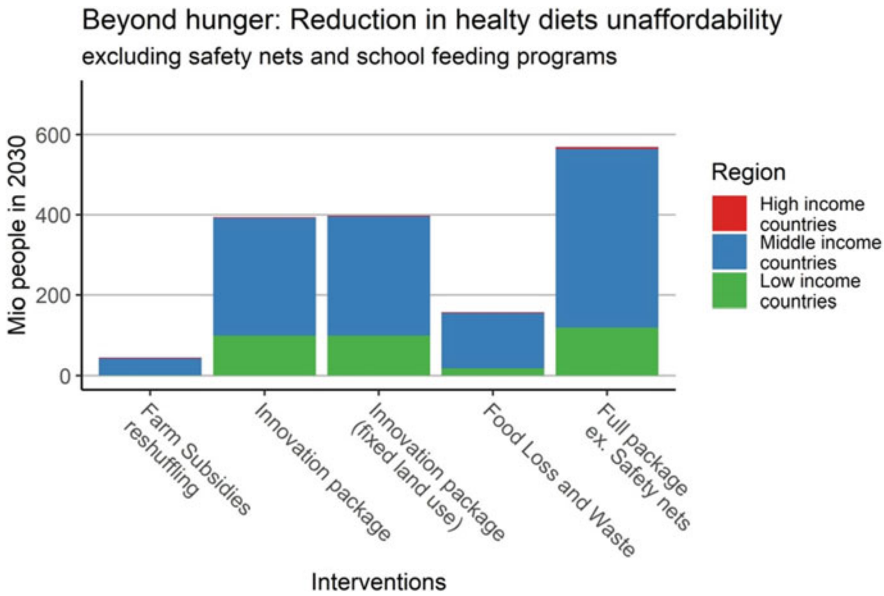


Fig. 7 Number of previously deprived people (mio) who will gain access to healthy diets by 2030. (Source: Authors' own elaboration)

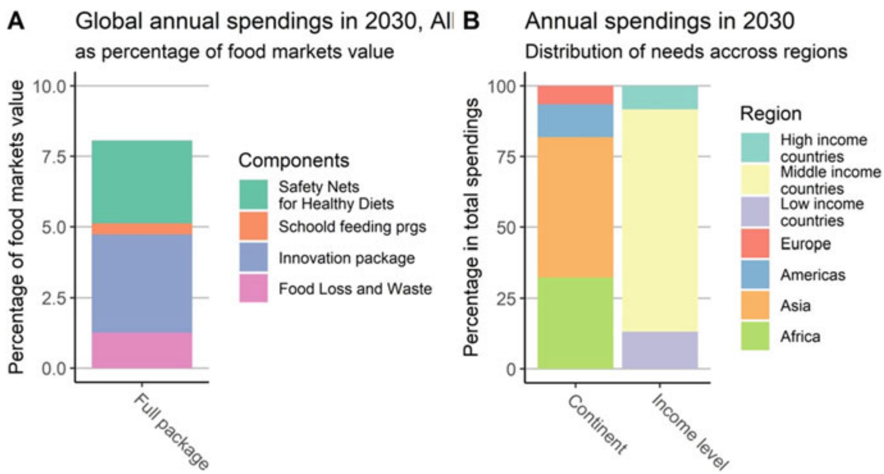


Fig. 8 The cost of actions: magnitude and distribution. (Source: Authors' own elaboration)

Finally, it is important to mention that the actions modeled will generate trade-offs in regard to GHG emissions (emissions from agricultural production, and net emissions from AFOLU), agricultural land, an increase in the use of chemical inputs (index of chemical inputs per hectare), biodiversity (i.e., reduction of forest habitat

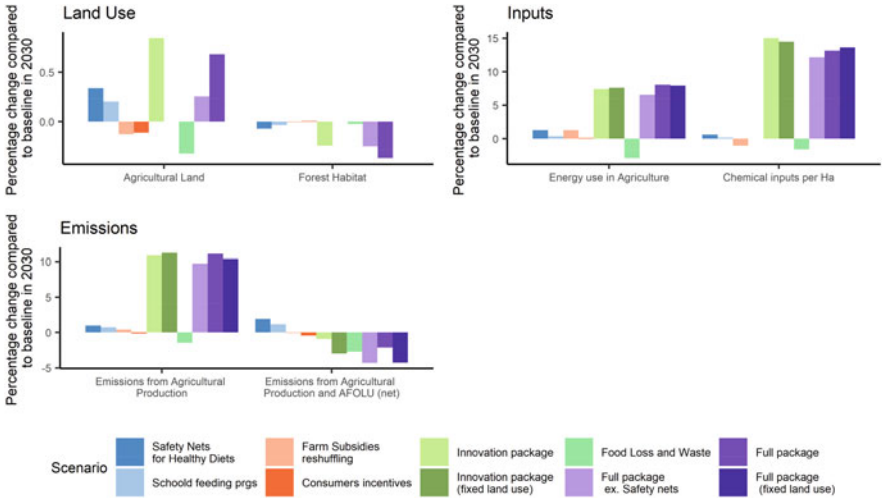


Fig. 9 Impacts of actions on environmental indicators. (Source: Authors' own elaboration)

and agricultural land) and energy consumption, as shown in Fig. 9. As shown, the levels of trade-offs across all interventions are relatively small, the highest being for the innovation and full package, but the effects are negative (i.e., an improvement) for the case of food loss and waste across all trade-offs. However, when looking at net agricultural emissions and AFOLU, the effect is negative, as in the case of forest land. This highlights the need for policies that stimulate investments in innovations for carbon farming (growing carbon in soil and trees as a tradable commodity) and related payment schemes for ecosystem services.

5 Conclusions

While identifying the conceptual linkages at play within the agrifood systems and the different trade-offs involved is essential, providing a quantification of these mechanisms is required to illustrate concepts, support informed decisions and trigger proper actions. Considering these interactions is a necessity during the whole process: at the diagnostic stage (i.e., quantifying trade-offs), on the way to achieving core SDG targets (i.e., the roadmap to 2030) and, finally, when designing policy responses that may also lead to various indirect effects.

This chapter tries to develop a proper quantification approach based on a modeling platform that combines state-of-the-art and up-to-date databases covering all the metrics of interest (hunger, poverty, nutrition, and environmental indicators) and dynamic simulation models that explore future pathways and optimal policy responses.

Various modeling approaches could be considered, however, the task to be addressed leads to very specific requirements. Tackling trade-offs within the agrifood system requires a holistic strategy, considering not only the supply side and the primary production sectors, but also the full set of value chains operating and interacting within the food system. It also needs to capture how the food system interacts within the broader economy within, and across, countries. Indeed, various market failures leading to inefficient and unsustainable agrifood systems take place in the initial stages of production.

Beyond these macro and meso requirements, the most important challenge is to capture the essence of the SDGs and the livelihood of people, in particular, the most vulnerable parts of the population. In this context, the modeling platform used includes explicit representation of household heterogeneity. Households differ in terms of income sources, production and consumption patterns. The conditions they face regarding food, labor and input markets are various, even within a country, and determine their choices regarding the food that they produce, buy and eat. Representing their features explicitly is a necessity for providing a realistic picture of the situation and a policy package that will be inclusive for all.

The quantitative framework used builds on an economic state-of-the-art dynamic global Computable General Equilibrium (CGE) model, MIRAGRODEP. The model includes many household groups and is combined with land use, farm and livestock components to approximate essential biophysical trade-offs. The model is able to capture both macroeconomic linkages (within and between countries), multisectoral interactions (agrifood systems are not limited to agriculture activities), and interaction for different households, including the poor and most vulnerable. Indeed, it will be presumptuous to properly assess specific SDG targets without addressing heterogeneity among households and inequalities.

Six interventions are modeled to study their impact on agrifood systems, undernutrition, and the environment. We also assessed the interventions as a group to consider the impact of synergies and complementarities. The first finding confirmed that ending chronic hunger at a 5% level by 2030 is possible, with key structural interventions to ramp up agrifood systems' efficiency. Through increased farm productivity and a reduction of food loss and waste, the number of chronically hungry people could be cut by 314 million. In addition, 568 million people would be able to afford healthy diets by 2030. Under these interventions, the cost of ending hunger represents 8% of the size of global food markets, a sum that can be mobilized and invested to generate impact through food value chains, national economies, and social safety nets. Furthermore, the use of well-targeted social safety nets could provide an additional 2.4 billion people with access to healthy diets.

The second critical finding was that various interventions could create synergies that not only address different causes of hunger, but also minimize the total cost of interventions. In addition, the levels of trade-offs across all interventions are relatively small, the highest being for the innovation and full package of technological innovation, but the effects are negative (i.e., an improvement) for the case of food loss and waste across all trade-offs. This highlights the need for policies that stimulate investments in innovations for carbon farming (growing carbon in soil and trees as a tradable commodity) and related payment schemes for ecosystem services.

Countries would have to redistribute \$1.4 trillion annually to fill the income gap of the 3 billion people who cannot afford healthy diets. However, by investing in various interventions, countries can drive down the cost of the safety nets by about two thirds, or \$428 billion, globally in 2030. Combined interventions can also address environmental trade-offs that are bound to occur.

Appendix

A Formal Representation of Our Objectives

The defined objective could be interpreted as an objective function in an optimization program. This section provides an illustration of this approach, with a rewriting of the problem in such terms. It also shows where the actual objectives will need to be more properly formulated, especially if we want to illustrate trade-offs correctly. In a second part, we provide graphical illustrations.

Mathematically, an optimization program can be seen as looking for the maximum (maximization) or minimum (minimization) of an objective function, X, subject to a number of constraints, Y, X, etc. Constraints could be written as $y \leq \overline{y}$, meaning that the variable y should not exceed a given upper limit $\overline{y}$, or $z \geq \overline{z}$, meaning that z remains above a given level. When these inequalities are replaced by equalities, we say that these constraints are binding.

In our setting, we can see X as a function defining the PoU. So, the function objective could be the minimization of X, the level of caloric hunger. But asking how to minimize hunger without a number of constraints is a useless question; there are many ways to achieve it: letting the hungry people die, spending trillions of dollars on inefficient measures, and so forth. Therefore, defining the right set of constraints is critical. We will not specify the obvious ones (e.g., a given level of population, the various technological constraints, etc.), but will instead focus on the most relevant one.

An important additional feature of such optimization is that maximizing X subject to $y \leq \overline{y}$ leads to the same results as maximizing/minimizing Y subject to $x \geq \overline{x}$. This is the duality principle, a key instrument in microeconomics analysis. The standard example is the consumer optimal choice: *Maximizing the utility U* provided by the consumption of a bundle of goods given, or subject to an available budget (or income, noted as y), such as $\leq \overline{y}$, generates the same optimal allocation of money across goods as minimizing the budget Y needed to achieve the least level of satisfaction, or utility, $u \geq \overline{u}$. We are going to use such properties in our example.

If we consider Objective 1, eradication of hunger, we can formulate it as the desire to minimize hunger, measured as the PoU, subject to some constraints. Indeed, we know that the PoU is bounded by 0, and, as pointed out above, a large number of pathways could lead to the same outcome. We can actually see two simple programs related to hunger:

Minimizing PoU subject to existing public budget $\overline{B}$ *i.e.,* $B \leq \overline{B}$. This program will identify how to allocate existing budget $\overline{B}$ across various policy instruments in order to achieve the lowest possible level of undernourishment. In this case, the starting point is to define the budget constraint $\overline{B}$. This can be seen as a **repurposing of public expenditures** to achieve better objectives. The symmetric program is to *Minimize public expenditure B* subject to a *PoU* target—for instance, 5%, i.e., $PoU \leq 5\%$. This is the approach actually used in the Ending Hunger project and detailed in Laborde et al. (2017).

In this framework, we can express **the trade-offs**. Assuming that we focus only on GHG emissions, and we do not care about fiscal constraints, **Objective 1** could be represented as ***Minimizing GHG emissions* subject to *PoU* ≤ 5%**. This is the simplest representation of minimizing trade-offs. It is qualitatively equivalent to ***Minimize PoU* subject to $GHG \leq \overline{GHG}$**, where GHG is an acceptable carbon footprint for agrifood systems (for instance, compatible with the 1.5C scenario).

The situation becomes more challenging to represent when we have several elements in our objective. Let's consider **Objective 2** now, and translate it with two indicators, the **PoU** (element A) and the **prevalence of overweight** (PoO, proxy for element B), while we also take GHG emissions into consideration (GHG, a proxy for element C). Conceptually, we want to achieve the lowest level of these three variables. However, this is mathematical nonsense. We can optimize only one variable. So, two approaches are possible:

(a) We define a multi-criteria objective function. This will be a social objective function. We can call it D, as it represents a Damage Function. It is a combination of PoU and PoO, for instance: $(PoU, PoO) = PoU^a PoO^b$. Two important things should be noticed: This is the logic beyond many **composite indices** showing how good, or bad, a multi-dimensional system is, and *a* and *b* are actual weights on the various dimensions. There are different ways to obtain these weights, knowing that none are perfect; the key challenge is to properly capture the social preferences regarding these different dimensions. These preferences are not universal, and should be specific to a specific community at a specific period. So, in this approach, we can represent our previous optimization problem as *Minimizing* $D(PoU, PoO)$ *subject to existing public budget* $\overline{B}$*, i.e.,* $B \leq \overline{B}$, or, if we think about environmental trade-off, we can represent it as ***Minimize* $D(PoU, PoO)$ subject to $GHG \leq \overline{GHG}$** or ***Minimize GHG* subject to $D(PoU, PoO) \leq \overline{D}$**.

(b) We maintain one objective, but combine different constraints, such as: ***Minimize GHG* subject to *U* ≤ 5% *PoO* ≤ 10%**, if we assume a 5% for PoU and 10% threshold for overweight.

Objective 3 will be achieving all of the elements at once, i.e., having three constraints binding. **$GHG \leq \overline{GHG}$, *PoU* ≤ 5%** and ***PoO* ≤ 10%**. There are no other dimensions for optimization, except the cost of achieving this goal. In this case, we will be in a similar framework as the one used in Ceres2030, which is actually

Minimizing B:public expenditures subject to SDG2.1: $\boldsymbol{PoU \leq 5\%}$**, SDG2.3:** $\boldsymbol{Income2030 \geq 2 * Income2015}$ **with Income: the small-scale food producer income, and SDG2.4:** $\boldsymbol{GHG \leq \overline{GHG}}$. In the agrifood systems framework, the small-scale food producer constraint is replaced by the malnutrition target. So, it can be *Minimizing B:public expenditures subject to* $GHG \leq \overline{GHG}$, $PoU \leq 5\%$ *and* $PoO \leq 10\%$. Of course, we will also have many more indicators, and therefore constraints (water, etc.).

We will discuss below the exact interpretation of **Objective 4**. But it can be seen as finding the minimal level of poverty compatible with Objective 3. Therefore, it is Maximizing **Poverty subject to** $\boldsymbol{GHG \leq \overline{GHG}}$, $\boldsymbol{PoU \leq 5\%}$ and $\boldsymbol{PoO \leq 10\%}$.

We will now propose some basic illustrations of the issues at stake. We will limit all illustrations to two-dimensional choices for the sake of easiness of visual representation.

First, let's start with a representation of the **frontier of production possibilities** (FPP) between two goods: Maize and Pulses, as displayed in Fig. A.1. It shows, for a given set of technologies and institutions, as well as endowments (factors of production: land, labor, capital), how much you can produce of each good. For the sake of simplicity, we will consider that this analysis is done globally (so there is no need to represent trade, although that is doable), and that we do not have other economic activities to consider, meaning that, for example, labor in agriculture is constant.

Panel (a) shows the basic story: If you want to produce more of one good, you need to sacrifice a number of units of the second good. This "marginal rate of transformation" (MRS) varies, and is indicated by the slope of the green curve. Producers make choices by equalizing this MRS to the relative prices between the two goods, maize and pulses. This is a first result of an optimization problem and an actual trade-off ("if I produce more of X, I need to produce less of Y"). Policies could change incentives between the two goods by changing relative prices through taxes

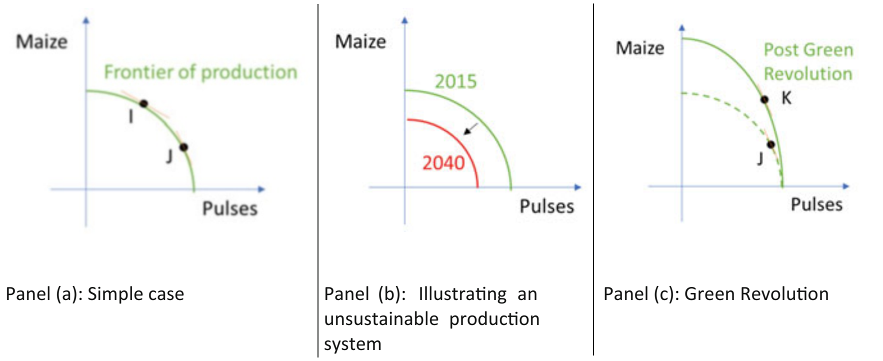


Fig. A.1 Frontier of production possibilities or subsidies. They could move the *free-market* choice of J to I, for instance, by subsidizing maize.

While, in the next paragraph, we are going to show how we move from this frontier of production to our objective and trade-off space, it is quite relevant to see how the FPP illustration could be used to show the impact of non-sustainable practices that can lead to a collapse of the space of potential production over time (Panel b), or how major technological innovation could modify this frontier, including in a biased way. Panel c illustrates a green revolution scenario in which a technological innovation has benefited one crop, maize, although it was not "against" pulses, but the new market equilibrium (from J to K) still results in more maize, and in this case, fewer pulses. So, some public policies could have **unintended consequences**.

Since the entire weight of production is consumed, and for a given distribution of income, we can associate the production of maize and pulses in terms of supply of calories, and therefore PoU outcome. Similarly, the production of maize and corn represented by the FPP is associated with a volume of GHG. So, each point of the FPP, within the space of quantity produced, could be projected in the space of objectives, with our two elements PoU (for Objective 1) and GHG emissions (for trade-off or Objective 3). This is displayed in Fig. A.2, Panel a. While we can end up having more hunger, and more emissions, for any combination of pulse and maize production by wasting resources and making sub-optimal choices, we are mainly interested in the **frontier of optimal trade-off** between undernourishment and GHG emissions. Visually, this frontier is inverted compared to the FPP, mainly because we are displaying "damages," and not positive outcomes.

The various analyses we will conduct will help us to move along this frontier, and potentially displace it, with new technologies or institutions.

Panel b shows the outcome of fixing a maximum level of acceptable PoU, represented by the red line (e.g., 5%). In this case, minimizing the environmental

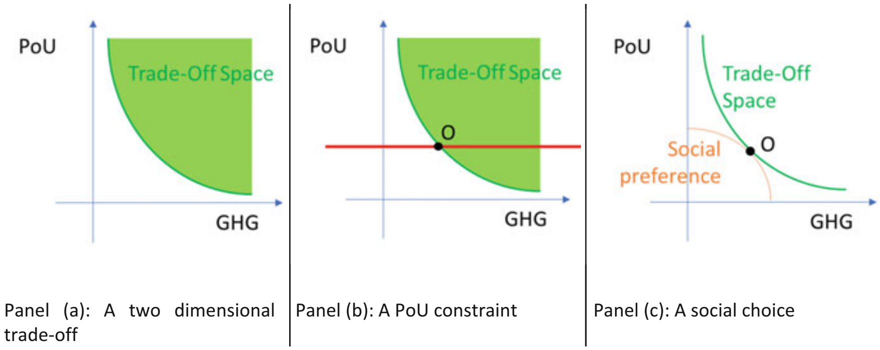


Fig. A.2 Trade-off space

damage created the PoU objective leads to selection of the point O. We can also generate such a result by specifying our social utility function, or preference, within the space of these two variables. Here, the curve represented is also a “reverse” iso-utility function, since the origin of the graph is the absolute best point for the social planner (0 PoU and 0 GHG, but still an unachievable utopia). The tangency between what is possible (green frontier) and what is desired (orange curve) is the optimal way to achieve our various objectives.

The representation introduced in Panel c has additional implications and mathematical properties, but we will not discuss them in the present document.

Illustrating Risk

In this appendix, based on Laborde et al. (2020a, 2021a), we illustrate how using 40 years of past data on weather could be used to assess the risk exposure of various populations (here, the example of select provinces in the DRC) using our analytical framework (Figs. A.3 and A.4).

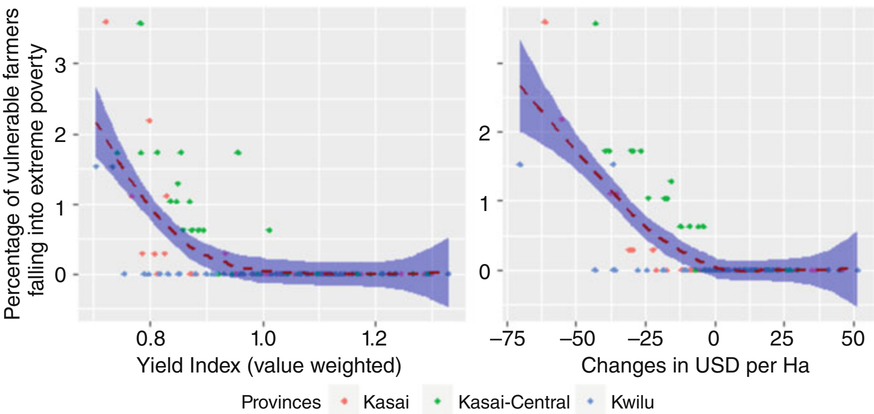


Fig. A.3 Poverty, yield changes and land rents: a 40-year simulation exercise in the DRC

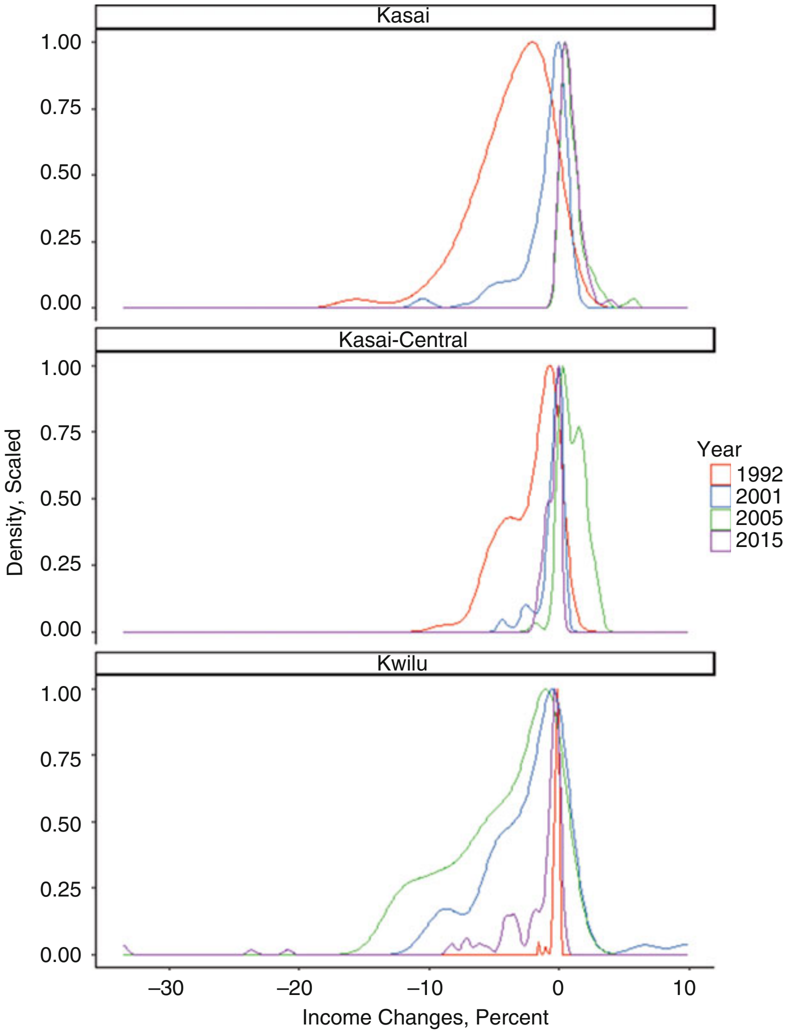


Fig. A.4 Value of production changes as a share of income for vulnerable farmers in select years

References

Arrow K, Cropper ML, Gollier C, Groom B, Heal GM, Newell RG, Nordhaus WD, Pindyck RS, Pizer WA, Portney PR, Sterner T, Tol RSJ, Weitzman ML (2014) Should Governments use a declining discount rate in project analysis? Rev Environ Econ Policy 8–2:145–163

Bleischwitz R, Spataru C, VanDeveer SD, Obersteiner M, van der Voet E, Johnson C, Andrews-Speed P, Boersma T, Hoff H, van Vuuren DP (2018) Resource nexus perspectives towards the United Nations Sustainable Development Goals. Nat Sustain 1:737–743. https://doi.org/10.1038/s41893-018-0173-2

Decreux Y, Valin H (2007) MIRAGE, updated version of the model for trade policy analysis focus on agriculture and dynamics. CEPII working paper 2007-15, (CEPII, 2007)

Laborde DD (2011) Assessing the land use change consequences of European biofuel policies. IFPRI mimeo

Laborde DD, Martin W (2018) Implications of the global growth slowdown for rural poverty. Agric Econ 49:325–338. https://doi.org/10.1111/agec.12419

Laborde D, Valin H (2012) Modeling land-use changes in a global CGE: assessing the EU biofuel mandates with the MIRAGE-BioF model. Clim Chang Econ 03(03). https://doi.org/10.1142/S2010007812500170

Laborde D, Robichaud V, Tokgoz S (2013) MIRAGRODEP 1.0: technical documentation. AGRODEP technical note (IFPRI, 2013)

Laborde D, Bizikova L, Lallemant T, Smaller C (2017) What is the link between hunger and migration. Int J Sustain Dev 197

Laborde M, Martin P, Vos R (2020a) Modeling the impacts of agricultural support policies on emissions from agriculture. World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/694451599729050318/modeling-the-impacts-of-agricultural-support-policies-on-emissions-from-agriculture

Laborde D, Parent M, Smaller C (2020b) Ending hunger, increasing incomes, and protecting the climate: what would it cost donors? Ceres 2030 sustainable solutions to end hunger. https://ecommons.cornell.edu/bitstream/handle/1813/72864/ending-hunger-2.0-V4.pdf?sequence=3&isAllowed=y

Laborde D, Mamun A, Martin W et al (2021a) Agricultural subsidies and global greenhouse gas emissions. Nat Commun 12:2601. https://doi.org/10.1038/s41467-021-22703-1

Laborde D, Martin W, Vos R (2021b) Impacts of COVID-19 on global poverty, food security and diets: insights from global model scenario analysis. Agric Econ 52:375–390. https://doi.org/10.1111/agec.12624

Lucas R (1976) Econometric policy evaluation: a critique. In: Brunner K, Meltzer A (eds) The Phillips curve and labor markets, Carnegie-Rochester conference series on public policy, vol 1. American Elsevier, New York, pp 19–46. ISBN 0-444-11007-0

Muhammad A, D'Souza A, Meade B et al (2017) How income and food prices influence global dietary intakes by age and sex: evidence from 164 countries. BMJ Glob Health 2:e000184. https://doi.org/10.1136/bmjgh-2016-000184

Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R (forthcoming) The battle for biomass: a systematic review of food-feed-fuel competition. Global Food Security

Preston AJ (1974) A dynamic generalization of Tinbergen's theory of policy. Rev Econ Stud 41(1):65–74

Tinbergen J (1952) On the theory of economic policy, 2nd edn. North Holland, Amsterdam

Part III
Actions for Equity and Resilience in Food Systems

Advance Equitable Livelihoods

Lynnette M. Neufeld, Jikun Huang, Ousmane Badiane, Patrick Caron, and Lisa Sennerby Forsse

1 Introduction

Food system transformation provides the opportunity to shift current trends in all forms of malnutrition, prioritizing nutritious food availability and affordability for all – from shifting priorities in agricultural production to facilitating improved food systems that favor nutrition and sustainability.

The purpose of the Action Track 4 science group is to provide the scientific basis for the work of the Action Track (AT). Our task as the science group encompasses reviewing both the evidence arising from studies of the nature of the issues and the potential solutions said evidence underpins. It also helps to identify uncertainty and the gaps in our knowledge. The central issue identified by the AT 4 team has been stated as:

L. M. Neufeld (✉)
International Union of Nutrition Scientists (IUNS), Knowledge Leadership, Global Alliance for Improved Nutrition (GAIN), Ottawa, Canada
e-mail: lynnetten@gmail.com

J. Huang
School of Advanced Agricultural Sciences and China Center for Agricultural Policy (CCAP), Peking University, Beijing, China

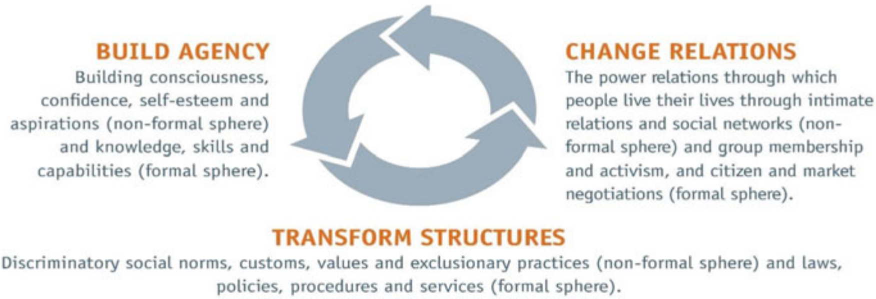
O. Badiane
International Food Policy Research Institute (IFPRI), Dakar, Senegal

P. Caron
University of Montpellier, Agropolis International and Montpellier Advanced Knowledge Institute on Transitions, Montpellier, France

L. S. Forsse
Royal Swedish Academy of Agriculture and Forestry (KSLA) and Swedish University of Agricultural Sciences, Stockholm, Sweden

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_8

Inequality and power imbalances – at the household, community, national and global levels – are consistently constraining the ability of food systems to deliver poverty reduction and sustainable, equitable livelihoods.



In developing solutions, AT 4 explicitly calls out inequities related to gender, age (both the youth and the elderly), minority status, migrant status, and indigenous people status. These solutions focus on small and medium-size enterprises (SMEs) across the food value chain, but also equitable access to employment and livelihoods for wage earners, extending the concerns of inequality to rural/urban and other social and geographic divides. Efforts to address inequality and power imbalances must build agency, change relations, and transform the structures that underpin this imbalance of power and result in inequalities, as illustrated in the following figure (Figure credit: Action Track 4 Discussion Starter, October 2020):

The most effective way to sustainably eradicate poverty and inequality is to boost the opportunities and capacities of the poor and those living in situations of vulnerability, through the more equitable redistribution of resources (e.g., land, incomes, social protection), assurance of quality education, progressive and not regressive taxation, and state infrastructure investments, among other approaches. Reducing inequalities requires that gains in productivity, production and income be assessed against their positive impact on marginalized groups. Decision-making must also become more participatory and accountable to those who are most negatively affected by our current food systems and their outcomes. Progress in advancing equitable livelihoods and value distribution therefore involves several key areas, including expanding access to assets, infrastructure and services, as well as other required measures to enhance the quality of living spaces. Interventions to produce real change on the ground need to empower the poor and those living in situations of vulnerability.

To fulfill our task as the science group, we need to step back and consider the evidence related to the drivers of inequality and power imbalances as they relate to livelihoods *across* the food system. We use the conceptual framework of food systems developed by the High Level Panel of Experts of the UN Committee on World Food Security in 2017 (HLPE 2017), updated in 2020 (HLPE 2020), and

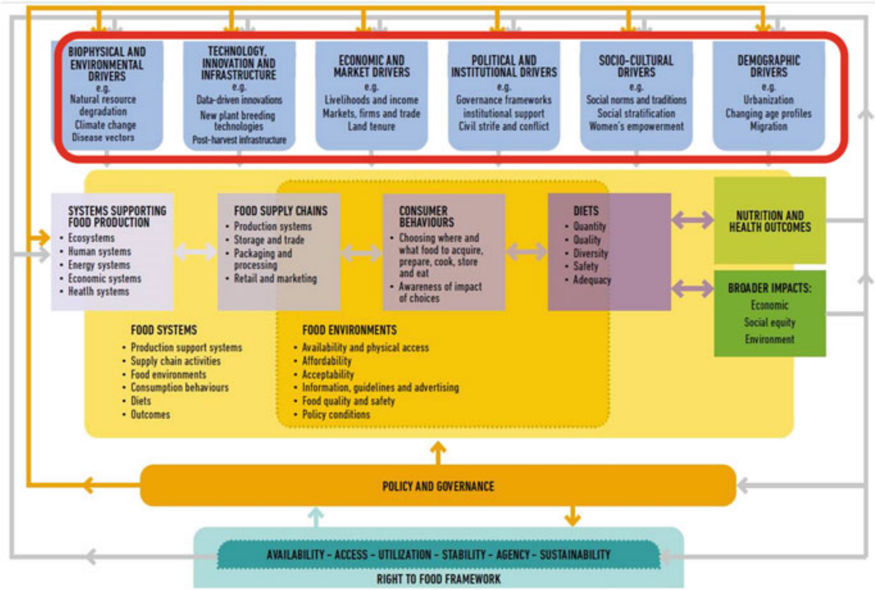


Fig. 1 Conceptual framework of sustainable food systems. (Reduced from HLPE 2020)

structure this review around the six drivers of food systems (as highlighted in the red box in Fig. 1).

Framed around the drivers of sustainable food systems (combining them where the nature of the evidence warrants), the following sections provide an overview of the nature of the issue as it relates to drivers of inequality and power imbalances. Our intent is to explore these drivers as they relate to livelihoods among those living in situations of vulnerability, including consumers and producers and all types of workers across all types of food systems and food system contexts (see von Braun et al. (2021) for definitions and concepts related to food systems). In the final section, we provide examples from the literature that can inform potential solutions to address the issues.

2 Biophysical and Environmental Drivers, Particularly Soil, Water and Climate Change

In the rural areas of many low- and middle-income countries (LMICs), natural resources are an important source of food, both through direct consumption and through providing the basis for income-generating activities (e.g., food and no-food cash crops, forest, and fishery products). Access to natural resources like land, water, forests and fisheries is a key element of livelihood strategies ("natural capital"), together with other elements such as access to employment and/or credit ("financial capital"). Because of this, measures to improve access to resources are an important element of strategies for the realization of the right to food (see conclusion section below for further discussion) (Cotula 2008). Small and medium-sized producers and people whose livelihoods depend on food systems in rural and urban areas are disproportionately affected by all biophysical and environmental drivers, including soil and water resources. Unequal opportunities for access to all types of resources defer overall production, resilience, and rural transformation, thus directly affecting the livelihoods of all actors across food value chains via diverse pathways.

The number of people whose livelihoods depends on degraded lands has been estimated to be about 1.5 billion worldwide (IPCC 2020). In India, for example, 146.8 million out of the estimated 329 million hectares of total geographical area is reported to be degraded (Sandrasekaran et al. 2017). People living in degraded areas depend directly on natural resources for subsistence, food security and income. Women and youths often have limited options and are especially vulnerable to land degradation and climate change. Land degradation reduces productivity and increases the workload of managing the land, disproportionately affecting women in some regions (OECD 2020a). Land degradation and climate change act as threat multipliers for already precarious livelihoods, with consequences for increased risks of poverty, food insecurity and, in some cases, migration, conflict and the loss of cultural heritage (IPCC 2021). The major anthropogenic drivers of erosion are land use and climate change, in particular, through a more intense hydrological cycle (O'Neal et al. 2005). While much research attention has focused on arable agriculture (Boardman and Poesen 2006), seminatural systems such as water may account for nearly half of global soil erosion (Borrelli et al. 2017). There are many indications that water is becoming an increasingly scarce resource, a point often made over the last 10 years (Molden et al. 2007; Falkenmark 1997). Access to water is now recognized as a prerequisite for poverty reduction (Sullivan and Meigh 2003). However, competition for water from many different sectors can divert attention from its role in the improvement of human livelihoods (Rogers et al. 2017).

Marine ecosystems are increasingly affected by fishing and climate change, including reduced ocean productivity, changes in species distributions, and increased disease, among other effects (Bindoff et al. 2019). These and the other climate-related changes discussed above may be especially challenging for the security and livelihoods of coastal communities, particularly for indigenous people and those in LMICs (Bindoff et al. 2019; FAO 2018).

Climate change is the defining issue of our time, and we are at a defining moment. From shifting weather patterns that threaten food production to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. The adverse effect of climate change and variability has become an environmental and socio-economic problem that is increasingly subjecting people around the world to climate-driven hazards (Scholze et al. 2006). The effects of climate change are likely to be more serious among countries with fewer capacities to respond and adapt and, within these countries, among the poorest and most vulnerable. Climate change serves as a serious inhibitor to the attainment of food security and the fulfillment of major development agendas in the majority of global economies. Climate change could undermine social welfare, equity, and the sustainability of future development. It is generally believed that LMICs, and disadvantaged groups within all countries, are more vulnerable to the impacts of climate change as a result of limited resources and low adaptive capacity (Munasinghe 2020).

3 Technology, Innovation, and Infrastructure Drivers

For both short and long distance value chains, infrastructure strongly influences the way food is produced, processed, transported, distributed, sold, conserved, and ultimately consumed. Infrastructure is required for food to move long distances and increase food security in areas of shortages, stabilize food prices, and minimize food-borne disease and food waste. Roads, railroads, shipping and cold chain facilities play an essential role. Poorly developed infrastructure impacts all dimensions of livelihoods for urban and rural populations. In particular, it affects the quality and safety of nutritious foods, limits access to them, and exacerbates issues of food loss and waste (HLPE 2014). In South Sudan and Somalia, for example, poor road infrastructure is a major barrier to food access (ACAPS 2017). Infrastructure improvements, technological advances and mechanization in the food value chain may generate positive externalities for production, trading and consumption, with the potential to generate off-farm employment in rural and, potentially, in urban areas. Examples may include factories located near the farm where the technology will be used, technicians and mechanics hired to operate and repair machinery and devices, other business-related employment, such as bookkeepers, sales staff, etc. They may also generate negative externalities.

Innovation, technology and infrastructure improvements have been and will be major drivers for food system transformation (HLPE 2017). Advances in all three have had important impacts on food production and sustainability, transportation and processing along food value chains, marketing, and ultimately diets, including consumption of both nutritious and unhealthy foods (Pingali 2012; Hueston and McLeod 2012). They can also generate risks to human and environmental health and may not yield equitable benefits for farmers or other food system workers (HLPE 2017). This raises questions about targeting technology policies and interventions according to their impact on improving livelihoods among the poor and those living in situations of vulnerability. The need to produce healthier and more accessible food and address SDG 2 and other SDGs through food system transformation will thus require innovative, responsible and targeted efforts by the actors in the world's food supply chains. Nonetheless, many breakthrough technologies spark disputes and sociotechnical controversies (Latour 1987), which increasingly generate dual oppositions and polarized polemics. This may distract from the goal of ensuring that the livelihood and equity impacts from modern biotechnology are widely shared. In some socio-ecological contexts, this requires measures to prevent such technology from resulting in market concentration in the industries that provide inputs to agriculture, prohibitively high seed prices or reduced farmer participation in breeding (HLPE 2019). It may also be necessary to ensure that the technology does not favor larger farm economic units with the likely accompanying displacement of smallholder farmers (Mascarenhas and Busch 2006; World Bank 2007; Glenna and Cahoy 2009; Heinemann et al. 2014). Whatever the controversial issue, evidence highlights how institutional environments are essential for directing technology and innovation impact. Ultimately, the potential for impact depends not only on characteristics of the technological advancement itself, but on access patterns, arrangements, and governance about who controls it (HLPE 2019).

Innovations in breeding methods, chemical synthetic inputs and food processing have changed the way food is produced, stored, distributed and consumed. Many agricultural innovations have prioritized yield and productivity, often disproportionately favoring high income country food systems, but some notable exceptions exist. Since 2004, HarvestPlus, in collaboration with CGIAR centers, has facilitated the release of 211 crop varieties in 30 countries, varieties that have been bred with increased content of one or more nutrients. An estimated 7.6 million farming households are now growing these crops, estimated to be benefiting some 38 million rural consumers (HarvestPlus 2018). This number will be enhanced as crops are sold in urban markets and used in various processed or pre-prepared foods. Another example promotes the better incorporation of fruit into local food systems, meeting the challenge of seasonal availability. McMullin et al. (2019) developed a methodology based on 'fruit-tree portfolios,' which selects, in partnership with farmers, the fruit-tree species for production that are both socio-ecologically suitable and nutrient-rich. Both examples have the dual advantage of potentially improving livelihoods and favoring nutrition outcomes through enhanced production and access to nutritious foods. Modern biotechnology can also improve livelihoods through increased crop production for smallholder farmers. Millions of small farmers in many LMICs (e.g., China and India) have benefited from adoption of Bt cotton since this technology was approved for commercialization in the late 1990s (Areal et al. 2013; Huang et al. 2002; Kathage and Qaim 2012; Qiao et al. 2017). Nonetheless, the impact of such technology on livelihoods, particularly for farmers in situations of vulnerability, is disputed and has been shown to depend on differentiated practices (Vognan and Fok 2019). Among the issues to be resolved in this regard is the ongoing debate related to access to seeds, as well as mechanisms to ensure that commercial interests in seed-line access do not negatively affect producers' and consumers' livelihoods (Kloppenburg 2010; Bonny 2017).

According to the CGIAR Research Program on Climate Change, Agriculture and Food Security (Dinesh et al. 2017). some of the most promising innovations in rural agriculture are technology- and service-based. With access to data, markets and financial services, farmers can plant, fertilize, harvest, and sell products more effectively. These approaches are gradually gaining favor as more people in emerging economies connect to mobile networks (Pew Research Center 2016) and applications designed to collect and share agricultural information become increasingly accessible (Qiang et al. 2012). Of course, the mere existence of this technology will not generate better livelihoods. Access to such technology has been highly constrained and must be resolved before this potential can be realized (World Bank 2016; Deichmann et al. 2016; Salemink et al. 2017; OECD 2019a) Similarly, tools must meet the needs of the farmers who use them, as well as expectations towards improving livelihood, including addressing power asymmetries. This demands that mobile technologies take into account differences in gender, education, and resource levels among farmers and consumers (Vesper 2021), and that they are responsive to changing circumstances. The impact and success of these tools and programs should be monitored and evaluated (Baumüller 2018), with ineffective approaches being improved or replaced (Samberg 2021). Capacitated endogenous institutions are vital to achieving an inclusive approach.

4 Economic and Political Drivers

Many economic and political factors are essential causes of inequality and power imbalances at the household, community, national and global levels, constraining the ability of food system transformation to deliver poverty reduction and sustainable, equitable livelihoods (International Monetary Fund 2014; Rodríguez-Pose and Ezcurra 2011). Improved education and literacy levels and access to public services and infrastructure, among other factors, help to address the issue (OECD 2019b, 2020b).

Social protection is a menu of policy instruments for addressing poverty and vulnerability, through social assistance, social insurance and efforts at social inclusion, with a eye towards addressing both long-standing and crisis-induced poverty (HLPE 2012). The precarity of the food systems in most countries, and particularly that of food system workers living in situations of vulnerability, is illustrated by the current COVID-19 crisis (Box 1). The lessons and experience from global efforts fighting the COVID-19 pandemic show the importance of developing a strong social network in coping with the fragility of food systems.

Conflicts and crises, usually resulting from an unstable political system and uncertain property rights arrangements, damage trust and social cohesion among the stakeholders throughout food systems, discourage public and private investment, and cause slowdowns in economic growth and less inclusive rural and structural transformations (Putnam 2000; Bourguignon and Dessus 2009). This does harm to vulnerable smallholder farmers, consumers and those engaged in micro enterprises and SMEs along food value chains, particularly those run by and employing youths, women, the disabled, and indigenous peoples.

The inclusive development of food systems is also constrained by lack of representative ***leadership***, reflected in inequality in access to productive resources, working opportunities, market participation rights and public services. Studies in almost all LMIC contexts, except for Latin America and the Caribbean, indicate a large proportion of total farmland belongs to small holders (less than 2 ha) (Lowder et al. 2016), and that in these places and for all food system workers, resources and public services are unequally allocated (de Pryck and Termine 2014). Barriers to active participation in leadership and decision-making must be broken down (Food and Agriculture Organization of the United Nations 2017).

Livelihood inequalities across the food system, including among smallholder farmers, small businesses and workers across the food value chain, can be reduced only if inequalities in ***access to land, water, employment,*** financial services, infrastructure, technology, markets, and other economic opportunities are resolved. Food system transformation that does not address these inequalities and specific vulnerabilities runs the risk of reinforcing and deepening inequalities into the future and undermining the resilience of food systems. Inequitable economic opportunities are usually caused by rigid institutional arrangements in land, water, credit and labor markets, a lack of information, market segregation/ monopoly, discriminative treatment, and distorted policies, among other things (Food and Agriculture Organization of the United Nations 2017). Subdivision among siblings makes it harder for rural youths to obtain as much land as their parents had; in many contexts, youths have historically been marginalized economically, socially and politically (Jayne et al. 2014). Research shows that respecting/upholding collective forms of land ownership and customary property regimes has important positive implications for livelihood equity (Vandergeten et al. 2016; King 1977). However, the nature of public goods such as water resources makes fair allocation difficult. Removing barriers to employment and other economic opportunities, in addition to various actions for reducing discrimination towards migrant workers, also works to increase income and improve livelihoods (IFPRI 2019).

As pointed out by the HLPE (HLPE 2017), ***globalization and trade*** have a critical role to play in ensuring food security and nutrition (FSN) and reducing inequalities. Trade can positively and negatively affect all four pillars of FSN (availability, access, utilization, stability). Evidence suggests that globalization and international trade may help to extend the value chain and generate opportunities to create wealth and equitable livelihoods among countries (OECD 2020b; Greenville et al. 2019a; Greenville et al. 2019b) International trade and financial flows are also associated with changes in production and consumption patterns that require taking into account the way livelihood is affected, in particular, through employment access, incomes and wealth distribution. Measures are needed to avoid unwanted outcomes, including increases in income inequality (Feenstra and Hanson 1996; Feenstra and Hanson 2008). While some farmers can improve their livelihoods by tapping into exportable agricultural production, considerable research shows that becoming part of export markets can make farmers, particularly small-scale farmers, more vulnerable to shocks in global commodity markets (González 2021; Oya 2012). These risks can be mitigated through collective action and policy support to soften the impact of such shocks among smallholders and other actors in the food system that lack the capacity to respond adequately.

Stabilizing food prices will help to reduce the risk of all stakeholders along food supply chains and will bring benefits to those small holders who are more vulnerable in the production system and consumers in rural and urban areas. In general, food supply is much more stable at the regional and global levels than it is within a given country (Badiane and Odjo 2016). This is because an efficient market provides the opportunity to supplement supplies in cases of domestic production shortfall or rapidly expanding demand, and thereby helps prevent sharp price increases that would affect access to food negatively. Inversely, in cases when rising domestic supplies threaten to depress local prices, an appropriate political regulation and management of stocks (in both the national and international dimensions), plus a transparent trade mechanism, would be appropriate.

The informal food processing sector has grown significantly over the last decade, thanks to rapid urbanization and growing middle classes, and has become one of the most dynamic segments of food staple value chains (Reardon 2020). In Africa, it is currently the fastest growing export sector, both for regional and outside markets (Bouët et al. 2020). It is estimated that upward of two-thirds of staple foods consumed in Africa by 2040 will be in processed form (Tschirley et al. 2015). The emerging staple food processing sector is currently characterized by a large and growing number of primarily female-headed small enterprises. Future strategies for promoting equitable livelihoods and value distribution in domestic food systems will need to reverse the current formality and size bias in order to tap into the employment and income opportunities resulting from the rapidly transforming staple food value chains for the benefits of farmers, unskilled workers, and consumers in urban centers and rural towns.

These political and economic factors may cause inequality and imbalances through a complex mechanism, but may also be the consequence of such inequality and imbalance. On the one hand, both political instability and poor economic performance are believed to contribute to rural poverty and inequality of livelihood in rural sectors of many LMICs in all regions (Dutt and Mitra 2008; Alesina 1996). On the other hand, a burgeoning literature illustrates that rapid economic growth is not a sufficient condition for inclusive development (Putnam 2000; Bourguignon and Dessus 2009; Acemoglu and Robinson 2002). In addition, the political and economic drivers may also interact with innovation, technology and infrastructure to influence food systems, as well as inequality and power imbalances affecting women, youths, smallholders and indigenous people. Consequently, the question is not only *whether* but also *how* economic growth and institutional/policy arrangements may affect inequality in access to production, employment and fair share opportunity (OECD 2020a; Losch et al. 2012; Independent Evaluation Group (IEG) 2014; IMF 2015). This calls for considering the way agency conditions or prevents the development of inclusive, equitable livelihoods (UNDESA 2020), in particular, through access to public services, before proper decision-making and agenda-setting could be brought about.

The pace of future improvement in livelihoods will depend on the ability of governments to find ways to maximize the impact of economic growth and investments in social sectors, such as health, education, and social protection towards enhancing capacities among the poor and vulnerable. This calls not only for better coordination of interventions across government, but also for recognition and effective exploitation of the fact that differences in services and how they are bundled produce different impacts on the livelihoods of the poor and those living in vulnerable situations. For instance, the impact of a given dollar amount spent on educational services on smallholder and low-skilled off-farm and urban labor productivity will depend on the extent to which it targets vocational training and other efforts to upgrade and develop skills in the relevant sectors (Ulimwengu and Badiane 2010). Against the background of the current COVID-19 pandemic, the same concept can be illustrated using the example of health services (Box 1). Furthermore, there is evidence that morbidity has a bigger impact on the productivity of the poor and vulnerable than among better off segments of the population (Badiane and Ulimwengu 2013). It has also been shown that different types of health services have different impacts on disease prevalence and morbidity (Wouterse and Badiane 2019). It is therefore possible to allocate public investment in health services such as to target diseases that have the largest effects on the productivity of smallholders and low-skilled laborers and excluded communities. Allen and co-authors (Allen et al. 2014). show that morbidity not only affects labor availability and productivity, but also the choice of technologies and decisions to return to the use of fertilizers and mechanization. More importantly, different health services have different impacts on disease prevalence, which affects efficiency, and thus livelihoods, differently, even among the poor, those living in vulnerable situations, and across gender (Badiane and Ulimwengu 2013; Quisumbing et al. 2019). The current COVID-19 pandemic illustrates the need and opportunity to rethink the delivery of social services in order to maximize their benefit and impact among the poor and vulnerable (Box 1). This applies equally to social protection policies in which the experience of productive safety nets in Ethiopia offers valuable lessons for designing programs that work for the poor and vulnerable (Knippenberg and Hoddinott 2017).

5 Socio-cultural and Demographic Drivers

Vast evidence illustrates that several socio-cultural drivers underpin inequalities among and within societies and constrain the potential for some to benefit from actions to improve livelihoods, particularly women, youths, the disabled, the elderly, and indigenous peoples (Food and Agriculture Organization of the United Nations 2017; International Fund for Agricultural Development 2016; Research Institute (IFPRI) IFP 2019). For example, there are approximately 185 million indigenous women in the world, belonging to more than 5000 different indigenous peoples. Despite the broad international consensus about the important role indigenous women play in eradicating hunger and malnutrition, there are still limitations in the recognition and exercise of their rights (FAO, IFAD, UNICEF, WFP, WHO 2020). Due to the long-term and ongoing impacts of colonialism and environmental degradation, many indigenous peoples, regardless of their geographic location, face high levels of obesity and chronic disease and are disproportionally affected by poverty and food insecurity (Batal and Decelles 2019; Domingo et al. 2020; Valeggia and Snodgrass 2015; Stephens et al. 2005). Past and present social and environmental injustices have led to the loss of food sovereignty, through dispossessing indigenous peoples from their traditional territories and undermining the transmission of intergenerational knowledge of cultural practices related to their food systems (Desmarais and Wittman 2014; Vernon 2015), and have been linked, as in the case of the experience of hunger in residential schools in Canada, to the rise of diabetes in these populations (Mosby and Galloway 2017).

Socio-cultural drivers also impact and set the norms for the dynamics of the other drivers, including political and economic drivers, demography, and innovation/technology, among others. As such, structural barriers for several groups, particularly women and youths, affect a number of potentially beneficial aspects of life, including land rights and access to financial services, among others. In addition, inequality of opportunity is an important constraint. Social protection has an important role to play in protecting those living in vulnerable situations and, depending on the nature of that action, seeking to address the underlying causes of poverty and exclusion (Levy 2006). Programs that direct resources to women have shown a greater impact on food security and other household-linked benefits (HLPE 2012). However, social and structural barriers may limit women's access to several types of social protection program, including public works and agricultural input and support (HLPE 2012). In addition to these considerations, language, culture and tradition may influence the willingness to participate and potential to benefit from social protection programs, unless national programs are adequately adapted to such sub-national contexts (Théodore et al. 2019).

Few, if any, economic or social transformations over the past decades can be brought into focus without explicit attention being paid to the demographic transition that is inextricably linked to several socio-cultural drivers. The growth of the urban sector, driven by both natural increase (fertility exceeding mortality) and rural-to-urban migration (Dyson 2011; United Nations 2001), helps to fuel agricultural transformation. The proportion of the population living in rural areas is declining in many countries, yet numbers are increasing in some, particularly in sub-Saharan Africa. Both fertility and mortality have been falling in rural areas, converging from levels higher than those in urban areas towards meeting those urban levels. Pressure and opportunity lead certain parts of growing rural cohorts to migrate to cities or to seek diversified livelihoods within the rural sector. This raises concerns, particularly in sub-Saharan Africa, where urban growth and the economic sectors are not in a position to cope with such a rapid transition and offer employment to rural dwellers, as has occurred historically on other continents (Losch et al. 2012).

Predominantly male migration among youths and young adults over the course of the urban transition may have additional impacts on the gendered nature of economic roles and the overall status of women (Lastarria-Cornhiel 2008; Gray 2009). Increased urbanization means a growing gap between the locations of food production and food consumption. It may also mean a change in lifestyle, including dietary changes. As a result, there is a growing need for food processing, transportation, and transformation beyond the farm level, providing opportunities for jobs and entrepreneurship. In Ethiopia, Malawi, Mozambique, Tanzania, Uganda and Zambia, the transformation of the food systems is forecast to add more jobs by 2025 than any other sector of the economy (Gustafson 2018). This is an opportunity to see that these jobs are also accessible to rural women and youths who may disproportionately live in vulnerable situations. Nonetheless, evidence suggests that women entrepreneurs face many additional barriers compared to their male counterparts, including lack of mobility, less access to finance, less access to business networks and mentors, limited leadership experience, lower literacy and numeracy, and discriminatory gender norms and stereotypes (Nordhagen and Condes 2020). Experience from other regions also illustrates the risks to nutrition as dietary traditions are lost and reliance on processed, often highly unhealthy food increases (Popkin and Reardon 2018).

Today, there are significant knowledge gaps concerning rural out-migration trends that need to be tackled. This is particularly the case for migration driven by distress, when people come to perceive that there is no other viable livelihood option except to migrate. Reliable data, disaggregated by sex, age, origin and destination, are necessary to understand the socio-economic conditions associated with migration. At the moment, these data are scarce (Carletto et al. 2015).

Box 1: The Unprecedented Range of COVID-19 Disruptions to the Food System and Livelihoods

The breadth and reach of the complex ramifications and disruptions from the COVID-19 pandemic are unprecedented (Bron et al. 2021). The impact from the pandemic parallels or exceeds the impact of major shocks over the past few decades, whether caused by natural disasters, disruption of financial and commodity markets, or conflict and civil strife. More challenging is the fact that, under Covid-19, all of these various shocks happened concurrently and engulfed the entire globe, with no regions left untouched, and thus poised to help fuel a possible recovery (Badiane and Collins 2020). There are therefore important lessons to be learned from the current pandemic as to how to help shape more effective strategies for managing future shocks and their impact on the livelihood of the excluded and marginalized.

The Effects of Covid on Marginalized Communities: Income, Poverty, and Nutrition

Policies of social distancing and other measures adopted by governments to contain the spread of the pandemic have drastically affected food supply chains, with serious repercussions for the poor and vulnerable, particularly in LMICs (Hobbs 2020; Barrett 2020; OECD 2021; Fei et al. 2020; Hatab et al. 2021). There is evidence that disruptions are more serious for the operation of the informal market networks that dominate supply chains for traditional food staples that people living in poverty and situations of vulnerability depend on more heavily (Resnick n.d.) Prices in these markets have reacted sharply to measures undertaken to control the pandemic (Matchaya et al. 2020; Guthiga et al. 2020). Moreover, higher food prices, the closing of informal markets and other disruptions to staple food supply chains have been shown to impact the

(continued)

Box 1 (continued)
micronutrient intake and nutritional status of the poor (Ulimwengu and Magne-Domgho 2020). Finally, the effects of the pandemic on global commodity markets and trading systems are shown to have had a significant impact on economic growth, and thus incomes and poverty levels, likely with a disproportionate burden on the same vulnerable communities in both urban and rural areas (Fofana and Sall 2020). This is almost certain to worsen inequalities, food insecurity and undernutrition, including child wasting (Headey et al. 2020). COVID-19 therefore will likely have substantial implications for the achievement of the Sustainable Development Goals in LMICs, in particular, SDG 2 (End hunger) and SDG 12 (Ensure sustainable consumption and production patterns) (Jribi et al. 2020).

Equity and Policy Responses to Covid and Similar Shocks

The Covid-19 crisis has particularly impacted already-marginalized segments of the population such as indigenous peoples, migrant workers, and informal sector employees (Gamlen 2020; International Labour Organization 2020; Marschke et al. 2021). High vulnerability to changing economic conditions is linked partly to a host of pre-existing barriers ranging from weak legal status to racism to a lack of access to health, social security and educational services, all leading to disproportional impacts of the pandemic among the poor and disadvantaged.

Persistent and chronic vulnerability, a major manifestation of marginalization and exclusion, not only exacerbates the human cost of shocks, but also complicates the search for effective responses. Resistance to confinement, curfews and other mitigation measures reported in the media across the world often arise from the considerable threat to livelihoods among the poorest and those living in situations of vulnerability (Resnick n.d.) Successful strategies for dealing with future shocks require having a better handle on equity and vulnerability before said shocks strike.

Lessons for Managing Future Shocks to Protect Livelihoods

Just like pre-existing conditions among humans raise the risk of serious consequences, chronic vulnerability patterns also raise the risk of exposure and the extent of damage among excluded and marginalized communities in cases of shocks such as Covid-19. Community vulnerability is determined by factors ranging from pre-existing levels of poverty, food insecurity, malnutrition, disease prevalence, poor health and education services to high population density (Ulimwengu and Collins 2020). Investment in the capacity to develop a good understanding of the patterns of vulnerability across various communities is therefore a major requirement for future preparedness, especially among LMICs.

(continued)

Box 1 (continued)

For example, a report from the Indigenous Navigator (IWGIA 2020) highlights the impact of Covid-19 on indigenous communities in 11 countries (Africa and Asia). On the one hand, the report identifies how pre-existing barriers in access to health, social security and education are fueling disproportional impacts of the pandemic on indigenous peoples. It also indicates a rise in food insecurity, related to loss of livelihoods and a lack of access to land and natural resources. On the other hand, it underlines the central role played by communities in building their response and recovery to the global crisis resulting from the pandemic. The emphasis on Covid-19 response and recovery measures springs from the fact that they need to be respectful of the rights of indigenous peoples and support their livelihoods, economies, and resilience.

Equally important is a good understanding of the nature of the operation of local food systems. Control measures that are not aligned with the basic features of food systems along complete value chains are certain to create second generation disruptions, leading to more serious impacts on livelihoods (Liverpool-Tasie et al. 2021).

Finally, boosting preparedness capacities will require investment in a minimum infrastructure for real-time data access and management. New development in remote sensing and machine learning offers real opportunities for better targeting and tracking in order to raise the effectiveness of response and mitigation measures to protect the poor and vulnerable (Ly et al. 2020).

6 Conclusions and Implications for the Development of Game-Changing Solutions That Will Enhance Equitable Livelihoods in Food Systems

The growth of food systems presents enormous employment opportunities (Gustafson 2018), but achievement of equitable livelihoods in food systems resulting from changes in said systems will require that substantial progress be made to address the drivers of inequality. Food system transformation must also find a balance to help create systems that favor and support healthy diets (i.e., those that minimize the risk of both undernutrition and overweight and obesity) (Neufeld et al. 2021), and do so in ways that are sustainable for the planet. We must transform not only the food systems, but also the structures and systems that continue to enable and exacerbate inequities. While we have reviewed and discussed the evidence related to drivers of inequitable livelihoods in relation to food system transformation within their respective categories, they are interconnected, and progress to address one driver will likely require change across several. For example, globalization and trade interact with other powerful drivers, especially technology resource mobilization and demographic trends, which shape food production, distribution and consumption (HLPE 2017).

We believe, therefore, that enhancing equitable livelihoods will require solutions that:

1. ***Are rights-based***: Solutions must recognize and hold stakeholders to account for human rights, including a living wage and the right to food (UN 1948), and advance the agenda towards the *right to a healthy diet*. Implications include not only a shift in policy and programmatic action, but also an increase in public pressure and the creation of monitoring and accountability mechanisms that hold governments, businesses, and all stakeholders to account to uphold rights.
2. ***Ensure long-term investment for structural changes***: Dismantling inequitable systems and structures that enable and exacerbate inequalities for food system workers and consumers requires long-term investment, while achieving short term gains. A long-term vision should inform investment priorities in needed structural changes across food systems, including those that will result in:

   - Dismantling barriers to expanded access to resources, technology, infrastructure and productive services among smallholders and other less powerful actors along food systems,
   - Policies and institutions that make sure that markets and trading regimes work for producers and consumers, including by raising agricultural incomes and improving food access,
   - Regulatory and administrative arrangements and other instruments for ensuring equitable access to productive assets.

3. ***Directly inform local and national policy and programs***: Transformational change towards healthy, sustainable, and equitable food systems will require a breaking down of current policy silos in favor of coordinated policy agendas that permit the mapping and balancing of benefits, harms and trade-offs to human and planetary health, including but not limited to agriculture, trade and food policies that simultaneously foster healthy diets, equitable opportunity and fair pay while also protecting the environment, complemented with strengthened and well-targeted social protection.
4. ***Enhance the development of and equitable deployment of contextually relevant innovation and technology***: The potential of innovation and technology to do good for human and planetary health is vast, but systems must be strengthened to ensure that it does not exacerbate inequalities and that the balance of potential benefits and harms can be assessed. The research, development and deployment of innovation and technology must meet the needs of both smallholder producers and small businesses across the food value chains and vulnerable consumers. Doing so requires enhanced processes and investments to develop such innovations and technologies, drawing on all forms of scientific evidence along with indigenous, local and contextual knowledge.

In the following section, we provide several general and more specific recommendations that can inform priorities for game-changing solutions, bearing in mind the four criteria above. This list is not intended to be comprehensive, but rather to focus priorities that surface from the evidence review. Where feasible, we have included specific examples that illustrate the potential gains and pitfalls.

6.1 Alter Power Structures to Enhance Inclusive Decision-Making

- At the global and regional levels, strengthen and enhance the existing institutional architecture to generate recommendations, good practice models, and technical support guidance for enhanced inclusive decision-making processes related to food systems within governments and organizations. Examples of key international organizations include FAO, IFAD, WFP, the World Bank Group, and CGIAR, among others.
- Engage a coalition of local, regional and international research institutions to generate and test a framework and parsimonious set of indicators that can be used to track progress towards inclusive decision-making processes and monitor livelihood improvements within international, national, regional and local governments and organizations.
- Create or build on an existing accountability mechanism with a mandate and resources to track progress towards and hold to account inclusive decision-making related to food system transformations and their impacts within governments and organizations.
- Strengthen producer, vender, market and consumer organizations and other forms of collective action across food systems to enhance effective, non-tokenistic participation in decision-making processes related to rural and food system transformation.
- Through all of these processes, explore demographic, social and cultural aspects that may influence participation in decision-making (Gustafson 2018) (e.g., gender, age, status as indigenous peoples) and ensure that mechanisms are developed to address and track progress responsive to these unique contextual factors.

  - Dimitra Clubs seek to transform gender relations, bringing women and men together to become more aware of gender inequalities in households and communities and work to transform gender relations. The over 3400 clubs that currently exist have reached an estimated two million rural people. Examples of success include fighting malnutrition by challenging dietary taboos, reconciling long-standing political disputes, mobilizing to meet environmental challenges and establishing a credit cooperative so that people can avoid debt (FAO 2021).
  - The model of mutual accountability developed by the African Union as part of its Comprehensive African Agriculture Development Programme (CAADP) is an innovative and effective approach to promoting transparency, participation and accountability for results. It involves two main components:

Country-level joint sector reviews (JSRs) that allow governments, farmer organizations, private sector actors, civil society organizations and development partner organizations, at least once a year, to collectively review policy and program implementation performance, as well as progress towards outcomes for the agricultural sector. The outcome is an action plan to deal with any major issues that emerge.

The continental-level biennial review (BR) based on formally agreed-upon target commitments related to agricultural sector investment, hunger and poverty, gender, youth, intra-African trade, and climate-smart agriculture. Every two years, a report is prepared by each member state and submitted to the African Union Commission, which uses it to rate each country on each of the target commitments. The report is submitted to Heads of State at their January Summit to debate the findings (Ulimwengu et al. 2020).

6.2 Protect the Livelihoods of Those Living in Situations of Vulnerability, While Creating Opportunities

– Expand the effective coverage of well-targeted social protection systems that uphold the livelihoods of those living in situations of vulnerability, using social protection instruments that can alleviate short-term crises, but go beyond sheer poverty reduction to enhance opportunities to build assets and create wealth.

  • One promising model of boosting productivity and improving livelihoods through skill development and advisory services financial transfer is the FOMENTO model from Brazil. Research looking into the impact of its transfer to the African setting has provided solid evidence on its effectiveness to raise assets and increase the earning potential of beneficiary farmers. This idea holds promise as a scalable approach to empowering and equipping the poor and those living in situations of vulnerability to integrate into the higher value segments of the food system value chains (Ambler et al. 2018).

– Using existing or enhanced technology, develop and deploy better models for predicting climate and other agricultural risks and use this data effectively to pre-empt and mitigate the impact of such risks on the production and livelihoods of small-scale agriculture and other producers in situations of vulnerability.

  • Climate Information Services (CIS) involve the production, translation (e.g., advisories, decision support), and communication and use of climate information. Appropriate information enables farmers to understand the role of climate vs. other drivers in perceived productivity changes and manage climate-related risks throughout the agricultural calendar. Econometric studies highlight CIS as one of the most important factors influencing the adaptation and transformation of farming systems. For example, an analysis across more than 5000 households in East and West Africa, South Asia, and Central America found access to CIS is a positive determinant of adaptation through agricultural diversification, and one of agricultural intensification in Bangladesh and India (Loboguerrero et al. 2019).

6.3 Adapt Institutions and Policies to Favor Equitable Food System Livelihoods

– At the global, national, sub-national and local levels, develop and implement a cohesive set of policy actions that will enable sequential food system transformations that favor the production, distribution and consumption of nutritious over unhealthy foods, produced with territorial approaches that favor planetary health (Caron et al. 2017) and ensure equitable livelihoods for producers and wage earners across the food system.

  • Africa's Regional Economic Communities (RECs) are key actors working in collaboration with the African Union (AU) to ensure peace and stability in their regions (Adepoju 2002). The RECs have been central to various transformative programs on the continent, including the New Partnership for Africa's Development (NEPAD) adopted in 2001. RECs have the immense challenge of working with governments, civil society, and the AU Commission in raising the standard of living of the people of Africa and contributing towards the progress and development of the continent through economic growth and social development (Office of the Special Adviser on Africa (OSAA) 2021).

– Adapt institutions and adopt policies that eliminate barriers in access to the fundamental services needed to enable those living in situations of vulnerability to take advantage of opportunities, ensuring, for example, the right to food, shelter and health. Facilitate more and better educational investments that enable and empower youths as part of the productive rural and urban labor force (UNICEF 2019; Menashe-Oren and Stecklov 2018).

  • The German dual training system for agricultural and horticultural professions is a good model for an institutional infrastructure that creates a path to good paying jobs and better livelihoods. It is a country-wide system that offers a mixture of practical, multi-year on-the-job training of apprentices by "master-farmers," ongoing theoretical training for active and aspiring farmers, and modular, usually short-term courses on specific skills and good practices (Thiele 2021).

– Adapt institutions and adopt policies that eliminate barriers in access to the natural (e.g., land (FAO 2016), water, forests), economic (e.g., credit, business planning) and technological resources (e.g., digital, appropriate modern biotechnology) needed to enhance and ensure equitable livelihoods for producers and SMEs across the food value chain. Such policy and institutional arrangements should explicitly favor those who have been traditionally excluded, particularly women, youths, and indigenous peoples.

  - The Land Matrix Initiative (Land Matrix 2021) is an independent global land monitoring initiative made up of a number of global and regional partners, originally established in 2009 to address the lack of robust data on large scale land acquisitions and investments. The initiative now covers almost 100 countries. It captures intended and failed attempts to acquire land through purchase, lease or concession and demonstrates the complexity and political dimension of land acquisition.

- Enhance the effectiveness of international organizations to facilitate global trade arrangements that promote and protect livelihoods and the right to food. An enhanced role for the World Trade Organization is particularly salient.

6.4 Increase Investment to Realize the Potential of Improved Institutional and Policy Actions

- More coordination among government entities would internalize externalities across sectors and address trade-offs such as to deliver the most impactful and site-adapted interventions for the poor and those living in vulnerable situations (Badiane and Makombe 2015; De Pinto and Ulimwengu 2017; IFPRI 2019). Increasing investment in public infrastructure (e.g., roads, markets, irrigation, etc.) also helps to enhance the livability of communities, while favoring the production, sale and consumption of nutritious food.
- Expand and use innovative financial mechanisms (e.g., impact investment) for small and medium-sized farmers and businesses along the food value chains to expand and intensify their production and improve safety, quality and sustainability, prioritizing nutritious over unhealthy foods.

  - There are two models for nurturing and supporting the development of the emerging processing processor and other segments of food system value chains to boost profits and employment for low-skilled workers. The first, with a well-documented impact (Sonobe and Otsuka 2011), is the model of cluster-based industrialization, which provides a critical mass of infrastructure, services and networking opportunities. The second is the Kaizen model from Japan, which has recently been tested in Africa with promising results (Sonobe et al. 2020).

6.5 Hold Governments, Businesses and Organizations to Account for Ensuring Equitable Livelihoods

– Engage a coalition of local, regional and international research institutions to generate and test a framework and parsimonious set of indicators and metrics that can be used to track progress towards equitable livelihoods within business, international, national, regional and local governments and organizations.
– Create or build on an existing accountability mechanism with a mandate and resources to track progress towards and hold to account equitable livelihoods in food systems across all businesses, governments and organizations, ensuring data can be and are presented disaggregated for women, youths, indigenous peoples, migrant workers, and others as appropriate.

6.6 Realize the Potential of Science, Innovation, Technology, and Evidence to Favor Equitable Livelihoods

– Apply advances in bioscience innovations, including genetic engineering and genome editing, as well as soil, plant and animal husbandry and health technologies and practices, for a successful transformation of food systems. Meeting food system challenges related to raising production, improving efficiency and saving and restoring production resources in the face of a changing climate will require that benefits from advances in these areas are broad-based and inclusive of the poor and marginalized actors in food system value chains. This, in turn, will require investing in adapting technology advances to local conditions for greater accessibility and affordability for, as well as safe utilization by, smallholder farmers.
– Develop and deploy digital innovations to advance the efficiency and inclusiveness of food systems. Both the digital services platform from eCommerce and financial and technology support services help link farmers and rural communities to actors and service providers in domestic and global value chains. Lower income countries can also overcome, at lower cost and within a shorter period of time, a number of institutional, infrastructural and financial obstacles to transforming food systems through the strategic deployment of remote sensing, big data, machine learning, artificial intelligence, robotics, drones and digital technologies for more efficient cropping systems.
– Improve the availability, quality, accessibility and use of data that can map and inform actions to reduce inequalities in food systems.
  • The newly developed food systems dashboard (Food Systems Dashboard - Diets and Nutrition 2021) is an important advance in this regard. The dashboard consolidates existing data from multiple sources, provides useful tools for visualizing and understanding the data, and is developing a set of

diagnostics that will permit the identification of potential policy and program priorities. That said, many data gaps exist, particularly at the national and sub-national levels, and the full potential of such tools will be realized only once such data gaps are filled (Fanzo et al. 2020).

– Assess deployment pathways (e.g., extension services, farmer schools, etc.) and the potential for those traditionally excluded (e.g., women, youths, small holders, indigenous peoples) to benefit when setting priorities for and making investment decisions related to the development of innovations and new technologies for food systems.
  - For example, new technologies are being used to very positive effect to ensure that nutrition does not "exit" the food supply chain (Fanzo et al. 2017). Improving traditional products and processes by reengineering the unit operations can be an efficient way to both generate rural employment in SMEs and incomes for family farmers and increase the safety and nutritional quality of foods while maintaining or improving the organoleptic characteristics of traditional products (Obodai et al. 2015; Pintado et al. 2016). Nonetheless, evaluation has also shown that several "good ideas" may have harmful side effects when a comprehensive approach to understanding all different pathways leading from agricultural interventions towards the nutrition of individuals is insufficiently considered (Dury et al. 2015).

– Develop and use creative approaches to learning, building on, and documenting indigenous knowledge related to food production, processing, consumption, and natural resource management in ways that such knowledge can be shared, adapted, and adopted and tested in new contexts if appropriate, as well as drawn on in the establishment of recommendations, guidance and good practice (Lugo-Morin 2020; Blanchet et al. 2020; Okanagan Nation Alliance 2021). New approaches are instrumental in order to revitalize indigenous food systems and produce, process and consume food in culturally relevant (Cree Hunters and Trappers Income Security Board 2021) and ecologically sustainable ways (Sherwood 2019).
  - Several examples exist illustrating the potential and power of mobilizing available indigenous knowledge for the establishment of policy recommendations (Grey and Patel 2014; Mabhaudhi et al. 2018; Kurashima et al. 2019; Asogwa et al. 2017), guidance (Ministerio de Salud Pública del Ecuador, FAO 2021) and good practice (Sherwood et al. 2017; Deaconu et al. 2019).
  - With the threat of climate change and the need to adapt to its adverse effects, indigenous communities are proving to be an important source of climate history and baseline data and are already playing a valuable role by providing local-scale expertise, monitoring impacts, and implementing adaptive responses at the local level. For example, on-farm conservation of crops is a dynamic process, in which varieties managed by indigenous farmers continue to evolve in response to natural and human selection, leading to crops with better adaptive potential. For instance, "kreb" is a mixture of wild and

cultivated species (such as Digitaria exilis or “fonio”) that is traditionally used in the Sahel by pastoralists. The latter harvest these seeds from the open grasslands and manage the wild species to ensure sustainable seed production for human consumption and fodder (Chianese n.d.).
- Rapid dietary change in indigenous peoples worldwide is posing threats to the use of traditional food and the traditional knowledge required for traditional food system maintenance (Kuhnlein and Receveur 1996). Several foods and combinations have illustrated the potential to decrease risk of micronutrient deficiencies (Kuhnlein 2004). Such traditions may be fundamental for slowing the nutrition transition and the accompanying increase in preventable diet-related non-communicable diseases.

References

ACAPS (2017) Famine: Northeast Nigeria, Somalia, South Sudan, and Yemen. https://reliefweb.int/sites/reliefweb.int/files/resources/20170522_acaps_famine_theme_final_report.pdf. Accessed 29 Nov 2020

Acemoglu D, Robinson JA (2002) The political economy of the Kuznets curve. Rev Dev Econ 6: 183–203

Adepoju A (2002) Fostering free movement of persons in West Africa: achievements, constraints, and prospects for intraregional migration. Int Migr 40:3–28

Alesina (1996) Income distribution, political instability, and investment. Eur Econ Rev 40:1203–1228

Allen S, Badiane O, Sene L, Ulimwengu J (2014) Government expenditures, health outcomes and marginal productivity of agricultural inputs: the case of Tanzania. J Agric Econ 65:637–662

Ambler K, de Brauw A, Godlonton S (2018) Agriculture support services in Malawi: direct effects, complementarities, and time dynamics. International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/1037800842

Areal FJ, Riesgo L, Rodríguez-Cerezo E (2013) Economic and agronomic impact of commercialized GM crops: a meta-analysis. J Agric Sci 151:7–33

Asogwa IS, Okoye JI, Oni K (2017) Promotion of indigenous Food preservation and processing knowledge and the challenge of food security in Africa. J Food Secur 5:75–87

Badiane O, Collins J. AKADEMIYA2063’s Multi-Workstream Agenda on Covid-19. AKADEMIYA2063 Covid-19 Bulletin No. 1, July. AKADEMIYA2063, Kigali, 2020

Badiane O, Makombe T (2015) Beyond a middle income Africa: transforming African economies for sustained growth with rising employment and incomes. https://doi.org/10.2499/9780896298927

Badiane O, Odjo S (2016) Regional trade and volatility in staple food markets in Africa. In: Food price volatility and its implications for food security and policy. Springer Open, pp 385–412

Badiane O, Ulimwengu JM (2013) Malaria incidence and agricultural efficiency in Uganda. https://doi.org/10.1111/j.1574-0862.2012.00626.x

Barrett CB (2020) Actions now can curb food systems fallout from COVID-19. Nat Food 1:319–320

Batal M, Decelles S (2019) A scoping review of obesity among indigenous peoples in Canada. J Obes 2019. https://doi.org/10.1155/2019/9741090

Baumüller H (2018) The little we know: an exploratory literature review on the utility of mobile phone-enabled services for smallholder farmers. J Int Dev 30:134–154

Bindoff NL, Cheung WWL, Kairo JG, et al (2019) Changing ocean, marine ecosystems, and dependent communities. In: IPCC special report on the ocean and cryosphere in a changing climate

Blanchet R, Willows N, Johnson S et al (2020) Traditional food, health, and diet quality in syilx okanagan adults in British Columbia, Canada. Nutrients:12. https://doi.org/10.3390/nu12040927
Boardman J, Poesen J (2006) Soil Erosion in Europe: major processes, causes and consequences. Soil erosion in Europe. Wiley, pp 477–487
Bonny S (2017) Corporate concentration and technological change in the global seed industry. Sustainability 9:1632
Boosting growth to end hunger by 2025: the role of social protection. ReSAKSS Annual Trends and Outlook Report 2017–2018. IFPRI, Washington, DC, 2018. https://doi.org/10.2499/9780896295988
Borrelli P, Robinson DA, Fleischer LR et al (2017) An assessment of the global impact of 21st century land use change on soil erosion. Nat Commun 8:1–13
Bouët A, Odjo SP, Zaki C (2020) Africa agriculture trade monitor 2020. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896293908
Bourguignon F, Dessus S (2009) Equity and development: political economy considerations
Bron GM, Siebenga JJ, Fresco LO (2021) In the age of pandemics, connection food systems and health: a global one health approach. Food Systems Summit Brief prepared by Research Parners of the Scientific Group of the Food Systems Summit
Carletto G, Ruel M, Winters P, Zezza A (2015) Farm-level pathways to improved nutritional status: introduction to the special issue. J Dev Stud 51:945–957
Caron P, Valette E, Wassenaar T, Coppens G, d'Eeckenbrugge G, Papazian V (2017) Living territories to transform the world. Quae, Paris. https://doi.org/10.35690/978-2-7592-2731-0
Chianese F The traditional knowledge advantage: indigenous peoples' knowledge in climate change adaptation and mitigation strategies. IFAD, Rome
Cotula L, Food and Agriculture Organization of the United Nations (2008) The right to food and access to natural resources using human rights arguments and mechanisms to improve resource access for the rural poor. FAO, Rome
Cree Hunters and Trappers Income Security Board. http://www.chtisb.ca/program/. Accessed 22 Mar 2021
De Pinto A, Ulimwengu JM (2017) A thriving agricultural sector in a changing climate: meeting Malabo declaration goals through climate-smart agriculture 2017. https://doi.org/10.2499/9780896292949
de Pryck JD, Termine P (2014) Gender inequalities in rural labor markets. Gender in Agriculture 343–70
Deaconu A, Mercille G, Batal M (2019) The agroecological farmer's pathways from agriculture to nutrition: a practice-based case from Ecuador's highlands. Ecol Food Nutr 58:142–165
Deichmann U, Goyal A, Mishra D (2016) Will digital technologies transform agriculture in developing countries? Agric Econ 47:21–33
Desmarais AA, Wittman H (2014) Farmers, foodies and first nations: getting to food sovereignty in Canada. J Peasant Stud 41:1153–1173
Dinesh D, Campbell BM, Bonilla-Findji O, Richards M (2017) 10 best get innovations for adaptation in agriculture: a supplement to the UNFCCC NAP technical guidelines. CGIAR Research Program on Climate change, Agriculture and Food Security (CCAFS), Wageningen, The Netherlands. www.ccafs.cgiar.org
Domingo A, Spiegel J, Guhn M, et al (2020) Predictors of household food insecurity and relationship with obesity in First Nations communities in British Columbia, Manitoba, Alberta and Ontario. Public Health Nutrition 1–13
Dury S, Alpha A, Bichard A (2015) The negative side of the agricultural-nutrition impact pathways: a literature review. World Food Policy 2:78–100
Dutt P, Mitra D (2008) Inequality and the instability of polity and policy*. Econ J 118:1285–1314
Dyson T (2011) The role of the demographic transition in the process of urbanization on JSTOR. Population and Development Review, Population Council 37:34–54

Falkenmark M (1997) Meeting water requirements of an expanding world population. Philos Trans R Soc London Ser B Biol Sci; published online July 29. https://doi.org/10.1098/rstb.1997.0072
Fanzo JC, Downs S, Marshall QE, de Pee S, Bloem MW (2017) Value chain focus on Food and nutrition security. In: de Pee S, Taren D, Bloem M (eds) Nutrition and health in a developing world. Humana Press, Cham, pp 753–770
Fanzo J, Haddad L, McLaren R et al (2020) The food systems dashboard is a new tool to inform better food policy. Nat Food 1:243–246
FAO (2016) Developing gender-equitable legal frameworks for land tenure. A legal assessment tool. FAO
FAO (2018) Impacts of climate change on fisheries and aquaculture. Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper 627
FAO Dimitra project: Gender, rural women and development. http://www.fao.org/dimitra/about-dimitra/en/. Accessed 20 Mar 2021
FAO, IFAD, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world 2020. Rome, FAO. https://doi.org/10.4060/ca9692en
Feenstra RC, Hanson GH (1996) Globalization, outsourcing, and wage inequality. National Bureau of Economic Research. https://doi.org/10.3386/w5424
Feenstra RC, Hanson GH (2008) Global production sharing and rising inequality: a survey of trade and wages. In: Handbook of international trade. Wiley, pp 146–185
Fei S, Ni J, Santini G (2020) Local food systems and COVID-19: an insight from China. Resour Conserv Recycl 162:105022
Fofana I, Sall LM (2020) Impact of trade shocks on growth and poverty in selected countries. Covid-19 Bulletin No. 13, November. AKADEMIYA2063, Kigali
Food and Agriculture Organization of the United Nations, editor. The future of food and agriculture: trends and challenges. Rome: Food and Agriculture Organization of the United Nations, 2017
Food Systems Dashboard - Diets and Nutrition. Food Systems Dashboard. https://foodsystemsdashboard.org/. Accessed 22 Mar 2021
Gamlen A (2020) Migration and mobility after the 2020 pandemic: the end of an age? International Organization for Migration (IOM), Geneva
Glenna LL, Cahoy DR (2009) Agribusiness concentration, intellectual property, and the prospects for rural economic benefits from the emerging biofuel economy. South Rural Sociol 24:111–129
González H. Specialization on a global scale and agrifood vulnerability: 30 years of export agriculture in Mexico. Development Studies Research An Open Access Journal 2014; published online Oct 15. https://www.tandfonline.com/doi/abs/10.1080/21665095.2014.929973. Accessed 16 Mar 2021
Gray C (2009) Environment, land, and rural out-migration in the southern Ecuadorian Andes. World Dev 37:457–468
Greenville J, Kawasaki K, Jouanjean M-A (2019a) Dynamic changes and effects of agro-food GVCS. OECD Publishing, Paris. https://doi.org/10.1787/43b7bcec-en
Greenville J, Kawasaki K, Flaig D, Carrico C (2019b) Influencing GVCs through agro-food policy and reform. OECD Publishing, Paris. https://doi.org/10.1787/9ce888e0-en
Grey S, Patel R (2014) Food sovereignty as decolonization: some contributions from indigenous movements to food system and development politics. Agric Hum Values 32:431–444
Gustafson S (2018) The Global Food System and Employment | Food Security Portal. Published online Feb 13. https://www.foodsecurityportal.org/blog/global-food-system-and-employment. Accessed 14 Mar 2021
Guthiga P, Kirui L, Karugia J (2020) The impact of the COVID-19 pandemic on staples food prices in local markets: The case of cooking banana (‘Matooke’) in Uganda. Covid-19 Bulletin No. 12, October. AKADEMIYA2063, Kigali
HarvestPlus (2018) Catalyzing Biofortified Food Systems: 2018 Annual Report. Washington, DC: HarvestPlus. https://www.harvestplus.org/sites/default/files/publications/153613_HarvestPlus_AR_2018_Proof.pdf. Accessed 9 Mar 2021

Hatab AA, Lagerkvist C-J, Esmat A (2021) Risk perception and determinants in small- and medium-sized agri-food enterprises amidst the COVID-19 pandemic: evidence from Egypt. Agribusiness 37:187–212
Headey D, Heidkamp R, Osendarp S et al (2020) Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. Lancet 396:519–521
Heinemann JA, Massaro M, Coray DS, Agapito-Tenfen SZ, Wen JD (2014) Sustainability and innovation in staple crop production in the US Midwest. Int J Agric Sustain 12:71–88
HLPE (2012) Social protection for food security. A report of the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome
HLPE (2014) Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome
HLPE (2017) Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome
HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome
HLPE (2020) Food security and nutrition: building a global narrative towards 2030. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security
Hobbs JE (2020) Food supply chains during the COVID-19 pandemic. Can J Agric Econ/Revue canadienne d'agroeconomie 68:171–176
Huang J, Rozelle S, Pray C, Wang Q (2002) Plant biotechnology in China. Science 295:674–676
Hueston W, McLeod A (2012) Overview of the global food system: changes over time/space and lessons for future food security. In: Improving food safety through a one health approach: workshop summary. National Academies Press (US), Washington, DC
IFPRI (2019) Global Food Policy Report. International Food Policy Research Institute. Washington, DC. https://doi.org/10.2499/9780896293502
IMF (2015) International monetary fund annual report 2015. International Monetary Fund, Washington, DC
Independent Evaluation Group (IEG) (2014) The World Bank Group and the Global Food Crisis: an evaluation of the World Bank Group response. The World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-0091-7
International Fund for Agricultural Development (2016) Rural development: report 2016: fostering inclusive rural transformation. IFAD, Roma
International Labour Organization (2020) Protecting migrant workers during the COVID-19 pandemic. Recommendations for policy-makers and Constituents
International Monetary Fund (2014) Fiscal policy and income inequality. Policy Papers 14. https://doi.org/10.5089/9781498343671.007
IPCC (2020) Special report on climate change and land. An IPCC special report on climate change, desertification, land degradation, sustainable land managmenet, food security, and greenhouse has fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change
IPCC. Sixth Assessment Report — IPCC. https://www.ipcc.ch/assessment-report/ar6/. Accessed 14 Mar 2021
IWGIA, ILO (2020) The impact of COVID-19 on indigenous communities: Insights from the Indigenous Navigator. The International Working Grioup for Indigenous Affairs, and the International Labour Organization
Jayne T, Chamberlin J, Headey D (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: a synthesis. Food Policy 48:1–17
Jribi S, Ismail HB, Doggui D, Debbabi H (2020) COVID-19 virus outbreak lockdown: what impacts on household food wastage? Environ Dev Sustain 22:3939–3955
Kathage J, Qaim M (2012) Economic impacts and impact dynamics of Bt (Bacillus thuringiensis) cotton in India. PNAS 109:11652–11656

King R (1977) Land reform: a world survey. Routledge
Kloppenburg J (2010) Impeding dispossession, enabling repossession: biological open source and the recovery of seed sovereignty. J Agrar Chang 10:367–388
Knippenberg E, Hoddinott J (2017) Shocks, social protection, and resilience: evidence from Ethiopia. IFPRI, Ethiopian Development Research Institute (EDRI), Ethiopia
Kuhnlein HV (2004) Karat, Pulque, and Gac: three shining stars in the traditional food galaxy. Nutr Rev 62:439–442
Kuhnlein HV, Receveur O (1996) Dietary change and traditional food systems of indigenous peoples. Annu Rev Nutr 16:417–442
Kurashima N, Fortini L, Ticktin T (2019) The potential of indigenous agricultural food production under climate change in Hawai'i. Nat Sustain 2:191–199
Land Matrix. https://landmatrix.org/. Accessed 22 Mar 2021
Lastarria-Cornhiel S (2008) Feminization of agriculture: trends and driving forces. Background paper for the World Development Report, Washington, DC
Latour B (1987) Science in action: how to follow scientists and engineers through society. Harvard University Press, Boston
Levy S (2006) Progress against poverty: sustaining Mexico's Progresa-Oportunidades program. Brookings Institution Press, Washington, DC
Liverpool-Tasie LSO, Reardon T, Belton B (2021) "Essential non-essentials": COVID-19 policy missteps in Nigeria rooted in persistent myths about African food supply chains. Appl Econ Perspect Policy 43:205–224
Loboguerrero AM, Campbell BM, Cooper PJM, Hansen JW, Rosenstock T, Wollenberg E (2019) Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. Sustainability 11:1372
Losch B, Freguin-Gresh S, White ET (2012) Structural transformation and rural change revisited – challenges for late developing countries in a globalizing world. World Bank, Washington, DC
Lowder SK, Bertini R, Karfakis P, Croppenstedt A. Transformation in the size and distribution of farmland operated by household and other farms in select countries of sub-Saharan Africa. 2016 Fifth International Conference, September 23–26, 2016, Addis Ababa, Ethiopia 2016; published online Sept. https://ideas.repec.org/p/ags/aaae16/246969.html. Accessed 25 Oct 2020
Lugo-Morin DR (2020) Indigenous communities and their food systems: a contribution to the current debate. J Ethn Food 7:6
Ly R, Dia K, Diallo M, Ahid M, Ceesay B. 2020 Pearl millet production forecasts for selected west African countries: Côte d'Ivoire, Mali, Burkina Faso, Sierra Leone, The Gambia, and Senegal. Covid-19 Bulletin No. 14, December. AKADEMIYA2063, Kigali
Mabhaudhi T, Chibarabada TP, Chimonyo VGP et al (2018) Mainstreaming underutilized indigenous and traditional crops into Food systems: a South African perspective. Sustainability 11:1–22
Marschke M, Vandergeest P, Havice E et al (2021) COVID-19, instability and migrant fish workers in Asia. Maritime Stud 20:87–99
Mascarenhas M, Busch L (2006) Seeds of change: intellectual property rights, genetically modified soybeans and seed saving in the United States. Sociol Rural 46:122–138
Matchaya G, Nhlengethwa S, Fakudze B, Greffiths J (2020) Maize grain price trends in food surplus and deficit areas of Mozambique under Covid-19. Covid-19 Bulletin No. 7, September. AKADEMIYA2063, Kigali
McMullin S, Njogu K, Wekesa B et al (2019) Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. Food Secur 11:1355–1372
Menashe-Oren A, Stecklov G (2018) Rural/urban population age and sex composition in sub-Saharan Africa 1980–2015. Popul Dev Rev 44:7–35
Ministerio de Salud Pública del Ecuador, FAO (2021) Guías Alimentarias del Ecuador. FAO, Quito. https://doi.org/10.4060/ca9928es

Molden D, Burton M, Bos MG (2007) Performance assessment, irrigation service delivery and poverty reduction: benefits of improved system management. Irrig Drain 56:307–320
Mosby I, Galloway T (2017) “Hunger was never absent”: how residential school diets shaped current patterns of diabetes among indigenous peoples in Canada. CMAJ 189:E1043–E1045
Munasinghe M (2020) Development, equity and sustainability (DES) in the context of climate change. In: Pichs R, Swart R, Leary N, Ormond F (eds) Development, sustainability and equity. Intergovernmental Panel on Climate Change, Geneva
Neufeld LM, Hendriks S, Hugas M. Healthy diet: a definition for the United Nations Food systems summit. 2021
Nordhagen S, Condes S. Supporting gender-equitable food systems through access to finance for small- and medium-sized companies. Geneva, Switzerland: Global Alliance for Improved Nutrition (GAIN), 2020
O’Neal M, Nearing M, Vining R, Southworth J, Pfeifer R (2005) Climate change impacts on soil erosion in midwest United States with changes in crop management. Catena 61:165–184
Obodai M, Uduro-Yeboah C, Amoa-Awua W et al (2015) Kenkey production, vending, and consumption practices in Ghana. Food Chain 4:275–288
OECD (2019a) Innovation, productivity and sustainability in food and agriculture: Main findings from country reviews and policy lessons. OECD Publishing, OECD Food and Agricultural Reviews. Paris. https://doi.org/10.1787/c9c4ec1d-en
OECD (2019b) Linking indigenous communities with regional development. OECD Publishing, Paris. https://doi.org/10.1787/3203c082-en
OECD (2020a) Rural well-being: geography of opportunities. OECD Publishing, Paris. https://doi.org/10.1787/d25cef80-en
OECD (2020b) Global value chains in agriculture and food: a synthesis of OECD analysis. OECD Publishing
OECD (2020) Food supply chains and COVID-19: impacts and policy lessons. http://www.oecd.org/coronavirus. Accessed 9 Mar 2021
Office of the Special Adviser on Africa (OSAA). https://www.un.org/en/africa/osaa/. Accessed 22 Mar 2021
Okanagan Nation Alliance – ałi kwu_swiwi-numtax, ałi kwu_suknaqinx, ałi axa/ L/tmxwula/xw. https://www.syilx.org/. Accessed 22 Mar 2021
Oya C (2012) Contract farming in sub-Saharan Africa: a survey of approaches, debates and issues. J Agrar Chang 12:1–33
Pew Research Center (2016) Smartphone ownership and internet usage continues to climb in emerging economies. https://www.pewresearch.org/global/2016/02/22/smartphone-ownership-and-internet-usage-continues-to-climb-in-emerging-economies/
Pingali PL (2012) Green revolution: impacts, limits, and the path ahead. Proc Natl Acad Sci U S A 109:12302
Pintado A, Monteiro M, Talon R et al (2016) Consumer acceptance and sensory profiling of reengineered kitoza products. Food Chem 198:75–84
Popkin BM, Reardon T (2018) Obesity and the food system transformation in Latin America. Obes Rev 19:1028–1064
Putnam P (2000) Bowling alone: The collapse and revival of American community. Simon & Schuster Paperbacks, New York
Qiang CZ, Kuek SC, Dymond A, Esselaar S (2012) Mobile applications for agriculture and rural development. ICT Sector Unit, World Bank, Washington, DC
Qiao F, Huang J, Wang X (2017) Fifteen years of Bt cotton in China: results from household surveys. World Dev 98:351–359
Quisumbing AR, Meinzen-Dick RS, Njuki J (2019) Annual trends and outlook report: Gender equality in rural Africa: From commitments to outcomes. https://doi.org/10.2499/9780896293649

Reardon. Transformation of African Agrifood Systems in the New Era of Rapid Urbanization and the Emergence of a Middle Class. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/130005. Accessed 25 Oct 2020
Resnick D. 16. COVID-19 lockdowns threaten Africa's vital informal urban food trade. 2
Rodríguez-Pose A, Ezcurra R (2011) Is fiscal decentralization harmful for economic growth? Evidence from the OECD countries. J Econ Geogr 11:619–643
Rogers V, Meara P, Barnett-Legh T, Curry C, Davie E (2017) Examining the LLAMA aptitude tests. J Eur Second Language Assoc 1:49–60
Salemink K, Strijker D, Bosworth G (2017) Rural development in the digital age: a systematic literature review on unequal ICT availability, adoption, and use in rural areas. J Rural Stud 54: 360–371
Samberg L (2021) How new technology could help to strengthen global good security. World Economic Forum https://www.weforum.org/agenda/2018/03/food-security-s-social-network/. Accessed 15 Mar 2021
Sandrasekaran M, Kasthuri T, Singh KO (2017) Soil and water conservation in India: strategies and research challenges-Indian journals. J Soil Water Conserv 16:312–319
Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. PNAS 103:13116–13120
Sherwood S (2019) Strengthening impact of the healthy food consumption campaign: 250,000 families in Ecuador. https://idl-bnc-idrc.dspacedirect.org/handle/10625/59373
Sherwood S, Arce A, Paredes M (eds) (2017) Food, agriculture and social change. The everyday vitality of Latin America. Routledge, London. https://doi.org/10.4324/9781315440088
Sonobe T, Otsuka K (2011) Cluster-based industrial development a comparative study of Asia and Africa United Kingdom: Palgrave Macmillan. https://doi.org/10.1057/9780230295124
Sonobe T, Jin K, Otsuka K (2020) Applying the Kaizen in Africa. Saint Philip Street Press
Stephens C, Nettleton C, Porter J, Willis R, Clark S (2005) Indigenous peoples' health—why are they behind everyone, everywhere? Lancet 366:10–13
Sullivan C, Meigh J (2003) Considering the water poverty index in the context of poverty alleviation. Water Policy 5:513–528
Théodore FL, Bonvecchio Arenas A, García-Guerra A et al (2019) Sociocultural influences on poor nutrition and program utilization of Mexico's conditional cash transfer program. J Nutr 149: 2290S–2301S
Thiele H. Deula: presentation of our Institution. https://www.deula.de/fileadmin/Redakteure/Witzenhausen/Presentation_institution.pdf. Accessed 22 Mar 2021
Tschirley DL, Snyder J, Dolislager M et al (2015) Africa's unfolding diet transformation: implications for agrifood system employment. J Agribusiness Dev Emerg Econ 5:102–136
Ulimwengu J, Badiane O (2010) Vocational training and agricultural productivity: Evidence from Rice production in Vietnam. J Agric Educ Ext 16:399–411
Ulimwengu JM, Collins J (2020) Assessing community vulnerability to Covid-19 in the Sahel Covid-19 Bulletin No. 10, October. AKADEMIYA2063, Kigali
Ulimwengu J, Magne-Domgho L (2020) Impact of COVID-19 on hidden hunger in Senegal. Covid-19 Bulletin No. 8, August. AKADEMIYA2063, Kigali
Ulimwengu JM, Matchaya G, Makombe T, Oehmke JF (2020) Mutual accountability in African agricultural transformation. In: Resnick D, Diao X, Tadesse G (eds) ReSAKSS annual trends and outlook report. International Food Policy Research Institute (IFPRI) and AKADEMIYA2063, Washington, DC and Kigali, pp 182–194
UN. Universal Declaration of Human Rights. 1948. https://www.ohchr.org/EN/UDHR/Documents/UDHR_Translations/eng.pdf
UNDESA World Social Report | DISD. https://www.un.org/development/desa/dspd/world-social-report.html. Accessed 25 Oct 2020
UNICEF (2019) Every Child Learns. UNICEF Education Strategy 2019–2030. UNICEF, New York

United Nations (ed) (2001) Replacement migration: is it a solution to declining and ageing populations? United Nations, New York

Valeggia CR, Snodgrass JJ (2015) Health of indigenous peoples. Annu Rev Anthropol 44:117–135

Vandergeten E, Azadi H, Teklemariam D, Nyssen J, Witlox F, Vanhaute E (2016) Agricultural outsourcing or land grabbing: a meta-analysis. Landsc Ecol 31:1395–1417

Vernon RV (2015) A native perspective: food is more than consumption. *1* 2015; 5: 137–42

Vesper I (2021) Evidence patchy on value of mobile apps for farmers. SciDev.Net. https://www.scidev.net/global/news/evidence-patchy-on-value-of-mobile-apps-for-farmers/. Accessed 9 Mar2021

Vognan G, Fok M (2019) Performance différenciée du coton Bt en début de diffusion : cas du Burkina Faso. Cah Agric 28:26

von Braun J, Afsana K, Fresco L, Hassan M, Terero M. Food systems – definition, concept and application for the UN food systems summit. A paper from the Scientific Group of the UN Food Sysetms Summit 2021. https://sc-fss2021.org/wp-content/uploads/2021/03/ScGroup_Food_Systems_paper_March-5-2021.pdf. Accessed 9 Mar 2021

World Bank (2007) World development report 2008. Washington, DC. https://doi.org/10.1596/978-0-8213-6807-7

World Bank. World development report 2016: digital dividends | world development report. 2016

Wouterse F, Badiane O (2019) The role of health, experience, and educational attainment in agricultural production: evidence from smallholders in Burkina Faso. Agric Econ 50:421–434

A Review of Evidence on Gender Equality, Women's Empowerment, and Food Systems

Jemimah Njuki, Sarah Eissler, Hazel Malapit, Ruth Meinzen-Dick, Elizabeth Bryan, and Agnes Quisumbing

1 Introduction

Women are key actors in food systems as producers, wage workers, processors, traders, and consumers. They do this work despite many constraints and limitations, including lower access to opportunities, technologies, finance and other productive resources, and weak tenure and resource rights. These constraints and limitations are shaped and reinforced by social and structural inequalities in food systems. Stark gender inequalities are both a cause and outcome of unsustainable food systems and unjust food access, consumption and production. In the agriculture sector, for example, evidence shows that women have unequal access, and, in some cases, unequal rights, to important resources, such as land, water, pasture, seeds, fertilizers, chemical inputs, technology and information, and extension and advisory services, all of which reduces their potential to be productive in agriculture, become empowered to make strategic decisions and act on those decisions, and realize their rights (Doss 2018; Meinzen-Dick et al. 2019a, b; Mulema and Damtew 2016; Madzorera and Fawzi 2020). In addition, compared with men, women are more vulnerable to chronic food and nutrition insecurity, as well as shock-induced food insecurity (Madzorera and Fawzi 2020; Theis et al. 2019).

J. Njuki (✉)
International Food Policy Research Institute, Africa Regional Office c/o ILRI Nairobi, Nairobi, Kenya
e-mail: jemimah.njuki@gmail.com

S. Eissler
Independent Consultant, Nairobi, Kenya

H. Malapit · R. Meinzen-Dick · E. Bryan · A. Quisumbing
International Food Policy Research Institute, Washington, DC, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_9

2 Conceptual Framing

We conceptualize gender as an important lever for progress across all aspects of food systems (Fig. 1) and draw upon key terms and definitions of women's empowerment, women's economic empowerment, and gender-transformative approaches (see definitions in Annex). Food system drivers are anchored in a gendered system with structural gender inequalities and are shaped by shocks and vulnerabilities that affect men and women in different ways. Structural gender inequalities and gendered shocks and vulnerabilities thus influence the ways in which men and women experience these drivers of food systems, which, in turn, shape the three main components of food systems: value chains, the food environment, and consumer behavior.

This conceptualization of gender in food systems recognizes and highlights the linkages and interconnectedness across these three components. For example, strengthened access to nutritious foods (food environment) is an important source and pathway to strengthening individual and household resilience (drivers), particularly as adverse effects of climate change will continue to negatively influence access to and consumption of diverse nutrient-rich foods (Fanzo et al. 2018; Theis et al. 2019). And, as food systems are both contributors to and impacted by climate change, nature-positive production schemes (production), such as sustainable agricultural intensification strategies, enable food systems to reduce their contribution to

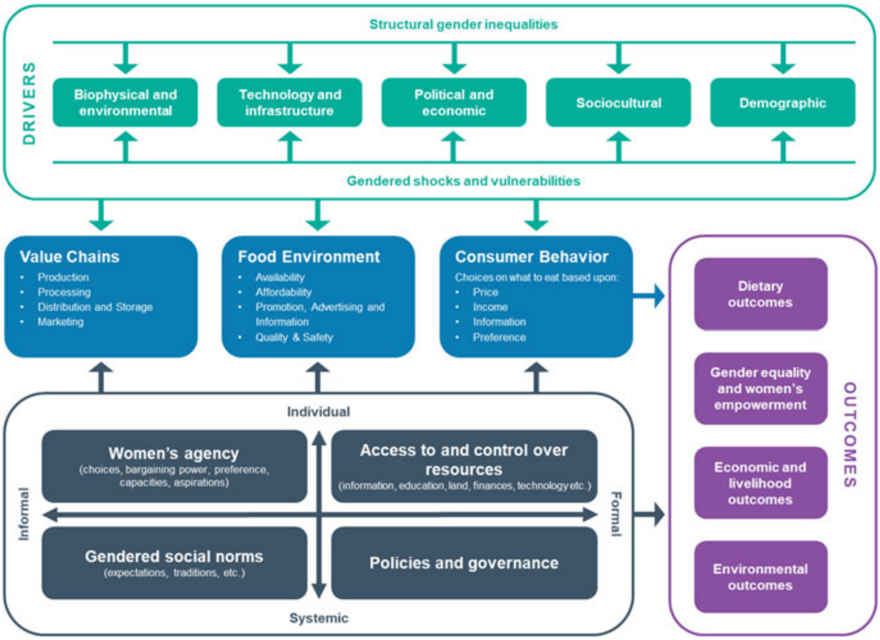


Fig. 1 Gendered food systems. (Source: Adapted from de Brauw et al. 2019)

and mitigate the impacts of climate change, thus strengthening resilience (drivers) (Campbell et al. 2014).

These three components of the food system interact with gender equality/inequality in a four-dimensional space: individual and systemic, formal and informal. Transforming food systems in equitable ways requires changes in gender equality at the individual and systemic levels and at the formal and informal levels. Changes must occur in: women's and men's consciousness, capacity, behavior and awareness (individual; informal); access to resources, services and opportunities (individual, formal); informal and implicit cultural norms, deep structure and the social values that undergird the way in which institutions operate(informal, systemic); and in formal policies, laws, and institutional arrangements (formal, systemic) in place to protect against social and gender discrimination and advance equality (Gender at Work n.d.). Change must go beyond simply reaching women through interventions, and requires facilitating the empowerment process so that women can benefit from food system activities (namely, increasing wellbeing, food security, income, and health) and can make and act upon strategic life decisions within food systems.[1] Women's agency, differences in access to and control over resources, gendered social norms, and existing policies and governance influence how men and women can participate in and benefit from food systems, leading to differences in overall outcomes (Fig. 1).

3 Methodology

This chapter uses a scoping review (Harris et al. 2021; Liverpool-Tasie et al. 2020) to assess the current evidence on gender issues in food systems. Given the broad range of key topics related to gender in food systems, topically relevant and published systematic reviews were purposively sampled to provide a baseline state of the evidence. After purposively sampling and identifying 16 systematic and scoping reviews to inform the baseline, additional articles were collected. Three databases (Google Scholar, ScienceDirect, and IFPRI's Ebrary) were used to gather and collect additional articles using key word searches aligned with 42 unique terms cross-referenced with the terms "gender" and "women." A total of 198 articles were selected from these databases for review after meeting the following inclusion criteria: the articles had to be empirical and peer-reviewed, published in English, and have a geographic focus in low- or middle-income countries (LMICs). The article also had to make an explicit reference to gender or women's empowerment *and* the key thematic term. For articles meeting these initial criteria, additional criteria were used to exclude some from the review, including if the methodology was inadequate to account for biases, or if the article was not relevant to agriculture or food systems. Duplicate articles from across the searches were eliminated from

[1] See Johnson et al. (2018) for a discussion of the Reach-Benefit-Empowerment framework.

the database. Finally, additional articles were identified for inclusion from the citations in the articles collected above. All collected articles were managed in Zotero reference manager software.[2]

4 Findings

This section presents the main findings of evidence relevant to the components of the gendered food system conceptual framework (Fig. 1): drivers and cross-cutting levers, shocks and stressors, food and value chains, food environment, consumer behavior, and outcomes.

In general, the evidence reveals that women are important actors and contributors to food systems, but their contributions are typically undervalued, unpaid, or overlooked in food systems research. A 2021 map of food systems and nutrition evidence from the International Initiative for Impact Evaluation (3ie) indicates that, although women have a major role in food systems, relatively few studies have examined strategies for or the effectiveness of interventions aimed at improving women's decision-making power or have measured outcomes related to empowerment (Moore et al. 2021). Many food system interventions have not collected evidence regarding gender, an oversight that may result in poor outcomes or the inefficient use of funds to improve food systems (Moore et al. 2021).

Overall, the literature is largely in agreement as to how to advance gender equality and women's empowerment in food systems, but offers little evidence on causal pathways or mechanisms (Moore et al. 2021). The existing evidence, in general, offers locally or contextually specific findings; limited evidence exists that applies across contexts or at a geographic scale.[3]

4.1 Drivers: Shocks and Stressors

Men and women are differently exposed and vulnerable to shock and stress events. As a result of social norms and differing access to important resources, men and women have different capacities to mitigate risk and respond to these events (Mahajan 2017; Codjoe et al. 2012). The types of capacities needed include absorptive, adaptive, and transformative capacities, which are built by developing and

[2] All articles reviewed for this paper are compiled in a separate Excel database, with the following metrics collected for each article: author(s) name, article title, year published, journal or organization of publication, national focus (if specified), regional focus, methods used, and main finding(s). Additional information on the search methods and articles selected are included in the full review paper (citation forthcoming).

[3] The findings presented in this paper are high-level. A further, more nuanced explanation of the findings can be found in the full review paper (citation forthcoming).

leveraging resources and networks to reduce the risk of adverse impacts and facilitate faster recovery from shock and stress events. Gendered impacts of shocks are nuanced, context-specific, and often unexpected (Quisumbing et al. 2018; Rakib and Matz 2014; Nielsen and Reenberg 2010). Gendered perceptions of climate change and ensuing effects are based on livelihood activities and household and community roles and responsibilities, and often influence how men and women can leverage adaptation strategies to respond (Quisumbing et al. 2018; Aberman et al. 2015; Nielsen and Reenberg 2010).

Many studies indicate that gender-differentiated access to or ownership of important resources—such as women having fewer assets and lacking access to information services or credit—is linked to different capacities to mitigate, adapt to, and recover from shock and stress events (Bryan et al. 2013; de Pinto et al. 2020; Fisher and Carr 2015). However, women's participation in collaborative farming schemes or group networks facilitates broader access to resources and additional social networks and types of social capital, which strengthen women's capacity to respond to these events (Vibert 2016). For example, participation in community groups and access to credit options in Mali have been positively associated with an uptake in climate-smart agriculture practices and technologies (Ouédraogo et al. 2019).

Women have fewer adaptation options than men, as social norms restrict women's mobility, freedom of movement, and access to transportation, as do time burdens associated with domestic and care responsibilities (Jost et al. 2016; Naab and Koranteng 2012; de Pinto et al. 2020). However, de Pinto et al. (2020) note evidence that certain components of women's empowerment led to increased crop diversification among small-scale agricultural producers in Bangladesh, suggesting that women do play an important and positive role in climate change adaptation. Access to context-specific and relevant climate information and appropriate technologies is a key determinant of adopting climate change adaptation practices, and women and men have different needs for and access to such information (see section below on Gendered Access to Services and Technology) (Bryan et al. 2013; Tambo and Abdoulaye 2012; Twyman et al. 2014; Mudege et al. 2017).

4.2 Food System Components

4.2.1 Agrifood Value Chains

Women are actively engaged across various roles in agricultural value chains, although women's positions are typically undervalued and overlooked in food systems research (Doss 2013). In Ethiopia, Abate (2018) found that women were predominately responsible for storage preparation, post-harvest processing, milk processing, barn cleaning, care for newborn livestock, cooking, grinding, fetching, and collecting fuelwood, and worked with men to weed, harvest, thresh, and protect crops from wildlife. Qualitative evidence from Benin suggests that women are predominately engaged in agricultural processing activities and, if they have access to land, are also engaged in production activities (Eissler et al. 2021a). Studies from

Benin and Tanzania also found that, regardless of the producer, men manage higher-value sales and marketing, while women only manage the marketing and negotiation of small-value sales (Eissler et al. 2021a; Mwaseba and Kaarhus 2015). Gupta et al. (2017) provided evidence that improving women's market access is strongly correlated with increased levels of women's empowerment in India.

Agriculture both contributes to and is affected by anthropogenic climate change. As population pressures continue to increase and place demands on food production, agricultural livelihoods across agrifood value chains must adapt approaches that will sustainably meet rising demand, reduce risk associated with adverse climatic events, and mitigate contributions to climate change. Such approaches include sustainable intensification (Tilman et al. 2011; Rockström et al. 2017), conservation agriculture (Montt and Luu 2020), and climate-smart and climate-resilient agriculture (Gutierrez-Montes et al. 2020; Duffy et al. 2020), among others. A growing body of evidence indicates that women producers are less able to adopt such sustainable and resilient production practices or methods given their limited access to necessary resources, including land, time, labor, information, and technologies (Theriault et al. 2017; Ndiritu et al. 2014; Grabowski et al. 2020; Farnworth et al. 2016; Meinzen-Dick et al. 2019a, b; Doss et al. 2015; Perez et al. 2015; Pradhan et al. 2019; Parks et al. 2015; Ayantunde et al. 2020; Khoza et al. 2019; Gathala et al. 2021; Montt and Luu 2020; Beuchelt and Badstue 2013; Halbrendt et al. 2014).

4.2.2 Food Environment

Several themes emerge from the evidence linking gender equality and women's empowerment with improving the availability of and access to safe and nutritious food. First, the affordability of nutritious food is an important issue for accessing nutrient-rich foods to advance gender equality and women's empowerment. Available evidence indicates that women are less likely than men to be able to afford a nutritious diet, as women often occupy lower-paying wage positions than men, earn and control smaller incomes than men, have less autonomy over household financial decisions, or have no income at all. For example, Raghunathan et al. (2021) estimated that, while nutritious diets have become substantially more affordable for both female and male wage workers in rural India, unskilled wage workers still cannot afford a nutritious diet; unskilled workers account for approximately 80–90% of female and 50–60% of male daily wage workers, and care for 63–76% of poor rural children.

Another important theme is ensuring equitable access to markets where nutritious foods can be purchased. Nutrient-dense foods, such as fruit, milk and vegetables, are difficult to transport and store, and therefore must be purchased locally, particularly in remote and rural areas (Hoddinott et al. 2015; Mulmi et al. 2016). Several articles linked women's mobility and freedom of movement to market access, and thus to positive nutrition and food security outcomes. For example, Aryal et al. (2019) found that physical distance to markets impacted household food security outcomes for female-headed households more than for male-headed households in Bhutan.

Shroff et al. (2011) found women's low autonomy in mobility was positively associated with wasting in children in India. The evidence seems to associate women's limited mobility with stricter social gender norms and religion.

4.2.3 Consumer Behavior

Agriculture can influence diets and dietary choices through the consumption of household-produced crops or increased purchasing power derived from the sale of agricultural products. Moore et al. (2021) found that, in research carried out since 2000, women's roles in food systems have mostly been examined in terms of their role as consumers, such as household cooks, or as mothers who are breastfeeding or whose health affects that of their children. Other studies link gender norms, roles and responsibilities to women as food preparers and managers of the quality of household diets (Eissler et al. 2020a; Sraboni and Quisumbing 2018). Komatsu et al. (2018) found a positive association between the amount of time women spent on food preparation and household dietary diversity, and Chaturvedi et al. (2016) found a positive association between the time mothers spent with their children and nutrition status.

There is evidence showing positive effects of nutrition counseling, nutrition education, and maternal education for nutrition, dietary diversity, and health outcomes for women and children (Choudhury et al. 2020; Akter et al. 2020; Kimambo et al. 2018; Reinbott and Jordan 2016; Reinbott et al. 2016; Rakotomanana et al. 2020; Ragasa et al. 2019). Interventions for sustainable and nutritious diets are found to be more effective when they include components on nutrition and communication about health behavior change, women's empowerment, water, sanitation and hygiene (WASH), and micronutrient-fortified products (Ruel et al. 2018). Gelli et al. (2017) found preliminary evidence that WASH components of a nutrition-sensitive agriculture intervention in Burkina Faso may have mitigated the potential harm, such as the health risks, of introducing and enhancing small livestock production. However, more evidence is needed to understand the best practices for reducing potential harm of increased livestock production and management in nutrition-sensitive agricultural programs (Ruel et al. 2018).

4.3 Food System Outcomes

Recent research has examined the link between maternal mental health and psychosocial indicators and nutrition outcomes. There is mixed evidence regarding the link between maternal depression and mental health symptoms and child or household nutrition. Wemakor and Iddrisu (2018) found no association between maternal depression and child stunting in northern Ghana, whereas Wemakor and Mensah (2016) and Anato et al. (2020) found positive associations between women experiencing depressive symptoms and child undernutrition in Ghana and Ethiopia.

Wemakor and Mensah (2016) observed that women experiencing the highest levels of depression were also those with the lowest incomes or from the lowest-income households. Cetrone et al. (2020) found that food security improvements resulting from participation in a nutrition-sensitive agriculture program mediated women's depression symptoms in Tanzania. Such evidence, which is both mixed and limited, suggests that further studies are needed to understand the psychosocial impacts of women's empowerment and mental health on household nutrition and health outcomes.

Evidence links access to resources and empowerment to outcomes in nutrition and children's education. For example, evidence indicates that female livestock ownership or production diversity, combined with market access and women's empowerment, are important drivers of diverse household consumption and nutritional status (Sibhatu et al. 2015; Mulmi et al. 2016; Hoddinott et al. 2015). Additionally, Malapit et al. (2019) found in Bangladesh that, while gaps in parental empowerment had only weak associations with children's nutrition status, mother's empowerment is positively associated with girls' education and keeping older children in school in general.

A growing body of research has examined the pathways through which women's empowerment is linked with household nutrition outcomes and access to nutritious foods (Alaofè et al. 2017; Reinbott and Jordan 2016; Bellows et al. 2020; Malapit and Quisumbing 2015; Heckert et al. 2019; Lentz et al. 2019). These pathways are contextual and vary across countries and regions (Na et al. 2015; Ruel et al. 2018; Quisumbing et al. 2021). Ruel et al. (2018) observe that, while the current evidence broadly associates women's empowerment and nutrition outcomes, this evidence is generally context-specific, given that women's empowerment and gender roles and norms are closely linked. As more evidence is generated from cross-context evaluations, future research can create typologies to better explain how gender roles more broadly interact with nutrition-sensitive agricultural interventions (Ruel et al. 2018).

Specific to equitable livelihood outcomes, evidence indicates that women face disproportionate barriers in accessing finance and credit options compared with men (Adegbite and Machethe 2020; Ghosh and Vinod 2017; Dawood et al. 2019; Kabir et al. 2019). For example, Kabir et al. (2019) found that in Bangladesh, a lack of access to credit is the most significant barrier women producers faced, followed by a lack of need-based training, high interest rates, insufficient land access, and a lack of quality seeds. Women's ability to earn incomes and participate in income-generating activities is strongly mediated by restrictive gender norms, a lack of access to resources, and time burdens arising from normative roles and responsibilities. In a study of urban women vegetable traders in Viet Nam, Kawarazuka et al. (2017) found that women were able to work in less socially respected spaces, such as street trading, but still needed to negotiate their access to informal employment spaces with their husbands.

Supporting women's entrepreneurship is suggested as an important pathway to advancing gender equality and women's empowerment in food systems. Malapit et al. (2019) suggest that this is not necessarily the case if these businesses are small and home-based; such businesses typically make little profit and tend to add to women's existing time burdens. And in a systematic literature review, Wolf and Frese (2018) emphasized the need to recognize that spousal support is a key factor for women's entrepreneurship or engagement in income-generating activities.

5 Cross-Cutting Gender and Food System Issues

5.1 Gendered Social Norms and Expectations

Social and cultural norms shape and reinforce the ways in which women and men can participate in, access, and benefit from opportunities and resources (Kristjanson et al. 2017; Meinzen-Dick et al. 2019a, b; Rao et al. 2019; Moosa and Tuana 2014). This has important consequences across all aspects of advancing women's empowerment and gender equality in food systems. For example, norms can hinder women's ability to access or adopt new agricultural practices (Kiptot and Franzel 2012; Njuki et al. 2014). Importantly, gender norms vary within contexts, such as by religious identity or social class. Kruijssen et al. (2016) noted that different normative expectations of women in Hindu and Muslim communities in Bangladesh influenced the ways in which these women were constrained or enabled in participating in aquaculture value chains.

In general, women often experience restrictive social norms that hinder their empowerment and full participation in household or community activities and value chains (Huyer and Partey 2020; Kruijssen et al. 2018). In a review of evidence on gender issues in global aquaculture value chains, Kruijssen et al. (2018) found that contextual gender norms shape the ways in which women and men participate in aquaculture value chains around the world, often limiting women's ability to participate in and benefit from aquaculture value chains equally.

Social gender norms are contextually and culturally specific and are strongly linked to women's empowerment (Eissler et al. 2020a, b, 2021a; Meinzen-Dick et al. 2019a, b; Bryan and Garner 2020). Emic understandings of an empowered woman and an empowered man vary, but importantly inform the understanding of cultural nuances and expectations of the roles and responsibilities of women (Meinzen-Dick et al. 2019a, b; Bryan and Garner 2020). Men are generally considered to be the household financial providers and decision-makers, whereas women are responsible for domestic chores, childcare, food preparation, and other unpaid care tasks. In rural agricultural settings, women may also provide household labor on their husbands' agricultural plots in addition to their domestic work, yet are not remunerated for this labor (Picchioni et al. 2020; Nahusenay 2017; Ghosh and Chopra 2019). Recent evidence also suggests that patterns of male dominance in the household are linked to individuals' gender norms, but are not necessarily correlated with intergenerational transfers of male dominance in intrahousehold decision-making (Leight 2021).

5.2 Gendered Access to and Control over Resources, Services and Technology

A large body of literature has examined differences in men's and women's access to, ownership of, and control over resources in the food system (Johnson et al. 2016; Uduji et al. 2019; Perez et al. 2015; Gebre et al. 2019; Fisher and Carr 2015; Lambrecht and Mahrt 2019). Evidence indicates that perceived or effective ownership of resources may be more important than actual ownership for women's empowerment and nutrition outcomes (Eissler et al. 2020b). Studies have found positive associations between women's land ownership and their participation in community groups or co-operative networks, suggesting that access to important resources, such as land, facilitates access to other resources, such as increased bargaining power and pooled assets. Further evidence indicates that when women's previously less lucrative or lower-valued activities begin to rise in value or earn higher incomes, control over the activity or resource may be transferred from women to men (Mwaseba and Kaarhus 2015).

Existing literature shows that women face social, cultural and institutional barriers to accessing and adopting agricultural technologies, information and services (Peterman et al. 2014; Peterman et al. 2011; Perez et al. 2015; Mudege et al. 2017; Ragasa et al. 2013; de Pinto et al. 2020; Raghunathan et al. 2019; Duffy et al. 2020). Men and women have different needs for and access to such information and technologies; gender analyses are therefore needed to tailor communication strategies so as to ensure that information and dissemination are adequately targeted towards men and women (Tall et al. 2014; Peterman et al. 2014; Diouf et al. 2019; Ragasa et al. 2013; Jost et al. 2016; Mudege et al. 2017; Duffy et al. 2020). Women have access to disproportionately less information than men overall, but they have access to more information regarding certain topics relevant to their gender-normative roles and responsibilities, such as post-harvest handling and small livestock production (Twyman et al. 2014).

Gender-sensitive program designs that aim to increase access to technologies have positive impacts on women's nutrition and health outcomes (Kassie et al. 2020; Alaofè et al. 2016a, b, 2019). An evaluation of a gender-sensitive irrigation intervention in northern Benin found that women in the program had higher dietary diversity, increased intake of vegetables, reduced rates of anemia, higher body mass indexes (BMI), and improved household nutritional status through direct consumption as a result of women's increased crop diversification and increased income that allowed them to make economic decisions (Alaofè et al. 2016a, b, 2019).

Interventions to benefit or empower women may overlook the time trade-offs required for women's participation or for intended outcomes (Picchioni et al. 2020; Komatsu et al. 2018; van den Bold et al. 2021). Importantly, measuring time use itself does not address women's agency over said time use or the intrahousehold decision-making surrounding how and on what activities women may spend their time (Eissler et al. 2021b). There is little research to show how women can control their own time use or how interventions can support women in managing their own time to advance their strategic choices in food systems.

5.3 Women's Agency: Decision-Making and Leadership

5.3.1 Household Level

Evidence suggests that there are positive nutrition, livelihood, wellbeing, and resilience outcomes when women are more involved and have greater influence in household decision-making. Several studies find that when women own or have joint title to land, they are significantly more involved or have greater influence in household decision-making, particularly regarding agricultural or productive decisions (Wiig 2013; Mishra and Sam 2016). And while Fisher and Carr (2015) found that women farmers in Ghana and Malawi were less likely to adopt drought-tolerant maize varieties due to differences in resource access, women strongly influenced the adoption of drought-tolerant maize varieties on plots controlled by their husbands.

5.3.2 Community Level

Diiro et al. (2018) found evidence that increases in women's empowerment, including women's participation in community leadership, is associated with higher agricultural productivity; and women from more food-secure households are more likely to participate in community leadership roles. Niewoehner-Green et al. (2019) found that, for women in rural Honduras, social norms and structural biases hindered their participation in leadership positions in agricultural groups and limited their influence and voice in community decisions. There is some evidence to suggest that men and women value and participate in different types of community groups. For example, women place a higher value on savings and credit groups than men and may have greater access to hyper-local institutions, whereas men have greater access to institutions and services from outside of their immediate community (Cramer et al. 2016; Perez et al. 2015). Other evidence suggests that women may participate in fewer groups than men (Mwongera et al. 2014).

5.3.3 Food Systems Level

Increasing women's voices and integrating their preferences into agricultural solutions, including technology design and implementation, is an under-researched pathway to empowerment and gender equality in food systems. For example, there is evidence that women may have different preferences than men with regard to crop varietals (Gilligan et al. 2020; Teeken et al. 2018), but there is limited evidence that breeders' consider these preferences in varietal design and profiles (Tufan et al. 2018; Marimo et al. 2020).

5.4 Institutional Barriers, Policy, and Governance

The prevalence of gender-based violence (GBV) is a systemic barrier for women's empowerment in food systems. There is extensive research in health literature on GBV; however, research on violence against women in the context of food systems is limited. Some studies find evidence that women's asset ownership deters GBV, suggesting that when women own assets, their status may increase, making it easier for them to leave harmful relationships (Grabe 2010; Grabe et al. 2014). Buller et al. (2018) and Lees et al. (2021) found that cash transfer programs decrease the incidence of GBV. The new project-level Women's Empowerment in Agriculture Index for Market Inclusion (pro-WEAI+MI) includes indicators on sexual harassment and violence against women in composite measurements of empowerment for women in agricultural value chains (Ragasa et al. 2021; Eissler et al. 2021a), providing a tool to measure the incidence of GBV and its impact on women's empowerment in food systems.

Institutions and policies that support gender equality and women's empowerment in food systems are generally lacking in low-income countries (Meinzen-Dick et al. 2013). Bryan et al. (2018) observed that a lack of policies and institutional capacity hinders research and gender integration into climate change adaptation programs across a range of contexts, specifically noting a lack of staff capacity on gender, a lack of funding to support gender integration, and sociocultural constraints as key barriers to gender integration. Some evidence suggests a tension between formal legislation and practiced law. Pradhan et al. (2019) found that, in practice, women's joint and personal property rights differ from legal definitions. Eissler et al. (2021a) observed that, while Benin has formal gender equality and antidiscrimination laws, these are poorly enforced and do not align with social norms toward GBV or harassment. For example, women working in agricultural value chains often may not report incidents of sexual harassment in the workplace for fear of upsetting their husbands, suggesting that women may feel a sense of responsibility for inviting the harassment.

6 Conclusions

This scoping review aimed to elucidate evidence and identify evidence gaps for advancing gender equality and women's empowerment in food systems. We see evidence that women have differing access to resources compared with men, such as essential services, knowledge and information, technology dissemination, land, credit options, time, and markets. This differing level of access is shaped and reinforced by contextual social gender norms. Existing evidence shows that context-specific pathways link women's empowerment to important outcomes, such as household nutrition and dietary diversity, noting that these pathways may vary between and within contexts. Cross-contextual evidence exists of positive associations between maternal education (and specifically, access to nutrition education) and positive outcomes for child and household nutrition and diet quality.

While this review was not systematic, it appears that only limited studies address important areas of inquiry regarding gender equality and women's empowerment in food systems. Specifically, only a few studies included in this review examined gender considerations in food systems for women in urban areas or aquaculture value chains. There have been few studies geared at understanding best practices and effective pathways for engaging men in the process of women's empowerment in food systems, or addressing issues of migration, crises or indigenous food systems. Additionally, while there are gender-informed evaluation studies examining the effectiveness of gender- and nutrition-sensitive agricultural programs, there is limited evidence to indicate the long-term sustainability of such impacts.

In conclusion, this review suggests that there is substantial agreement about pathways to improve women's empowerment and gender equality in food systems, but the actual evidence to support these pathways, specifically cross-contextual evidence, is limited. Existing evidence is extremely localized and context-specific, limiting its application beyond the focus area of the study. And finally, relatively few studies included a gender-informed design and conceptual framework to best understand mechanisms for promoting equality and empowerment. Moving forward, further research is required to produce stronger evidence on cross-contextual pathways to improve gender equality and women's empowerment in food systems.

7 Recommendations for Investment

7.1 Invest in Maternal Education, Particularly Nutrition-Focused Education and Counseling

Cross-contextual evidence indicates that maternal education and experiences with nutrition counseling are positively associated with improved diet quality and diversity, leading to better nutrition outcomes at the household level. For example, Choudhury et al. (2019) found a positive association of maternal education and maternal health, household dietary diversity, and nutrition and health outcomes for household members in 42 countries, suggesting that dietary diversity may be driven by preferences and knowledge. In Tanzania, Kimambo et al. (2018) found positive associations between women's nutrition knowledge and consumption of African vegetables. Rakotomanana et al. (2020) found that, in Madagascar, children of mothers with knowledge and positive attitudes about complementary nutrient-rich foods had more nutrient-diverse diets, while those with mothers who had lower incomes and greater time burdens had less nutrient-diverse diets. Studies also found benefits from involving grandmothers in nutrition counseling, education and dialogues in Sierra Leone (Aidam et al. 2020; MacDonald et al. 2020) and Nepal (Karmacharya et al. 2017). Investments should focus on increasing women's educational attainment, coupled with nutrition-focused counseling.

7.2 Invest in Programs/Interventions that Aim to Improve Women's Influence and Role in Decision-Making and Leadership at All Levels of the Food System (Household, Community, and Systems)

Women's influence and role in decision-making is associated positively with nutrition, women's empowerment, and livelihood outcomes at all levels of food systems. At the household level, in northern Ghana, for example, women are less likely to have decision-making autonomy over productive decisions, purchasing, selling or transferring assets, and speaking in public (Ragsdale et al. 2018). In Bangladesh, de Pinto et al. (2020) found that households have higher levels of crop diversification when women have more influence in productive household decision-making, suggesting that an increase in women's bargaining power can lead to more resilient agricultural livelihoods. At the community level, evidence indicates that women's participation in community groups also enhances resilience, increases access to important resources such as land and labor, builds and facilitates social networks, and increases their influence and participation in community-level decision-making (Kumar et al. 2019; Aberman et al. 2020). For example, Kabeer (2017) found that women in Bangladesh who expand their active social networks through community groups have higher levels of empowerment. Raghunathan et al. (2019) found that Indian women's participation in self-help groups was positively associated with increased levels of information and participation in some agricultural decisions, but did not affect agricultural production or outcomes, possibly because of women's limited time, financial constraints, or restrictive social norms. At the systems level, there is limited evidence to suggest that technology development (including crop breeding, for example) incorporates women's different preferences and needs into design (Tufan et al. 2018; Marimo et al. 2020). Investments should be made in interventions that address and facilitate improvements for women's influence and participation in decision-making at all levels.

7.3 Invest in Interventions that Promote Positive and Equal Gender Norms at the Household, Community, and Systems Levels

Gender norms and associated expectations vary by context; however, restrictive gender norms shape and, in many ways, hinder women's empowerment across contexts and limit their ability to participate in and act upon strategic decisions or activities to advance their own empowerment across all components of food systems. For example, a study in Egypt found that a woman's normative role as an unpaid household caregiver limited her ability to sell fish compared with her husband, who did not face time burdens associated with caregiving and who maintained decision-making control over his and his wife's activities (Kantor and Kruijssen 2014). In Papua New Guinea, Kosec et al. (2021) found that men are more likely to support women challenging normative gender roles in terms of their economic participation during periods of household economic stress because this can raise household income, not because they support transforming women's role in society more generally. Contextual gender norms may also shape women's food allocation preferences, which hold important implications for nutrition. In Ethiopia, for example, women may favor sons over daughters for more nutrient-dense foods (Coates et al. 2018). Sraboni and Quisumbing (2018) found that women's preferences in allocating nutritious foods were influenced heavily by social norms in Bangladesh, where women favored sons over daughters because of male advantage in labor markets and property rights. Investments should be made to promote positive and equal gender norms for and with men and women across contexts and scales from the household to system levels.

7.4 Invest in Interventions and Efforts that Improve Women's Access to Important and Necessary Resources

The evidence overwhelmingly indicates that, across contexts, women have less access to important resources than men. These resources include, but are not limited to, land, agricultural inputs, financing options, financial services, technology, technical services, and time. Nuanced variations exist across and within contexts. For example, in sub-Saharan Africa, studies indicate that women may rely on informal sources of information, such as personal connections, whereas men rely on formal sources of information, such as extension or the private sector; however, in Colombia, men may have more access to information overall compared to women, but both rely on the same sources of information (Twyman et al. 2014; Mudege et al. 2017). With regard to time, Komatsu et al. (2018) found that women's time allocation and household nutrition outcomes varied by local context, such that women's time in domestic work was positively associated with diverse diets in Bangladesh, Cambodia, Ghana, Mozambique and Nepal, but in Mozambique, the relation between women's time in agricultural work and children's diet quality varied with women's asset poverty. Picchioni et al. (2020) found that, in India and Nepal, women and men participate equally in productive work that requires high levels of energy, but women shoulder most of the reproductive work at the expense of leisure opportunities. Van den Bold et al. (2021) found that a nutrition-sensitive agricultural intervention in Burkina Faso significantly increased the time women spent on agriculture and led to improved maternal and child nutrition outcomes, and that women's increased time spent on agriculture did not have deleterious effects on their own or their children's nutrition. Investments should be made to target improving women's access to and control and ownership over such resources so as to ensure that they are able to effectively benefit from these resources.

7.5 *Target Research to Yield More Cross-Contextual Evidence for Advancing Gender Equality and Women's Empowerment in Food Systems*

Finally, the overall outcome of this review revealed that the current evidence on advancing women's empowerment and gender equality in food systems is locally specific and linked to contextual gender norms. Developing cross-contextual typologies can support the development of evidence that has broader application. More targeted research is required to identify patterns of successful and effective interventions and pathways to advance women's empowerment and gender equality in food systems with contextual norms. The outcome of such research would be clear typologies that link successful interventions and recommendations by gender norms.

Annex: Key Terms and Definitions[a]

Term	Definition	Source
Women's empowerment	One's ability to make and act upon strategic and meaningful choices and decisions related to one's life.	Kabeer (1999)
Power within	One's subjectivity, consciousness, and sense of self-worth, self-awareness, self-knowledge and aspirations	Rowlands (1998)
Power to	One's access to and ability to use important resources (material, human, social) to employ greater control over key aspects of one's life and realize one's own aspirations	
Power with	Collaborative and collective power with others that occurs through mutual support, collaboration, and collective action that recognizes and respects differences	
Women's economic empowerment	"The process which increases women's real power over economic decisions that influence their lives and priorities in society. Women's economic empowerment can be achieved through equal access to and control over critical economic resources and opportunities, and the elimination of structural gender inequalities in the labor market including a better sharing of unpaid care work"	Törnqvist and Schmitz (2009, p. 9)

(continued)

Term	Definition	Source
Gender-transformative	Approaches that "go beyond the 'symptoms' of gender inequality to address the social norms, attitudes, behaviors, and social systems that underlie them"	Hillenbrand et al. (2015, p. 5)

[a]We acknowledge that a fourth type of power—power over—is also addressed in the literature as one's control over people, resources, or others' lives (Rowlands 1998)

References

Abate N (2018) An investigation of gender division of labour: the case of Delanta District, South Wollo Zone, Ethiopia. J Agric Ext Rural Dev 9(9):207–214

Aberman N, Ali S, Behrman J, Bryan E, Davis P, Donnelly A, Gathaara V, Kone D, Nganga T, Ngugi J, Okoba B, Roncoli C (2015) Climate change adaptation assets and group-based approaches: gendered perceptions from Bangladesh, Ethiopia, Mali, and Kenya, IFPRI discussion paper 01412. International Food Policy Research Institute, Washington, DC

Aberman N, Birner R, Odoyo EAO, Oyunga M, Okoba B, Okello G (2020) Gender-inclusive governance of 'self-help' groups in rural Kenya, IFPRI discussion paper 01986. International Food Policy Research Institute, Washington, DC

Adegbite O, Machethe C (2020) Bridging the financial inclusion gender gap in smallholder agriculture in Nigeria: an untapped potential for sustainable development. World Dev 127 (March):104755

Aidam B, MacDonald C, Wee R, Simba J, Aubel J, Reinsma K, Girard A (2020) An innovative grandmother-inclusive approach for addressing suboptimal infant and young child feeding practices in Sierra Leone. *Current Developments in Nutrition* 4(12):nzaa174

Akter R, Yagi N, Sugino H, Thilsted SH, Ghosh S, Gurung S, Heneveld K, Shrestha R, Webb P (2020) Household engagement in both aquaculture and horticulture is associated with higher diet quality than either alone. Nutrients 12(9):2705

Alaofè H, Burney J, Naylor R, Taren D (2016a) Solar-powered drip irrigation impacts on crops production diversity and dietary diversity in Northern Benin. Food Nutr Bull 37(2):164–175

Alaofè H, Burney J, Naylor R, Taren D (2016b) The impact of a solar market garden programme on dietary diversity, women's nutritional status and micronutrient levels in Kalalé District of Northern Benin. Public Health Nutr 22(14):2670–2681

Alaofè H, Zhu M, Burney J, Naylor R, Douglas T (2017) Association between women's empowerment and maternal and child nutrition in Kalale District of Northern Benin. Food Nutr Bull 38(3):302–318

Alaofè H, Burney J, Naylor R, Taren D (2019) The impact of a solar market garden programme on dietary diversity, women's nutritional status and micronutrient levels in Kalalé district of northern Benin. Public Health Nutr 22(14):2670–2681

Anato A, Baye K, Tafese Z, Stoecker BJ (2020) Maternal depression is associated with child undernutrition: a cross-sectional study in Ethiopia. Matern Child Nutr 16(3):e12934

Aryal JP, Rahut DB, Mottaleb KA, Ali A (2019) Gender and household energy choice using exogenous switching treatment regression: evidence from Bhutan. Environ Dev 30(June):61–75

Ayantunde AA, Oluwatosin BO, Yameogo V, van Wijk M (2020) Perceived benefits, constraints and determinants of sustainable intensification of mixed crop and livestock systems in the Sahelian Zone of Burkina Faso. Int J Agric Sustain 18(1):84–98

Bellows AL, Canavan CR, Blakstad MM, Mosha D, Noor RA, Webb P, Kinabo J, Masanja H, Fawzi WW (2020) The relationship between dietary diversity among women of reproductive age and agricultural diversity in rural Tanzania. Food Nutr Bull 41(1):50–60

Beuchelt TD, Badstue L (2013) Gender, nutrition- and climate-smart food production: opportunities and trade-offs. Food Secur 5(5):709–721
Bryan E, Garner E (2020) What does empowerment mean to women in northern Ghana? Insights from research around a small-scale irrigation intervention, IFPRI discussion paper 01909. International Food Policy Research Institute, Washington, DC
Bryan E, Ringler C, Okoba B, Roncoli C, Silvestri S, Herrero M (2013) Adapting agriculture to climate change in Kenya: household strategies and determinants. J Environ Manag 114(January):26–35
Bryan E, Bernier Q, Espinal M, Ringler C (2018) Making climate change adaptation programmes in sub-Saharan Africa more gender responsive: insights from implementing organizations on the barriers and opportunities. Clim Dev 10(5):417–431
Buller AM, Peterman A, Ranganathan M, Bleile A, Hidrobo M, Heise L (2018) A mixed-method review of cash transfers and intimate partner violence in low- and middle-income countries. World Bank Res Obs 33(2):218–258
Campbell B, Thornton P, Zougmoré R, van Asten P, Lipper L (2014) Sustainable intensification: what is its role in climate smart agriculture? Curr Opin Environ Sustain 8(October):39–43
Cetrone H, Santoso M, Petito L, Bezner-Kerr R, Blacker L, Kassim N, Mtinda E, Martin H, Young S (2020) A participatory agroecological intervention reduces women's risk of probable depression through improvements in food security in Singida, Tanzania. Curr Dev Nutr 4(Supplement 2):819–819
Chaturvedi S, Ramji S, Arora NK, Rewal S, Dasgupta R, Deshmukh V (2016) Time-constrained mother and expanding market: emerging model of under-nutrition in India. BMC Public Health 16(July):632
Choudhury S, Headey DD, Masters WA (2019) First foods: Diet quality among infants aged 6–23 months in 42 countries. Food Policy 88:101762.
Choudhury S, Shankar B, Aleksandrowicz L, Tak M, Green R, Harris F, Scheelbeek P, Dangour A (2020) What underlies inadequate and unequal fruit and vegetable consumption in India? An exploratory analysis. Glob Food Sec 24(March):100332
Coates J, Patenaude BN, Rogers BL, Roba AC, Woldetensay YK, Tilahun AF, Spielman KL (2018) Intra-household nutrient inequity in rural Ethiopia. Food Policy 81(December):82–94
Codjoe S, Atidoh L, Burkett V (2012) Gender and occupational perspectives on adaptation to climate extremes in the Afram Plains of Ghana. Clim Chang 110(1):431–454
Cramer L, Förch W, Mutie I, Thornton PK (2016) Connecting women, connecting men: how communities and organizations interact to strengthen adaptive capacity and food security in the face of climate change. Gend Technol Dev 20(2):169–199
Dawood TC, Pratama H, Masbar R, Effendi R (2019) Does financial inclusion alleviate household poverty? Empirical evidence from Indonesia. Econ Soc 12(2):235–252
De Brauw A, van den Berg M, Brouwer I, Snoek H, Vignola R, Melesse M, Lochetti G, van Wagenberg C, Lundy M, d'Hotel E, Ruben R (2019) Food system innovations for healthier diets in low and middle-income countries, IFPRI discussion paper 01816. International Food Policy Research Institute, Washington, DC
De Pinto A, Seymour G, Bryan E, Bhandari P (2020) Women's empowerment and farmland allocations in Bangladesh: evidence of a possible pathway to crop diversification. Clim Chang 163(2):1025–1043
Diiro GM, Seymour G, Kassie M, Muricho G, Muriithi BW (2018) Women's empowerment in agriculture and agricultural productivity: evidence from rural maize farmer households in Western Kenya. PLoS One 13(5):e0197995
Diouf NS, Ouédraogo I, Zougmoré RB, Ouedraogo M, Partey ST, Gumucio T (2019) Factors influencing gendered access to climate information services for farming in Senegal. Gend Technol Dev 23(2):93–110
Doss C (2013) Intrahousehold bargaining and resource allocation in developing countries. World Bank Res Obs 28(1):52–78

Doss C (2018) Women and agricultural productivity: reframing the issues. Dev Policy Rev 36(1): 35–50

Doss C, Kovarik C, Peterman A, Quisumbing A, van den Bold M (2015) Gender inequalities in ownership and control of land in Africa: myth and reality. Agric Econ 46(3):403–434

Duffy C, Toth G, Cullinan J, Murray U, Spillane C (2020) Climate smart agriculture extension: gender disparities in agroforestry knowledge acquisition. Clim Dev 13(January):1–13

Eissler S, Sanou A, Heckert J, Myers EC, Nignan S, Thio E, Pitropia LA, Ganaba R, Pedehombga A, Gelli A (2020a) Gender dynamics, women's empowerment, and diets: qualitative findings from an impact evaluation of a nutrition-sensitive poultry value chain intervention in Burkina Faso, IFPRI discussion paper 01913. International Food Policy Research Institute, Washington, DC

Eissler S, Sanou A, Heckert J, Myers EC, Nignan S, Thio E, Pitropia LA, Ganaba R, Pedehombga A, Gelli A (2020b) Gendered participation in poultry value chains: qualitative findings from an impact evaluation of a nutrition-sensitive poultry value chain intervention in Burkina Faso, IFPRI discussion paper 01928. International Food Policy Research Institute, Washington, DC

Eissler S, Diatta A, Heckert J, Nordhen C (2021a) A qualitative assessment of a gender-sensitive agricultural training program in Benin: findings on program experience and women's empowerment across key agricultural value chains, IFPRI discussion paper 02005. International Food Policy Research Institute, Washington, DC

Eissler S, Heckert J, Myers E, Seymour G, Sinharoy S, Yount KM (2021b) Exploring gendered experiences of time-use agency in Benin, Malawi, and Nigeria as a new concept to measure women's empowerment, IFPRI discussion paper 02003. International Food Policy Research Institute, Washington, DC

Fanzo J, Davis C, McLaren R, Choufani J (2018) The effect of climate change across food systems: implications for nutrition outcomes. Glob Food Sec 18(September):12–19

Farnworth CR, Baudron F, Andersson JA, Misiko M, Badstue L, Stirling CM (2016) Gender and conservation agriculture in east and southern Africa: towards a research agenda. Int J Agric Sustain 14(2):142–165

Fisher M, Carr E (2015) The influence of gendered roles and responsibilities on the adoption of technologies that mitigate drought risk: the case of drought-tolerant maize seed in Eastern Uganda. Glob Environ Chang 35(November):82–92

Gathala MK, Laing AM, Tiwari TP, Timsina J, Rola-Rubzen F, Islam S, Maharjan S et al (2021) Improving smallholder farmers' gross margins and labor-use efficiency across a range of cropping Systems in the Eastern Gangetic Plains. World Dev 138(February):105266

Gebre GG, Isoda H, Rahut DB, Amekawa Y, Nomura H (2019) Gender differences in agricultural productivity: evidence from maize farm households in southern Ethiopia. GeoJournal 86 (November):843–864

Gelli A, Becquey E, Ganaba R, Headey D, Hidrobo M, Huybregts L, Verhoef H, Kenfack R, Zongouri S, Guedenet H (2017) Improving diets and nutrition through an integrated poultry value chain and nutrition intervention (SELEVER) in Burkina Faso: study protocol for a randomized trial. Trials 18(1):412

Gender at Work (n.d.) Gender at work framework. https://genderatwork.org/analytical-framework/

Ghosh A, Chopra D (2019) Paid work, unpaid care work and women's empowerment in Nepal. Contemp South Asia 27(4):471–485

Ghosh S, Vinod D (2017) What constrains financial inclusion for women? Evidence from Indian micro data. World Dev 92(April):60–81

Gilligan D, Kumar N, McNiven S, Meenakshi J, Quisumbing A (2020) Bargaining power, decision making, and biofortification: the role of gender in adoption of orange sweet potato in Uganda. Food Policy 95(June):101909

Grabe S (2010) Promoting gender equality: the role of ideology, power, and control in the link between land ownership and violence in Nicaragua. Anal Soc Issues Public Policy 10(1): 146–170

Grabe S, Grose R, Dutt A (2014) Women's land ownership and relationship power: a mixed methods approach to understanding structural inequities and violence against women. Psychol Women Q 39(1):7–19

Grabowski PP, Djenontin I, Zulu L, Kamoto J, Kampanje-Phiri J, Darkwah A, Egyir I, Fischer G (2020) Gender- and youth-sensitive data collection tools to support decision making for inclusive sustainable agricultural intensification. Int J Agric Sustain. https://doi.org/10.1080/14735903.2020.1817656

Gupta S, Pingali PL, Pinstrup-Andersen P (2017) Women's empowerment in Indian agriculture: does market orientation of farming systems matter? Food Secur 9(6):1447–1463

Gutierrez-Montes I, Arguedas M, Ramirez-Aguero F, Mercado L, Sellare J (2020) Contributing to the construction of a framework for improved gender integration into climate-smart agriculture projects monitoring and evaluation: MAP-Norway experience. Clim Chang 158(1):93–106

Halbrendt J, Kimura AH, Gray SA, Radovich T, Reed B, Tamang BB (2014) Implications of conservation agriculture for men's and women's workloads among marginalized farmers in the Central Middle Hills of Nepal. Mt Res Dev 34(3):214–222

Harris J, Tan W, Mitchell B, Zayed D (2021) Equity in agriculture-nutrition-health research: a scoping review. Nutr Rev. https://doi.org/10.1093/nutrit/nuab001

Heckert J, Olney DK, Ruel MT (2019) Is Women's empowerment a pathway to improving child nutrition outcomes in a nutrition-sensitive agriculture program? Evidence from a randomized controlled trial in Burkina Faso. Soc Sci Med 233(July):93–102

Hillenbrand E, Karim N, Mohanraj P, Wu D (2015) Measuring gender-transformative change: a review of literature and promising practices, Working paper. CARE USA, Washington, DC

Hoddinott J, Headey D, Dereje M (2015) Cows, missing milk markets, and nutrition in rural Ethiopia. J Dev Stud 51(8):958–975

Huyer S, Partey S (2020) Weathering the storm or storming the norms? Moving gender equality forward in climate-resilient agriculture. Clim Chang 158(1):1–12

Johnson N, Kovarik C, Meinzen-Dick R, Njuki J, Quisumbing A (2016) Gender, assets, and agricultural development: lessons from eight projects. World Dev 83(July):295–311

Johnson N, Balagamwala M, Pinkstaff C, Theis S, Meinzen-Dick R, Quisumbing A (2018) How do agricultural development projects empower women? Linking strategies with expected outcomes. J Gend Agric Food Secur 3(2):1–19

Jost C, Kyazze F, Naab J, Neelormi S, Kinyangi J, Zougmoré R, Aggarwal P, Bhatta G, Chaudhury M, Tapio-Bistrom M, Nelson S, Kristjanson P (2016) Understanding gender dimensions of agriculture and climate change in smallholder farming communities. Clim Dev 8(2):133–144

Kabeer N (1999) Resources, agency, achievements: reflections on the measurement of women's empowerment. Dev Chang 30(3):435–464

Kabeer N (2017) Economic pathways to Women's empowerment and active citizenship: what does the evidence from Bangladesh tell us? J Dev Stud 53(5):649–663

Kabir MS, Marković MR, Radulović D (2019) The determinants of income of rural women in Bangladesh. Sustainability 11(20):5842

Kantor P, Kruijssen F (2014) Informal fish retailing in rural Egypt: opportunities to enhance income and work conditions for women and men. WorldFish, Penang

Karmacharya C, Cunningham K, Choufani J, Kadiyala S (2017) Grandmothers' knowledge positively influences maternal knowledge and infant and Young child feeding practices. Public Health Nutr 20(12):2114–2123

Kassie M, Fisher M, Muricho G, Diiro G (2020) Women's empowerment boosts the gains in dietary diversity from agricultural technology adoption in rural Kenya. Food Policy 95(August):101957

Kawarazuka N, Locke C, McDougall C, Kantor P, Morgan M (2017) Bringing analysis of gender and social–ecological resilience together in small-scale fisheries research: challenges and opportunities. Ambio 46(2):201–213

Khoza S, Van Niekerk D, Nemakonde LD (2019) Understanding gender dimensions of climate-smart agriculture adoption in disaster-prone smallholder farming communities in Malawi and Zambia. Disaster Preven Manag Int J 28(5):530–547

Kimambo J, Kavoi MM, Macharia J, Nenguwo N (2018) Assessment of factors influencing farmers' nutrition knowledge and intake of traditional African vegetables in Tanzania. Afr J Food Agric Nutr Dev 18(2):13353–13371

Kiptot E, Franzel S (2012) Gender and agroforestry in Africa: a review of women's participation. Agrofor Syst 84(1):35–58

Komatsu H, Malapit HJL, Theis S (2018) Does women's time in domestic work and agriculture affect women's and children's dietary diversity? Evidence from Bangladesh, Nepal, Cambodia, Ghana, and Mozambique. Food Policy 79(August):256–270

Kosec K, Mo CH, Schmidt E, Song J (2021) Perceptions of relative deprivation and women's empowerment. World Dev 138(February):105218

Kristjanson P, Bryan E, Bernier Q, Twyman J, Meinzen-Dick R, Kieran C, Ringler C, Jost C, Doss C (2017) Addressing gender in agricultural research for development in the face of a changing climate: where are we and where should we be going? Int J Agric Sustain 15(5):482–500

Kruijssen F, Rajaratnam S, Choudhury A, McDougall C, Dalsgaard JPT (2016) Gender in the farmed fish value chain of Bangladesh: a review of the evidence and development approaches, Program brief: 2016–38. WorldFish, Penang

Kruijssen F, McDougall C, van Asseldonk I (2018) Gender and aquaculture value chains: a review of key issues and implications for research. Aquaculture 493(1):328–337

Kumar N, Raghunathan K, Arrieta A, Jilani A, Chakrabarti S, Menon P, Quisumbing AR (2019) Social networks, mobility, and political participation: the potential for women's self-help groups to improve access and use of public entitlement schemes in India. World Dev 114(February):28–41

Lambrecht I, Mahrt K (2019) Gender and assets in rural Myanmar: a cautionary tale for the analyst, IFPRI discussion paper 01894. International Food Policy Research Institute, Washington, DC

Lees S, Kyegombe N, Diatta A, Zogrone A, Roy S, Hidrobo M (2021) Intimate partner relationships and gender norms in Mali: the scope of cash transfers targeted to men to reduce intimate partner violence. Violence Against Women 27(3–4):447–469

Leight J (2021) Like father, like son, like mother, like daughter: intergenerational transmission of intrahousehold gender attitudes in Ethiopia. World Dev 142(June):105359

Lentz E, Narayanan S, De A (2019) Last and least: findings on intrahousehold undernutrition from participatory research in South Asia. Soc Sci Med 232(July):316–323

Liverpool-Tasie L, Wineman A, Young S, Tambo J, Vargas C, Reardon T, Adjognon G, Porciello J, Gathoni N, Bizikova L, Gaile A, Celestin A (2020) A scoping review of market links between value chain actors and small-scale producers in developing regions. Nat Sustain 3(October):799–808

MacDonald CA, Aubel J, Aidam BA, Girard AW (2020) Grandmothers as change agents: developing a culturally appropriate program to improve maternal and child nutrition in Sierra Leone. Curr Dev Nutr 4(1):nzz141

Madzorera I, Fawzi W (2020) Women empowerment is central to addressing the double burden of malnutrition. Clin Med 20(February):100286

Mahajan K (2017) Rainfall shocks and the gender wage gap: evidence from Indian agriculture. World Dev 91(March):156–172

Malapit HJL, Quisumbing AR (2015) What dimensions of women's empowerment in agriculture matter for nutrition in Ghana? Food Policy 52(April):54–63

Malapit HJL, Sraboni E, Quisumbing AR, Ahmed AU (2019) Intrahousehold empowerment gaps in agriculture and children's well-being in Bangladesh. Dev Policy Rev 37(2):176–203

Marimo P, Caron C, Van den Bergh I, Crichton R, Weltzien E, Ortiz R, Tumuhimbise R (2020) Gender and trait preferences for banana cultivation and use in Sub-Saharan Africa: a literature review. Econ Bot 74(2):226–241

Meinzen-Dick R, Bernier Q, Haglund E (2013) The six ‘ins’ of climate-smart agriculture: inclusive institutions for information, innovation, investment, and insurance, CAPRi working paper 114. International Food Policy Research Institute, Washington, DC

Meinzen-Dick R, Quisumbing A, Doss C, Theis S (2019a) Women’s land rights as a pathway to poverty reduction: framework and review of evidence. Agric Syst 172(June):72–82

Meinzen-Dick R, Rubin D, Elias M, Mulema AA, Myers E (2019b) Women’s empowerment in agriculture: lessons from qualitative research, IFPRI discussion paper 1797. International Food Policy Research Institute, Washington, DC

Mishra K, Sam AG (2016) Does Women’s land ownership promote their empowerment? Empirical evidence from Nepal. World Dev 78(February):360–371

Montt G, Luu T (2020) Does conservation agriculture change labour requirements? Evidence of sustainable intensification in Sub-Saharan Africa. J Agric Econ 71(2):556–580

Moore N, Lane C, Storhaug I, Franich A, Rolker H, Furgeson J, Sparling T, Snilstveit B (2021) The effects of food systems interventions on food security and nutrition outcomes in low- and middle-income countries, 3ie evidence gap map report 16. International Initiative for Impact Evaluation, New Delhi

Moosa CS, Tuana N (2014) Mapping a research agenda concerning gender and climate change: a review of the literature. Hypatia 29(3):677–694

Mudege NN, Mdege N, Abidin PE, Bhatasara S (2017) The role of gender norms in access to agricultural training in Chikwawa and Phalombe, Malawi. Gender Place Cult 24(12):1689–1710

Mulema A, Damtew E (2016) Gender-based constraints and opportunities to agricultural intensification in Ethiopia: a systematic review, ILRI project report. International Livestock Research Institute, Nairobi

Mulmi P, Block SA, Shively GE, Masters WA (2016) Climatic conditions and child height: sex-specific vulnerability and the protective effects of sanitation and food Markets in Nepal. Econ Hum Biol 23(December):63–75

Mwaseba DJB, Kaarhus R (2015) How do intra-household gender relations affect child nutrition? Findings from two rural districts in Tanzania. Forum Dev Stud 42(2):289–309

Mwongera C, Shikuku KM, Twyman J, Winowiecki LA, Ampaire EL, Koningstein M, Twomlow S (2014) Rapid rural appraisal report of northern Uganda. International Center for Tropical Agriculture/CGIAR research program on climate change, Agriculture and Food Security (CCAFS), Cali-Palmira/Wageningen

Na M, Jennings L, Talegawkar SA, Ahmed S (2015) Association between women’s empowerment and infant and child feeding practices in sub-Saharan Africa: an analysis of demographic and health surveys. Public Health Nutr 18(17):3155–3165

Naab JB, Koranteng H (2012) Using a gender lens to explore farmers’ adaptation options in the face of climate change: results of a pilot study in Ghana, Working paper 17. CGIAR Research Program on Climate Change, Agriculture and Food Security, Wageningen

Nahusenay A (2017) An investigation of gender division of labour: the case of Delanta district, South Wollo zone, Ethiopia. J Agric Ext Rural Dev 9(9):207–214

Ndiritu S, Kassie M, Shiferaw B (2014) Are there systematic gender differences in the adoption of sustainable agricultural intensification practices? Evidence from Kenya. Food Policy 49(1): 117–127

Niewoehner-Green J, Stedman N, Galindo S, Russo S, Carter H, Colverson K (2019) The influence of gender on rural Honduran Women’s participation and leadership in community groups. J Int Agric Ext Edu 26(2):48–63

Njuki J, Waithanji E, Sakwa B, Kariuki J, Mukewa E, Ngige J (2014) Can market-based approaches to technology development and dissemination benefit women smallholder farmers? A qualitative assessment of gender dynamics in the ownership, purchase, and use of irrigation pumps in Kenya and Tanzania, IFPRI discussion paper 01357. International Food Policy Research Institute, Washington, DC

Østergaard Nielsen J, Reenberg A (2010) Cultural barriers to climate change adaptation: a case study from northern Burkina Faso. Glob Environ Chang 20(1):142–152

Ouédraogo M, Houessionon P, Zougmoré RB, Tetteh Partey S (2019) Uptake of climate-smart agricultural technologies and practices: actual and potential adoption rates in the climate-smart village site of Mali. Sustainability 11(17):4710
Parks MH, Christie ME, Bagares I (2015) Gender and conservation agriculture: constraints and opportunities in the Philippines. GeoJournal 80(1):61–77
Perez C, Jones EM, Kristjanson P, Cramer L, Thornton PK, Förch W, Barahona C (2015) How resilient are farming households and communities to a changing climate in Africa? A gender-based perspective. Glob Environ Chang 34(September):95–107
Peterman A, Quisumbing A, Behrman J, Nkonya E (2011) Understanding the complexities surrounding gender differences in agricultural productivity in Nigeria and Uganda. J Dev Stud 47(10):1482–1509
Peterman A, Behrman JA, Quisumbing AR (2014) A review of empirical evidence on gender differences in nonland agricultural inputs, technology, and services in developing countries. In: Quisumbing AR, Meinzen-Dick R, Raney TL, Croppenstedt A, Behrman JA, Peterman A (eds) Gender in agriculture. Springer, Dordrecht, pp 145–186
Picchioni F, Zanello G, Srinivasan CS, Wyatt AJ, Webb P (2020) Gender, time-use, and energy expenditures in rural communities in India and Nepal. World Dev 136(December):105137
Pradhan R, Meinzen-Dick R, Theis S (2019) Property rights, intersectionality, and women's empowerment in Nepal. J Rural Stud 70(August):26–35
Quisumbing A, Kumar N, Behrman J (2018) Do shocks affect men's and women's assets differently? Evidence from Bangladesh and Uganda. Dev Policy Rev 36(1):3–34
Quisumbing AR, Sproule K, Martinez EM, Malapit H (2021) Do tradeoffs among dimensions of women's empowerment and nutrition outcomes exist? Evidence from six countries in Africa and Asia. Food Policy 100(April):102001
Ragasa C, Berhane G, Tadesse F, Taffesse AS (2013) Gender differences in access to extension services and agricultural productivity. J Agric Educ Ext 19(5):437–468
Ragasa C, Aberman N, Alvarez Mingote C (2019) Does providing agricultural and nutrition information to both men and women improve household food security? Evidence from Malawi. Glob Food Sec 20(March):45–59
Ragasa C, Malapit H, Rubin D, Myers E, Pereira A, Martinez E, Heckert J, Seymour G, Mzungu D, Kalagho K, Kazembe C, Thunde J, Mswelo G (2021) 'It takes two': women's empowerment in agricultural value chains in Malawi, IFPRI discussion paper 02006. International Food Policy Research Institute, Washington, DC
Raghunathan K, Kannan S, Quisumbing AR (2019) Can women's self-help groups improve access to information, decision-making, and agricultural practices? The Indian case. Agric Econ 50(5): 567–580
Raghunathan K, Headey D, Herforth A (2021) Affordability of nutritious diets in rural India. Food Policy 99(February):101982
Ragsdale K, Read-Wahidi MR, Wei T, Martey E, Goldsmith P (2018) Using the WEAI+ to explore gender equity and agricultural empowerment: baseline evidence among men and women smallholder farmers in Ghana's northern region. J Rural Stud 64(November):123–134
Rakib M, Matz J (2014) The impact of shocks on gender-differentiated asset dynamics in Bangladesh. J Dev Stud 52(3):377–395
Rakotomanana H, Hildebrand D, Gates GE, Thomas DG, Fawbush F, Stoecker BJ (2020) Maternal knowledge, attitudes, and practices of complementary feeding and child undernutrition in the Vakinankaratra Region of Madagascar: a mixed-methods study. Curr Dev Nutr 4(11):nzaa162
Rao N, Gazdar H, Chanchani D, Ibrahim M (2019) Women's agricultural work and nutrition in South Asia: from pathways to a cross-disciplinary, grounded analytical framework. Food Policy 82(January):50–62
Reinbott A, Jordan I (2016) Determinants of child malnutrition and infant and Young child feeding approaches in Cambodia. World Rev Nutr Diet 115:61–67

Reinbott A, Schelling A, Kuchenbecker J, Jeremias T, Russell I, Kevanna O, Krawinkel MB, Jordan I (2016) Nutrition education linked to agricultural interventions improved child dietary diversity in rural Cambodia. Br J Nutr 116(8):1457–1468

Rockström J, Williams J, Daily G, Noble A, Matthews N, Gordon L, Wetterstrand H, DeClerck F, Shah M, Steduto P, de Fraiture C, Hatibu N, Unver O, Bird J, Sibanda L, Smith J (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46(1):4–17

Rowlands J (1998) Questioning empowerment: working with women in Honduras. Oxfam, Oxford

Ruel M, Quisumbing A, Balagamwala M (2018) Nutrition-sensitive agriculture: what have we learned so far? Glob Food Sec 17(June):128–153

Shroff MR, Griffiths PL, Suchindran C, Nagalla B, Vazir S, Bentley ME (2011) Does maternal autonomy influence feeding practices and infant growth in rural India? Soc Sci Med 73(3): 447–455

Sibhatu KT, Krishna VV, Qaim M (2015) Production diversity and dietary diversity in smallholder farm households. Proc Natl Acad Sci 112(34):10657–10662

Sraboni E, Quisumbing A (2018) Women's empowerment in agriculture and dietary quality across the life course: evidence from Bangladesh. Food Policy 81(December):21–36

Tall A, Kristjanson PM, Chaudhury M, McKune S, Zougmoré RB (2014) Who gets the information? Gender, power and equity considerations in the design of climate services for farmers, CCAFS working paper 89. CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen

Tambo JA, Abdoulaye T (2012) Climate change and agricultural technology adoption: the case of drought tolerant maize in rural Nigeria. Mitig Adapt Strateg Glob Chang 17(3):277–292

Teeken B, Olaosebikan O, Haleegoah J, Oladejo E, Madu T, Bello A, Parkes E, Egesi C, Kulakow P, Kirscht H, Tufan HA (2018) Cassava trait preferences of men and women farmers in Nigeria: implications for breeding. Econ Bot 72(3):263–277

Theis S, Bryan E, Ringler C (2019) Addressing gender and social dynamics to strengthen resilience for all. In: Quisumbing AR, Meinzen-Dick RS, Njuki J (eds) 2019 annual trends and outlook report: gender equality in rural Africa: from commitments to outcomes. International Food Policy Research Institute, Washington, DC, pp 126–139

Theriault V, Smale M, Haider H (2017) How does gender affect sustainable intensification of cereal production in the west African Sahel? Evidence from Burkina Faso. World Dev 92(April):177–191

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108(50):20260–20264

Törnqvist A, Schmitz C (2009) Women's economic empowerment: Scope for Sida's engagement. Sida

Tufan HA, Grando S, Meola C (eds) (2018) State of the knowledge for gender in breeding: case studies for practitioners, Working paper 3. CGIAR Gender and Breeding Initiative, Lima

Twyman J, Green M, Bernier Q, Kristjanson P, Russo S, Tall A, Ampaire E, Nyasimi M, Mango J, McKune S, Mwongera C, Ndourba Y (2014) Adaptation actions in Africa: evidence that gender matters, Working paper 83. CGIAR Research Program on Climate Change, Agriculture and Food Security, Copenhagen

Uduji JI, Okolo-Obasi EN, Asongu SA (2019) Corporate social responsibility and the role of rural women in sustainable agricultural development in sub-Saharan Africa: evidence from the Niger Delta in Nigeria. Sustain Dev 27(4):692–703

Van den Bold M, Bliznashka L, Ramani G, Olney D, Quisumbing A, Pedehombga A, Ouedraogo M (2021) Nutrition-sensitive agriculture programme impacts on time use and associations with nutrition outcomes. Matern Child Nutr 17(2):e13104

Vibert E (2016) Gender, resilience and resistance: South Africa's Hleketani community garden. J Contemp Afr Stud 34(2):252–267

Wemakor A, Iddrisu H (2018) Maternal depression does not affect complementary feeding indicators or stunting status of Young children (6–23 months) in northern Ghana. BMC Res Notes 11(1):408

Wemakor A, Mensah KA (2016) Association between maternal depression and child stunting in northern Ghana: a cross-sectional study. BMC Public Health 16(1):869

Wiig H (2013) Joint titling in rural Peru: impact on Women's participation in household decision-making. World Dev 52(December):104–119

Wolf K, Frese M (2018) Why husbands matter: review of spousal influence on women entrepreneurship in sub-Saharan Africa. Afr J Manag 4(January):1–32

The Future of Small Farms: Innovations for Inclusive Transformation

Xinshen Diao, Thomas Reardon, Adam Kennedy, Ruth S. DeFries, Jawoo Koo, Bart Minten, Hiroyuki Takeshima, and Philip Thornton

1 Introduction

By 2050, the United Nations projects that 68% of the world population will live in cities (UN DESA 2019). However, with continuous population growth, the number of people living in rural areas of many low- and middle-income countries (LMICs) will continue to rise. Two-thirds of the extreme poor live in rural areas (World Bank 2016), and the livelihoods of two to three billion rural people, often the most food insecure and vulnerable, still depend primarily on small farms (Laborde Debucquet et al. 2020; Woodhill et al. 2020).

There are various estimates of the number of small farms in the world, but they all suggest that these farms are numerous. Lowder et al. (2016) used agricultural census data from 167 countries to estimate that, of the total 570 million[1] farms in the world, 475 million have less than 2 hectares (ha), dominating agriculture in most LMICs, where farm sizes continue to fall. Africa south of the Sahara has the highest rural population growth rate globally, and thus the number of small farms is expected to increase more than in other regions. Africa's share of total world rural poverty is also

[1] Hickson and Thornton (2020) updated the total to 590 million farms, which probably increases the total of small farms above the Lowder et al. (2016) estimate.

X. Diao (✉) · A. Kennedy · J. Koo · B. Minten · H. Takeshima
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: X.DIAO@CGIAR.ORG

T. Reardon
Michigan State University, East Lansing, MI, USA

R. S. DeFries
Columbia University, New York, NY, USA

P. Thornton
International Livestock Research Institute, Nairobi, Kenya

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_10

expected to rise from 39.6% in 2015 to 58.1% in 2050 (Thurlow et al. 2019). Transforming Africa's agriculture sector is thus a priority embodied in the Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods (AU 2014). However, to meet the Malabo goals and achieve multiple SDGs in all LMICs by 2030, creating an enabling environment where small farms are included in and benefit from rapid growth and transformation of agrifood systems is urgent (Barrett et al. 2020a).

Small farms not only contribute to feeding the households that operate them, but also make two broader contributions. First, small farms are important to the overall food security of LMICs. Samberg et al. (2016) noted that farms less than 5 ha are responsible for 53% of the global production of food calories for human consumption. Herrero et al. (2017) reported that, in Africa and South and Southeast Asia, small farms with less than 2 ha produce around 30% of food and make valuable contributions to micronutrient-rich food production. Ricciardi et al. (2018) estimated that farms under 2 ha globally produce 30–34% of the food supply. Nonetheless, small farm households themselves are often unable to afford a nutritious diet.

Second, small farms contribute to the sustainability of agrifood systems by maintaining the genetic diversity of crops and livestock and supporting ecosystem services. Small farms have more crop diversity and harbor greater non-crop biodiversity at the farm and landscape scales than do larger farms (Ricciardi et al. 2021). Subsistence-oriented small farmers plant a greater diversity of traditional crops and maintain genetic resources by cultivating land races (Fifanou et al. 2011; McCord et al. 2015). Small fields have more edges than larger fields, creating a heterogeneous landscape and providing habitat for non-crop species (Ouin and Burel 2002). To the extent that small farms have more tree cover than larger farms, they provide above- and below-ground carbon storage, with global benefits for climate mitigation (Ritchie and Roser 2017). Trees on farms can also improve water infiltration, a hydrological service that benefits other water users in the landscape and downstream (Anache et al. 2019).

For small farms to be part of inclusive and sustainable agrifood system transformation, both innovative technology and market institutions are required to support LMICs' diverse agroecological and socioeconomic contexts. Many debates on the future of small farms focus only on farm production, rather than the whole context of farm household livelihoods, which include off-farm activities, or the agrifood system on which farms depend for buying inputs and selling outputs (Reardon et al. 2019; Giller et al. 2020). The future of small farms should instead be assessed using a holistic livelihoods and agrifood system lens.

2 Who Will be Small Farmers in the Future?

More than 410 million farms are very small, with less than 1 ha of land, and another 70 million are between 1 and 2 ha (Lowder et al. 2016). However, discussions of farm size often ignore land quality considerations (Eastwood et al. 2010). For example, a 5 ha farm in a rainfed zone with poor quality soil may support less production than a 1 ha farm in an irrigated zone with good soil. Thus, mere farm size ranges tell us nothing about differences in agroecological land quality, or about the socioeconomic contexts in which they operate, such as market and infrastructural conditions (FAO 2014; Graeub et al. 2016). While the product mix of small farms varies depending on this context, many are diversifying that mix, driven by urbanization, consumers' dietary preferences, technology, infrastructure development, and rural-urban links. Moreover, households that operate small farms tend to have diversified income sources, including non-farm activities, and that diversification is expected to increase over time, although at different rates among different sets of small farmers (Davis et al. 2017).

Despite the strong heterogeneity across small farms, they can be categorized in ways that make our analysis more tractable. Following Vorley (2002) and Hazell (2018), and based primarily on Hazell (2020), we classify small farmers in LMICs into three groups.

Commercial small farmers run their farms as businesses. While commercial agriculture is an important source of income for them, many also undertake rural non-farm employment (RNFE). Most commercial small farmers do not specialize in high-value crops or livestock, as many also produce food crops. Their product and activity mix are conditioned by agroecological circumstances, urban market proximity, rural infrastructure, and the agro-processors, logistics, exporters, and wholesale enterprise investment and density in their area. Climate change and economic transformation also condition their farm businesses and will create new challenges and opportunities even over the next 10 years. Some commercial small farms will continue to focus on today's traditional export crops—for example, cocoa in Ghana, cotton in Mali, and coffee in Ethiopia—while increasing numbers will turn to products that cater to the diversifying diets of burgeoning domestic urban markets, including fruits, vegetables, fish, poultry, edible oils, milk, and feed grains such as soy. Non-cereal products are especially labor-demanding and often offer little or no economies of scale, allowing small farms to be competitive. Over time, we expect to see greater specialization in the farming of high-value products and a movement away from the combination of cash and staple crop farming, similar to what one sees among specialized vegetable farmers in the Shandong province of China (Huang et al. 2010) or specialized poultry and pig farmers near Yangon in Myanmar (Belton et al. 2020).

Small farmers in transition often depend heavily on RNFE while also maintaining small plots for home food consumption, plus some semi-commercialized food or non-food products. They tend to buy a substantial share of their food. These farmers are in zones where favorable non-farm opportunities exist locally or in near-by towns. With demand growing for high-value farm products in cities, some transitional farmers will commercialize their small farms while continuing their RNFE. However, others may exit agriculture or maintain just small food plots because access to food markets in their area is uncertain, or because the RNFE labor market itself is uncertain or limited (de Janvry and Sadoulet 2006). Thus, many small farmers in this group will continue to have one foot in farming and one foot in

RNFE as their major sources of income, and their number is expected to remain large over the next decade.

Subsistence-oriented small farmers are marginalized for a variety of reasons, many of which will be difficult to change in the next decade, such as ethnic discrimination, sickness, age, or their farm's location in a remote area with limited agricultural potential. We expect the number of these small farms to fall with economic transformation, but it is unrealistic to expect most will disappear in the next decade. These farm households tend to undertake some RNFE or farm wage labor (usually the domain of the poorest farmers or the landless), but many of the same factors that constrain their farming also prevent them from undertaking remunerative RNFE to become transition farmers. These subsistence-oriented farmers are typically net buyers of staple foods. While market and technology development will help them improve farm productivity, the above constraints limit even this. They need social protection policies and other public support beyond what the agrifood system and rural labor market can provide.

RNFE is an important income source for rural small farm households and, on average, occupies more of their working time than farming in many African and Asian LMICs (Dolislager et al. 2020). For commercialized and transition small farmers, who are often in places with favorable agroclimates and adequate infrastructure, RNFE helps fund farming by providing cash or collateral for credit to buy inputs and diversifying income risk from agriculture. This can incentivize experimentation with new production technologies and riskier products like vegetables, poultry, and fish that have higher values. Increases in local RNFE activities often lead to rising rural wages (Lanjouw and Murgai 2009), which can induce the adoption of mechanization (Wang et al. 2016). However, in less favorable agroclimatic zones or hinterland areas, where most subsistence-oriented small farmers are located, RNFE is used mainly to fund food purchases and competes with, but also compensates for, unprofitable farming (Davis et al. 2009).

3 Innovations for the Future of Small Farms

The future of small farms will depend on technological and institutional innovations that are now appearing in some developed and developing country contexts or have yet to be developed (Herrero et al. 2020, 2021). Technological innovations have the potential to benefit small farms in LMICs, but ensuring their appropriateness remains a challenge. High transaction costs, lack of collective action, and failures in production and marketing coordination all introduce risks for small farms and are commonly seen as barriers to adopting modern technologies and participating in value chains. Many subsistence farmers may be too remote from markets or lack the capacity to benefit from new technologies. Transition farmers can be disincentivized from adopting new technologies if they are labor-intensive and compete with their non-farm employment. Even for commercial small farmers, the adoption of new technologies requires enabling conditions from output and input supply chains.

Small farmers' adoption of new technologies and the cultivation of higher-value products thus requires that they have the proper profit incentives and market access, which are, in large part, a function of the broad market institutional context. Effective market institutions require improved infrastructure that facilitates input supply chains upstream from the farm and connects small farmers to cities downstream from their farms.

Downstream from the farm, output market conditions affect small farmers' prices, risk, and transaction costs. Critical factors include urban market size and proximity; the density and quality of roads between farmers and markets; and the midstream (wholesalers, logistics firms, and processors) and downstream (retailers) accessibility to and conduct toward small farmers. Developments in these enabling conditions in LMICs are themselves local innovations, which often rapidly improve market access for small farmers, as in the examples from Ethiopia, Nigeria, and India discussed below. Changes in these conditions will continue to be the main factor affecting small farmers' technology adoption, income growth, and inclusion in agrifood system transformation in the next decade. Some emerging technologies, such as e-commerce linked to digitalization, are also promising innovative market institutions that will impact the relationship between small farmers and markets in the next few decades.

The urban market now makes up the largest share of national food consumption in LMICs (Reardon et al. 2019, 2021a, b). Proximity to urban markets in primary and secondary cities and small towns asserts a strong influence on market conditions and the technology and product choices of small farmers (Vandercasteelen et al. 2018). Highways and rural roads connecting farmers to urban markets likewise are critical to small farmers' access to these booming urban markets, suggesting the importance of public investment in rural infrastructure (Stifel et al. 2016).

The combination of growing urban markets, expanding road connections, and the development of wholesale markets provides favorable conditions for the spontaneous formation of clusters of wholesalers, cold storages, processors, and logistics enterprises that provide crucial services enabling small farmers to access urban markets. The emergence of clusters of small and medium enterprises (SMEs) offering potato cold storages in Bihar, India, is a good example; these have allowed small farmers to store their produce and wait for much higher prices in the off-season (Minten et al. 2014). In Ethiopia, the spontaneous development of a teff value chain connecting rural areas to Addis Ababa has been facilitated by the growth of midstream private SMEs utilizing public infrastructure and improvements in wholesale markets. Midstream market development also spurred the adoption of new technology and a new teff variety by small farmers (Minten et al. 2016). Many thousands of small chicken farmers in Nigeria, mostly women, benefited from the rapid growth of long north–south maize supply chains, operated by thousands of SME wholesalers and feed millers, to market their chicken and eggs in towns and secondary cities (Liverpool-Tasie et al. 2017). Spontaneous clusters of traders and input suppliers are also seen in aquaculture districts of Bangladesh and are a key determinant of small farmer technology adoption (Hu et al. 2019).

The relations of supply chain firms with small farmers are a critical determinant of small farmers' participation in markets for high-value agricultural products. These firms not only buy from small farms, but also often provide resources and services that small farmers need to participate in the market, from inputs and credit allowing them to adopt new technologies that meet market requirements to services such as aggregating, sorting, and packing. This facilitation is offered through formal contract-farming arrangements with large processors and retailers (Swinnen and Kuijpers 2019), as well as through informal relationships with SME wholesalers and processors that reduce the price risk for small farms (Liverpool-Tasie et al. 2020). Relative to the "traditional" arrangement of spot markets, this facilitation can be broadly seen as a market institution innovation, especially in the poorer LMICs. We expect these relationships to expand over the next decade as the double-pronged food system revolution continues its rapid course, with both the proliferation of SMEs and of modern large-scale firms underpinning the growth of rural-urban supply chains (Reardon et al. 2019).

Despite still being in its infancy in LMICs, e-commerce (marketing online) and e-procurement (buying intermediate inputs online) are emerging rapidly. The diffusion of Internet access, mobile phones, and computers helps the spread of "delivery intermediaries," whose expansion has been particularly rapid during the COVID-19 pandemic as consumers tried to avoid in-person shopping (Reardon and Swinnen 2020). COVID-19 accelerated e-commerce growth, for example, from 30% to 70% per year in India, 10% to 20% in China, and 20% to 50% in Nigeria (Vardhan 2020). The benefits of e-commerce for small farmers will depend on three conditions. First, widespread access to e-commerce will depend on mobile phone rates and Internet costs, which currently are particularly high in Africa (Torero 2019). Second, while e-commerce can make it easier for small farmers to sell to urban markets, their costs and product quality must still be competitive with medium and large farmers and importers. Small farmers linked to e-commerce may be better able to compete in more proximate niche markets. Third, e-commerce as digitalization per se only informs a buyer of a seller and a seller of a buyer; the final transaction still relies on delivery intermediaries, roads, and logistics, and the same high transaction costs that have constrained the development of non-digitized supply chains will constrain large numbers of small farmers from participating in e-commerce.

Encouragingly, there are interesting examples of e-commerce that are inclusive of small farmers with potential to spread in the future, depending on the three conditions noted above. In Indonesia, the Rumah Sayur Group, a vegetable farm co-op with 2500 farmers, sold to supermarkets, wet markets, and food-service businesses in Jakarta before the pandemic. During the pandemic, they turned to Alibaba's Lazada to sell directly to consumers and retailers. In Malaysia, Lazada connected SME flower suppliers to online florists to gain a new customer base when COVID-19-related restrictions interrupted the traditional marketing system. In Africa, Facebook and other e-platforms have helped small farmers sell directly to consumers. Examples include Koop direk von boer (buy directly from the farmer), a Facebook group of farmers created in May 2020 that attracted 46,000 members across South Africa in just 2 weeks (Masiwa 2020).

Upstream from the farm, market conditions affect the input prices, risk, and transaction costs facing small farmers, just as the output market affects the profitability of adopting new farm technologies and the transition to higher-value products, as do input supply chains. Importantly, input market conditions are parallel to output market conditions, affected by many of the same policies and public investments discussed in the context of downstream factors. Again, the development of these conditions is a local innovation. Changes in these conditions can rapidly improve input market access for small farmers, spurring technology change at the farm level.

Some particularly interesting market institutions and technological innovations in agricultural service markets appear to be helping small farmers. We characterize them as the development of **mobile "outsource" services**. They include a wide range of services available to farmers on a fee basis. For an individual small farmer, the outlays of capital for machines required would not be affordable given their small scale and the large lump-sum fixed cost for machinery. In the early 1880s, such on-demand operational services emerged in the United States and European countries, where large farmers dominated. Small farmer demand for mechanization and agricultural operational services has risen in recent years in LMICs, first in Asia and Latin America and, more recently, in Africa. These services, perhaps especially as they are facilitated by communications innovations, appear to provide important support to small farming technological change. In general, mobile technology can help service supply and extension reach widely dispersed small farmers (Van Campenhout et al. 2021). For example, mobile mechanization services for land preparation, harvesting, and threshing are hired by many small farmers in South and Southeast Asia (Zhang et al. 2017; Paudel et al. 2019; Diao et al. 2020; Yagura 2020; Belton et al. 2021). They are increasingly accessible for small farmers in Africa (Berhane et al. 2016; Kahan et al. 2018; Takeshima 2018; Diao et al. 2020; Cabral 2021). Mobile phones are widely used for connecting service providers and small farmers, and new digital platforms appear to have potential to reach groups of small farmers. Examples include Hello Tractor in Nigeria, TroTro Tractor in Ghana, Rent to Own in Zambia, and EM3, Trringo, and farMart in India (Birner et al. 2021; Daum et al. 2020).

Moreover, other SME services are emerging in various agricultural operations traditionally carried out by small farmers themselves, such as for rice seeding and transplanting in southern China (Li et al. 2015; Gong et al. 2012); spraying, pruning, land preparation, harvesting, and marketing for mango farmers in Indonesia (Qanti et al. 2017); seed propagation, digging wells and ponds, spraying, and loading trucks for vegetable farmers in Ethiopia (Minten et al. 2020); and bee pollination services for vegetable and fruit growers throughout China (Altay News 2019). Many of these services have replaced labor-intensive farming activities with machines or specialized techniques, helping small farmers who lack the cash to invest in machines, the skills to use machines and other techniques, or simply the time to spend farming because of non-farm employment. These services also introduce small farmers to new technologies that they otherwise might have been unaware of had they not been provided as part of a package of services by SMEs, such as flower hormone use to extend the harvesting of mangoes in Indonesia (Qanti et al. 2017).

New institutional innovations can also benefit small farmers through contributions to **sustainable land stewardship**. Market-based institutions that incentivize farmers to maintain ecosystem services and biodiversity have been used for over a decade. With payments for ecosystem services (PES), the private or public sector pays land stewards (farmers) to protect watersheds, sequester carbon through tree planting, or conserve biodiversity (Milder et al. 2010). In the case of carbon, for example, the institution providing payments receives offset credits in the voluntary or regulatory carbon market. Another scheme involves certification of agricultural commodities, such as coffee, palm oil, and cacao. Certification schemes are generally implemented by non-governmental organizations (NGOs) and rely on consumers paying a premium for production practices that conform to sustainable social and environmental goals (Brandi et al. 2015; Giovannucci and Ponte 2005; Ruysschaert and Salles 2014). Smallholder farmers have benefited from these schemes only to a modest degree due to high transaction costs, low demand for ecosystem services, and poor access to information.

For carbon markets, smallholder participation is impeded by the required technical capacity, as well as the costs of monitoring and complex requirements for reporting (Brandi et al. 2015; Wells et al. 2017). With certification schemes, evidence indicates mixed success for environmental, social, and economic goals. The supply of certified products is generally larger than the demand (DeFries et al. 2017). Insecure land tenure, lack of credit, and insufficient profit to warrant the required investments hamper smallholder participation in both PES and certification schemes.

With rising recognition of the importance of land stewardship for climate mitigation and conservation of biodiversity, institutions to incentivize protection of ecosystem services and sustainability goals are likely to become more widespread in the coming decades. Carbon markets, which, to date, have largely been unable to stem land clearing and greenhouse-gas-emitting practices on agricultural land, will likely be a more significant driver of farmers' decisions in the future. In combination with digital technology, institutional innovations have the potential to reduce transaction costs and enable participation by smallholders to maximize their ability to benefit from these schemes, both to boost their incomes and to contribute to society's sustainability goals. Technology and training for smallholders to access and interpret satellite data, monitor their lands, and fulfill reporting requirements are needed if they are to benefit from a growing demand for ecosystem services.

4 Policies for Inclusive Small Farm Transformation Through Innovation

This chapter has sought to imagine the future of small farms and identify promising innovations in agrifood systems to improve their prospects over the next 10 years. Because small farms are heterogeneous and dynamic, we classed them into three groups: commercial, in-transition, and subsistence-oriented small farms. Each has its own set of challenges and opportunities, and policies and investments that prioritize inclusive small farm transformation must be differentiated to best target the needs of each group as agrifood systems evolve (Hazell 2020).

Commercial small farmers are the vanguard of agrifood transformation and best prepared to take advantage of the opportunities that growing market demand for agrifood products will create. They tend to be located in more favorable agroclimates, nearer to cities and towns, and in areas better served by infrastructure and midstream SMEs that facilitate input and output markets. These same market opportunities will incentivize some transitional farmers to invest in their small farms and become commercial farmers. **To enhance small commercial and transitional farmers' competitiveness to pursue these market opportunities, the following government policies and public investments are important**:

- Increase investments in infrastructure, including rural roads connecting to secondary and tertiary cities, that can create economies of agglomeration and a critical mass of proximate services such as wholesale, logistics, and farm input provision for small farmers in the surrounding rural areas, thus reducing transaction costs. Often, mobile agricultural services are clustered in towns and fan out to serve small farms in a hub-and-spoke model (Zhang et al. 2017). Many new digital technologies applied in e-commerce, information provision, and farm service businesses also depend on good infrastructure. While initial investments need to come from governments, they will serve to lure in private investments from both large companies and SMEs.
- Promote education and training programs that target rural youths to develop the skills and knowledge required to support modern agriculture and marketing. These skills are necessary for both farm management and off-farm jobs in logistics, machinery maintenance/repair services, and broader RNFE.
- Facilitate co-operatives and farmer groups that can collectively pursue emerging opportunities in urban markets and modern farm technology. Local networks can also be strengthened through village-level innovation platforms to link smallholder farmers with extension and research, such as China's Science and Technology Backyard (Barrett et al. 2020a). These show promise for drawing together the wisdom of (small farmer) crowds and the knowledge of cutting-edge scientific researchers to accelerate discovery, adaptation, and diffusion (Nelson 2019; van Etten et al. 2019).
- Support SMEs upstream and downstream from farms by reducing unnecessary regulations and informal restrictions that often discourage SME development. SMEs are more accessible to small farmers than larger enterprises, and small farmers value the mix of services that SMEs provide (Liverpool-Tasie et al. 2020).

RNFE is the main economic activity of transitional farmers and is increasingly the main source of income for most small farmers. RNFE provides small farmers with cash, both to purchase food and for farm investments to raise productivity, expand commercial activities, and produce higher-value products. RNFE is also important for some marginalized farmers, helping them reduce their reliance on risky, low-yield agriculture. For these farmers, RNFE development will directly improve food security in a way that marginally boosting agricultural production cannot (ZEF and FAO 2020; Frelat et al. 2016). Public investments and policies that facilitate growth of the agrifood system must pay more attention to creating enabling environments for the development of RNFE and strengthening the synergy between agriculture and RNFE in rural areas. In this regard, the following actions are promising for **governments to actively promote agriculture–RNFE synergies for rural development and agrifood system transformation**:

- Pursue policies that have broad effects across economic activities in rural areas and do not limit interventions to farming alone. RNFE and farming are complementary, and both are needed for inclusive growth in rural areas.
- Develop an enabling environment—including basic infrastructure, property rights, and legal systems with enforcement mechanisms—favorable to rural businesses that encourage and facilitate inclusive RNFE (Haggblade et al. 2007).
- Identify engines of regional growth through consultation with the private sector and farmers, and conduct supply chain diagnostics for prioritization of strategic interventions (Haggblade et al. 2007). Emphasize differentiated strategies and flexible institutional coalitions for implementation appropriate to diverse rural areas.

This chapter emphasizes the importance of market institution innovations for achieving higher agricultural productivity and quality through small farm technology adoption and improving incomes for small farm households through participation in both farm and non-farm economic activities. In addition to the policy recommendations discussed above, some **additional policy recommendations** are listed here, although adapting and differentiating policies over heterogeneous contexts across LMICs requires context-specific research and consultation with stakeholders (Barrett et al. 2020b):

- Support new technologies that reduce risk and are attractive to small farmers when viewed in a holistic way, taking into account farmers' resource environment, as well as their livelihood strategies. Do not automatically assume labor-intensive innovations are appropriate for small farmers, who often want to reduce, not intensify, their farm labor use (Hazell 2020). For transitional farmers who depend on RNFE, proposing new labor-intensive farming activities could fail if they cut into the time farmers have available for RNFE livelihood strategies (Moser and Barrett 2006).
- Ensure that agricultural interventions to support sustainable farming practices are economically viable for farmers and provide direct economic benefits. In the longer term, farmers are most strongly motivated to adopt and maintain sustainable practices when they perceive positive outcomes of these practices for their farm or the environment (Piñeiro et al. 2020).
- Scale up productive social protection programs for subsistence farmers in hinterland areas who face barriers in accessing markets and other economic opportunities. Safety net programs ease liquidity constraints and increase tolerance for

risk among small farms and, when integrated with measures to increase agricultural productivity, have the potential to make significant progress toward the eradication of hunger (Wouterse et al. 2020).

References

African Union, AU (2014) Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods Doc. Assembly/Au/2 (Xxiii)

Altay News (2019) Shu Xinanda: 'Visit Huiju' Task Force Asked Bees to Work to Spread Pollination to Promote Income. August 14. https://baijiahao.baidu.com/s?id=1641857490903640521&wfr=spider&for=pc (in Chinese)

Anache JAA, Wendland E, Rosalem LMP, Youlton C, Oliveira PTS (2019) Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado. Hydrol Earth Syst Sci 23(3): 1263–1279

Barrett CB, Benton T, Fanzo J, Herrero M, Nelson RJ, Bageant E, Buckler E et al (2020a) Socio-technical innovation bundles for Agri-food systems transformation, report of the international expert panel on innovations to build sustainable, equitable, inclusive food value chains. Cornell Atkinson Center for Sustainability and Springer Nature, Ithaca/London

Barrett CB, Reardon T, Swinnen J, Zilberman D (2020b) Agri-food value chain revolutions in low- and middle-income countries. J Econ Lit

Belton B, Cho A, Payongayong E, Mahrt K, Abaidoo E (2020) Commercial Poultry and Pig Farming in Yangon's Peri-Urban Zone. Research Paper 174. Food Security Policy Project (FSPP), Feed the Future Innovation Lab for Food Security Policy, Michigan State University. https://www.canr.msu.edu/fsp/publications/research-papers/RP_174.pdf

Belton B, Thida Win M, Zhang X, Filipski M (2021) The rapid rise of agricultural mechanization in Myanmar. Food Policy 101

Berhane G, Hirvonen K, Minten B (2016) Synopsis, Agricultural Mechanization in Ethiopia: Evidence from the 2015 Feed the Future Survey, ESSP II Research Note 48. International Food Policy Research Institute (IFPRI) and Ethiopian Development Research Institute (EDRI), Washington, DC/Addis Ababa

Birner R, Daum T, Pray C (2021) Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. Appl Econ Perspect Policy 43(4):1260–1285

Brandi C, Cabani T, Hosang C, Schirmbeck S, Westermann L, Wiese H (2015) Sustainability standards for palm oil: challenges for smallholder certification under the RSPO. J Environ Dev 24(3):292–314

Cabral L (2021) Of zinc roofs and mango trees: tractors, the state and agrarian dualism in Mozambique. J Peasant Stud 49. https://doi.org/10.1080/03066150.2020.1860026

Daum T, Capezzone F, Birner R (2020) Using smartphone app collected data to explore the link between mechanization and intra-household allocation of time in Zambia. Agric Hum Values 38(2):411–429

Davis B, Winters P, Reardon T, Stamoulis K (2009) Rural nonfarm employment and farming: household-level linkages. Agric Econ 40(2):119–123

Davis D, Di Giuseppe S, Zezza A (2017) Are African households (not) leaving agriculture? Patterns of households' income sources in rural sub-Saharan Africa. Food Policy 67:153–174

De Janvry A, Sadoulet E (2006) Making conditional cash transfer programs more efficient: designing for maximum effect of the conditionality. World Bank Econ Rev 20(1):1–29

DeFries R, Fanzo J, Mondal P, Remans R, Wood S (2017) Is voluntary certification of tropical agricultural commodities achieving sustainability goals? A review of the evidence. Environ Res Lett 12(3):033001

Diao X, Takeshima H, Zhang X (eds) (2020) An evolving paradigm of agricultural mechanization development: how much can Africa learn from Asia? International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/9780896293809
Dolislager M, Reardon T, Arslan A, Fox L, Liverpool-Tasie S, Sauer C, Tschirley D (2020) Youth and adult Agrifood system employment in developing regions: rural (Peri-urban to hinterland) vs urban. J Dev Stud 57(4):571–593
Eastwood R, Lipton M, Newell A (2010) Farm Size. In: Pigali P, Evenson RE (eds) Handbook of agricultural economics, vol 4. Elsevier BV Academic Press, Burlington, pp 3323–3397
FAO (Food and Agriculture Organization of the United Nations) (2014) The state of food and agriculture. Innovation in Family Farming, Rome
Fifanou VG, Ousmane C, Gauthier B, Brice S (2011) Traditional agroforestry systems and biodiversity conservation in Benin (West Africa). Agrofor Syst 82(1):1–13
Frelat R, Lopez-Ridaura S, Giller KE, Herrero M, Douxchamps S, Djurfeldt AA et al (2016) Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proc Natl Acad Sci 113(2):458–463
Giller KE, Delaune T, Silva JV, Descheemaeker K, van de Ven G, Schut AGT, van Wijk M, Hammond J, Hochman Z, Taulya G, Chikowo R, Narayanan S, Kishore A, Bresciani F, Teixeira HM, Andersson J, van Ittersum M (2020) The future of farming: who will produce our food? Background paper for the Towards Inclusive, Sustainable, Nutritious and Efficient Food Systems project
Giovannucci D, Ponte S (2005) Standards as a new form of social contract? Sustainability initiatives in the coffee industry. Food Policy 30(3):284–301
Gong J, Zhang H, Hu Y, Wang L, Long H, Mao C, Mao H, Dai Q, Luo Z, Xui K, Wei H (2012) An analysis on the rising Rice commercialized centralized seedling. China Rice 18(4):26–30. (in Chinese)
Graeub BE, Chappell MJ, Wittman H, Ledermann S, Kerr RB, Gemmill-Herren B (2016) The state of family farms in the world. World Dev 87:1–15
Haggblade S, Hazell P, Reardon T (eds) (2007) Transforming the rural nonfarm economy: opportunities and threats in the developing world. International Food Policy Research Institute and Johns Hopkins University Press, Washington, DC/Baltimore
Hazell P (2018) Urbanization, agriculture and smallholder farming. In: Serraj R, Pingali P (eds) Agriculture and food systems to 2050: global trend, challenges and opportunities. World Scientific Publishing, Singapore, pp 137–160
Hazell P (2020) Importance of smallholder farms as a relevant strategy to increase food security. In: y Paloma SG, Riesgo L, Louhichi K (eds) The role of smallholder farms in food and nutrition security. Springer, Cham, pp 29–43
Herrero M, Thornton P, Power B, Bogard J, Remans R, Fritz S, Gerber J, Nelson G, See L, Waha K, Watson R, West P, Samberg L, van de Steeg J, Stephenson E, van Wijk M, Havlík P (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):E33–E42
Herrero M, Thornton PK, Mason-D’Croz C, Palmer J, Benton TG, Bodirsky BL, Bogard J et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1: 266–272
Herrero M, Thornton PK, Mason-D’Croz C, Palmer J, Bodirsky BL, Pradhan P, Barrett CB et al (2021) Articulating the impact of food systems innovation on the sustainable development goals. Lancet Planet Health 5(1):E50–E62
Hickson K, Thornton P (2020) Updates to the Number of Agricultural Holdings by Country Dataset of Lowder et al. (2016). Unpublished, CIAT and ILRI
Hu C, Zhang X, Reardon T, Hernandez RA (2019) Value-chain clusters and aquaculture innovation in Bangladesh. Food Policy 83(February):310–326
Huang H, Gong X, Huang B (2010) The competitive advantages of agricultural industrial clusters based on specialization: a case study of Shouguang County vegetable industry cluster. Agric Econ Issues 4:64–111. (in Chinese)

Kahan D, Bymolt R, Zaal F (2018) Thinking outside the plot: insights on small-scale mechanization from case studies in East Africa. J Dev Stud 54(11):1939–1954
Laborde Debucquet D, Murphy S, Parent M, Porciello J, Smaller C (2020) Ending hunger, increasing incomes, and protecting the climate: what would it cost donors? International Institute for Sustainable Development (IISD), Winnipeg
Lanjouw P, Murgai R (2009) Poverty decline, agricultural wages, and nonfarm employment in rural India: 1983–2004. Agric Econ 40(2):243–263
Li S, Zhu C, Ma X, Li H (2015) Centralized seedlings and machine-transplanted Rice in Nantong City in China. China Rice 213:72–74. (in Chinese)
Liverpool-Tasie LSO, Omonona B, Sanou A, Ogunleye W, Padilla S, Reardon T (2017) Growth and transformation of chicken and eggs value chains in Nigeria. Nigerian J Agric Econ 7(1): 1–15
Liverpool-Tasie LSO, Reardon T, Belton B (2020) 'Essential non-essentials': COVID-19 policy missteps in Nigeria rooted in persistent myths about African food value chains. Appl Econ Perspect Policy 43(1):205–224
Lowder SK, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev 87(November):16–29
Masiwa D (2020) Fed-up farmers to turn to Facebook to sell their produce. Food for Mzansi (May 13)
McCord PF, Cox M, Schmitt-Harshe M, Evans T (2015) Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. Land Use Policy 42(January):738–750
Milder JC, Scherr SJ, Bracer C (2010) Trends and future potential of payment for ecosystem services to alleviate rural poverty in developing countries. Ecol Soc 15(2):4
Minten B, Reardon T, Singh KM, Sutradhar R (2014) The new and changing roles of cold storages in the potato supply chain in Bihar. Econ Polit Wkly 49(52):98–108
Minten B, Tamru S, Engida E, Kuma T (2016) Feeding Africa's cities: the case of the supply chain of Teff to Addis Ababa. Econ Dev Cult Chang 64(2):265–297
Minten B, Mohammed B, Tamru S (2020) Emerging medium-scale tenant farming, gig economies, and the COVID-19 disruption: the case of commercial vegetable clusters in Ethiopia. Eur J Dev Res 32(October):1402–1429
Moser CM, Barrett CB (2006) The complex dynamics of smallholder technology adoption: the case of SRI in Madagascar. Agric Econ 35(3):373–388
Nelson J (2019) No Smallholder Farmer Left Behind. Time for Specifics on the Sustainable Development Goals, Leave No One Behind
Ouin A, Burel F (2002) Influence of herbaceous elements on butterfly diversity in hedgerow agricultural landscapes. Agric Ecosyst Environ 93(1-3):45–53
Paudel GP, Kc DB, Rahut DB, Justice SE, McDonald AJ (2019) Scale-appropriate mechanization impacts on productivity among smallholders: Evidence from Rice Systems in the mid-Hills of Nepal. Land Use Policy 85(June):104–113
Piñeiro V, Arias J, Dürr J, Elverdin P, Ibáñez AM, Kinengyere A et al (2020) A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nature Sustainability 3(10):809–820
Qanti SR, Reardon T, Iswariyadi A (2017) Triangle of linkages among modernizing markets, sprayer traders, and mango-farming intensification in Indonesia. Bull Indones Econ Stud 53(2):187–208
Reardon T, Swinnen J (2020) COVID-19 and resilience innovations in food supply chains. In: Swinnen J, McDermott J (eds) COVID-19 & global food security. International Food Policy Research Institute, Washington, DC, pp 132–136
Reardon T, Echeverría R, Berdegué J, Minten B, Liverpool-Tasie S, Tschirley D, Zilberman D (2019) Rapid transformation of food Systems in Developing Regions: highlighting the role of Agricultural Research & Innovations. Agric Syst 172(June):47–59

Reardon T, Belton B, Liverpool-Tasie LSO, Lu L, Nuthalapati CSR, Tasie O, Zilberman D (2021a) E-Commerce's fast-tracking diffusion and adaptation in developing countries. Appl Econ Perspect Policy 43. https://doi.org/10.1002/aepp.13160
Reardon T, Heiman A, Lu L, Nuthalapati CSR, Vos R, Zilberman D (2021b) 'Pivoting' by food industry firms to cope with COVID-19 in developing regions: E-commerce and 'co-pivoting' delivery-intermediaries. Agricultural Economics (preprint). https://doi.org/10.1111/agec.12631
Ricciardi V, Ramankutty N, Mehrabi Z, Jarvis L, Chookolingo B (2018) How much of the world's food do smallholders produce? Glob Food Sec 17(May):64–72
Ricciardi V, Mehrabi Z, Wittman H, James D, Ramankutty N (2021) Higher yields and more biodiversity on Smaller farms. Nat Sustain 4. https://doi.org/10.1038/s41893-021-00699-2
Ritchie H, Roser M (2017) CO_2 and greenhouse gas emissions. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions
Ruysschaert D, Salles D (2014) Towards global voluntary standards: questioning the effectiveness in attaining conservation goals: the case of the roundtable on sustainable palm oil (RSPO). Ecol Econ 107(November):438–446
Samberg LH, Gerber JS, Ramankutty N, Herrero M, West PC (2016) Subnational distribution of average farm size and smallholder contributions to global food production. Environ Res Lett 11(November):124010
Stifel D, Minten B, Koru B (2016) Economic benefits of rural feeder roads: evidence from Ethiopia. J Dev Stud 52(9):1335–1356
Swinnen J, Kuijpers R (2019) Value chain innovations for technology transfer in developing and emerging economies: conceptual issues, typology, and policy implications. Food Policy 83(February):298–309
Takeshima H (2018) Mechanize or exit farming? Multiple-treatment-effects model and external validity of adoption impacts of mechanization among Nepalese smallholders. Rev Dev Econ 22(4):1620–1641
Thurlow J, Dorosh P, Davies B (2019) Demographic change, agriculture and rural poverty. In: Campanhola C, Pandey S (eds) Sustainable food and agriculture: an integrated approach. Elsevier and FAO, London, pp 31–53
Torero M (2019) A Digital Revolution without a Digital Divide for sub-Saharan Africa. In Africa Agriculture Status Report: The Hidden Middle: A Quiet Revolution in the Private Sector Driving Agricultural Transformation (Issue 7). Alliance for a Green Revolution in Africa (AGRA) (editor). Nairobi, Kenya: AGRA. https://agra.org/wp-content/uploads/2019/09/AASR2019-The-Hidden-Middleweb.pdf
United Nations (2019) Department of Economic and Social Affairs, Population Division, UN DESA (2019). World Population Prospects 2019: Highlights. ST/ESA/SER.A/423
Van Campenhout B, Spielman DJ, Lecoutere E (2021) Information and communication technologies to provide agricultural advice to smallholder farmers: experimental evidence from Uganda. Am J Agric Econ 103(1):317–337
van Etten J, de Sousa K, Aguilar A, Barrios M, Coto A, Dell'Acqua M et al (2019) Crop variety management for climate adaptation supported by citizen science. Proc Natl Acad Sci 116(10):4194–4199
Vandercasteelen J, Beyene ST, Minten B, Swinnen J (2018) Big cities, small towns, and poor farmers: evidence from Ethiopia. World Dev 106(June):393–406
Vardhan V (2020) Impact of the COVID-19 pandemic on retailing in emerging countries. [PowerPoint]. Euromonitor International. Unpublished
Vorley B (2002) Sustaining agriculture: policy, governance, and the future of family-based Farming. IIED, London, pp 1–196
Wang X, Yamauchi F, Huang J (2016) Rising wages, mechanization, and the substitution between capital and labor: evidence from small scale farm system in China. Agric Econ 47(3):309–317
Wells G, Fisher JA, Porras I, Staddon S, Ryan C (2017) Rethinking monitoring in smallholder carbon payments for ecosystem service schemes: devolve monitoring, understand accuracy and identify co-benefits. Ecol Econ 139(September):115–127

Woodhill J, Hasnain S, Griffith A (2020) Farmers and food systems: what future for small-scale agriculture? Environmental Change Institute, University of Oxford, Oxford

World Bank (2016) Poverty and shared prosperity 2016: taking on inequality, Washington, DC

Wouterse F, Murphy S, Porciello J (2020) Social protection to combat hunger. Nat Food 1(9): 517–518

Yagura K (2020) Rapid diffusion of combine harvesters in Cambodian Rice farming: a business analysis. Asian J Agric Dev 17(1):71–88

ZEF (Center for Development Research) and FAO (Food and Agriculture Organization of the United Nations) (2020) Investment costs and policy action opportunities for reaching a world without hunger (SDG2), Rome/Bonn

Zhang X, Yang J, Reardon T (2017) Mechanization outsourcing clusters and division of labor in Chinese agriculture. China Econ Rev 43(April):184–181

Diversification for Enhanced Food Systems Resilience

Thomas Hertel, Ismahane Elouafi, Morakot Tanticharoen, and Frank Ewert

Global change and an increasingly interconnecting society are inducing unprecedented hazards that are likely to prove disastrous for many of the world's most vulnerable populations (UN Office for Disaster Risk Reduction 2019). Food systems are at the heart of this challenge and need to become more resilient to ensure access to food while also providing livelihoods for a large share of the world's poorest households (Hertel et al. 2021). A resilient food system must be financially equitable (economic resilience), supportive of the entire community (social resilience), and it must minimize harmful impacts on the natural environment (ecological resilience). Towards this end, the UN Food Systems Summit 2021 designated resilience as one of five 'Action Tracks'. Reviewing this subject for the summit (Hertel et al. 2021), one central theme has emerged: the importance of diversification. Diversification of the food system can occur across the entire food supply chain and at different levels of organization (Fig. 1). Here we focus on the diversification of production and markets, and household responses, to illustrate the growing importance of diversification. We also highlight research gaps and challenges for its adoption.

T. Hertel (✉)
Department of Agricultural Economics, Purdue University, West Lafayette, IN, USA
e-mail: hertel@purdue.edu

I. Elouafi
UN-FAO, Rome, Italy

M. Tanticharoen
The National Science and Technology Development Agency, Bangkok, Thailand

F. Ewert
Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany

University of Bonn, Bonn, Germany

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_11

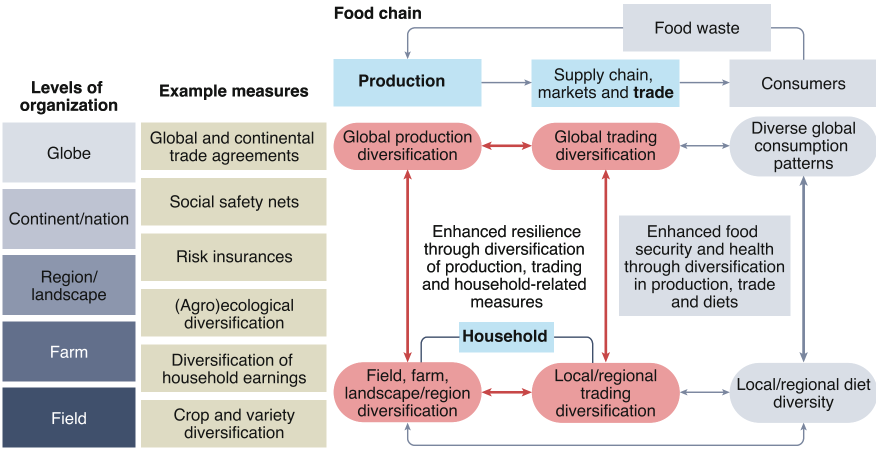


Fig. 1 The importance of food system diversification across levels of organization with selected example measures to enhance food systems' resilience. Note that diversification of processing and diets are not addressed in this comment but are closely related to diversification of production, household livelihoods and trade

1 Diversification of Production

Diversification of production, particularly for crops and cropping systems, has received increasing attention in recent years (Hufnagel et al. 2020) as a means of building resilience to climate change and increasing extreme weather events and also to improve the ecological performance of crops, reducing their harmful impacts on the climate and the environment (Tamburini et al. 2020). Increasing evidence also shows that bio-diverse ecosystems are capable of delivering additional ecosystem services without compromising crop yields (Tamburini et al. 2020) or even with benefits for crop production (Dainese et al. 2019).

Importantly, diversification of production should encompass different levels of the organisation (Fig. 1). Agroecology, an approach receiving increasing attention in research and agricultural practice (Wezel et al. 2014), attempts to explicitly leverage the benefits of agroecological relationships. Agroecological practices including diversification refer to the field, farm, landscape and regional scale and up to the broader food system (Wezel et al. 2014). However, while diversification of crops and cropping systems have frequently been investigated (Hufnagel et al. 2020), diversification of agricultural landscapes and regions also deserves consideration as it has many beneficial effects on biodiversity and ecosystem services (Tscharntke et al. 2021).

Any attempt to integrate approaches to diversify production across organizational levels will need to go beyond the land-based production sub-sector encompassing other sub-sectors such as aquaculture as well as vertical and urban farming. The importance of aquaculture as an integrated part of the global food system has been highlighted (Naylor et al. 2021) and in some world regions (e.g., Asia), food contributions from inland-aquaculture is critically important (Naylor et al. 2021). However, despite progress in recent years, issues remain regarding the sustainability of production and the development of markets (Naylor et al. 2021) jointly with other production sectors to improve food systems resilience.

The concrete solutions for diversification of production will depend on the local and regional natural (e.g., soils, climate and geography) but also socio-economic and cultural conditions determining present farming systems. Understanding the ecological-economic trade-offs of diversified farming systems (Rosa-Schleich et al. 2019) is crucial for successful diversification strategies. Positive outcomes of crop diversity for agricultural employment worldwide have been reported but the economic costs of diversifying farming systems often outweigh the ecological benefits (Rosa-Schleich et al. 2019) suggesting the need for adequate policies to support the development of diverse and sustainable (ecological, economic and social) production and farming systems and households (FAO et al. 2021).

2 Diversification at the Household Level

A key goal of the food system is to enhance the well-being of individuals, and the households to which they belong. This requires a household-centric view of diversification and resilience. Given the prominent role of income in ensuring household well-being, diversification of income sources is critical. Three important sources of income diversification are: risk management, safety nets and labor market diversification.

Diversification across states of nature: With extreme weather events expected to become more frequent in the future (IPCC 2021), new forms of risk management will be needed. Traditional methods of community-based risk sharing are no longer viable when entire communities face common risks from drought, flooding and heat stress. Weather index insurance has been developed specifically for such circumstances (Hazell et al. 2010). Households enroll at the beginning of the season and payouts for all farmers in the disaster-affected region are made when an index for (e.g.) rainfall in the region drops below a pre-determined trigger level. This allows households to diversify their incomes across different 'states of nature', paying out money when the weather is normal and receiving money when drought or flooding disasters strike. This form of diversification has great potential to stabilize rural agricultural household incomes.

Since its inception, weather index insurance has faced challenges in reaching the poorest households – as they typically confront severe credit constraints. However, recent technological innovations like remote sensing and e-banking are permitting index insurance to thrive across the developing world. India and China, where 80% of all farms have some form of insurance, have led the way (GIZ 2021). In Africa, where 70% of the programs are private sector led – albeit often in partnership with the public sector – this market penetration is still very small. One of the most successful programs is the Agriculture and Climate Risk Enterprise (ACRE) program which has reached more than 1.7 million farmers in East Africa. ACRE works with local institutions such as cooperatives and agricultural finance providers to reach individual farmers (GIZ 2021). ACRE weather index insurance has allowed three-quarters of participants to access credit that would otherwise have not been available to them due to the risk of catastrophic losses. While promising, reaching its full potential will require education about the benefits of insurance as well as also improved historical weather information which is still scarce in much of the region (GIZ 2021).

Social safety nets: While weather index insurance provides an important source of income diversification for agricultural producers, it does not directly benefit non-farm households and fails to shield net buyers of food from food price spikes in the wake of extreme weather events. For these households, other social safety nets can play an important role. While widespread throughout much of the world, social protection programs have only recently emerged on the scene in Africa where they are rapidly expanding (Correa et al. 2021). This trend has been further accelerated in the context of the COVID-19 pandemic.

While social assistance and social insurance can be viewed as sources of income diversification in their own right, recent research suggests that such programs can also have important impacts on households' livelihood strategies. By providing an assured source of income, social protection can reduce the risk associated with investments in new activities, including increased participation in commercial agricultural markets and increased farm productivity, as well as increased engagement in non-farm activities (Correa et al. 2021). In a recent study of the Harmonized Social Cash Transfer program targeting ultra-poor, labor constrained households in remote, rural Zimbabwe, Pace et al. (2021) find significant impacts on income diversification over the medium run (four years). Specifically, they identify a shift from survival-led diversification, driven by seasonality, climatic uncertainty, land constraints and limited market access, to opportunity-led diversification, including higher paying non-farm activities, with attendant increases in food and non-food consumption.

Rural-Urban Migration and Income Diversification: While rural off-farm work can provide important income diversification opportunities, many rural households also choose to send one or more family members to work in urban areas. Rural-urban migration has been a long-standing means of diversifying and raising household income, with remittances from migrants to their communities of origin helping to ensure food security, reduce poverty, support children's education, ease credit constraints in farming, pay for farm inputs and repay debts (Deshingkar 2006). Furthermore, when an urban disaster arises, such as the East Asian financial crisis of 1997, the rural household connection can provide an important safety net.

The importance of migrants' remittances to rural household well-being has been underscored during the COVID-19 pandemic. Border closures and lockdown restrictions have resulted in significant loss of jobs and economic activities throughout much of the developing world. Consequently, these remittances, a vital source of income for the rural villagers, have been largely lost (World Bank 2020). Thus, not only has the pandemic worsened poverty and inequality, it is also likely to leave long-lasting scars on labor markets, reversing progress on poverty and income inequality in many economies and reducing resilience.

3 Diversification Through the Global, Regional and Local Trading Systems

Weather index insurance, safety nets and household income diversification are necessary to ensure households' food security, but they are not sufficient in the face of widespread weather disasters such as droughts and flooding which may jeopardize local and regional food availability. Here, robust markets and trade play a critical role in ensuring food security. There is perhaps no better illustration than that provided by pre-colonial India, where weather-induced famines were common, resulting in tens of millions of deaths. However, with the introduction of railroads in colonial India, large-scale interstate trade became possible and there was a dramatic reduction in the number of deaths associated with extreme weather events; improved market integration greatly enhanced food security by allowing for timely imports from food surplus regions (Burgess and Donaldson 2010).

Trade amongst nations can play the same role – mediating between food surplus and food deficit regions in the face of scarcity. However, this is only possible if government and private actors operate under a rules-based system with adequate information provided to everyone engaged in agricultural markets. The potential for markets to be destabilized by panic and misinformation was on dramatic display during the 2006–2008 food crisis when cascading export bans and panic greatly exacerbated the price rises for rice and wheat (Martin and Anderson 2012). These price spikes were particularly severe for consumers in the poorest countries. In the wake of that experience, the G-20 Ministers of Agriculture initiated a multinational, multiagency effort to provide improved market information. Nicknamed AMIS, this information system documents in detail government interventions – their scope, duration and modification, on a real time basis, along with up to date information on commodity stocks and production. As a consequence, over-reactions on the part of governments and markets to the disruptions posed by the COVID-19 pandemic were avoided (Jansen 2020). However, merely documenting these interventions is insufficient. It is important to reach a new multilateral agreement in agriculture that will prevent countries from intervening in markets during these crisis periods.

Of course, it is not enough to integrate national markets into the global economy. Many of the world's smallholder farmers and rural households are poorly integrated into local and regional markets, thus limiting their ability to benefit from intra- and international trade. In Ethiopia, a pilot effort dubbed P4P: Purchase for Progress, run by the World Food Program, works through farmer organizations in order to better integrate farm households into regional markets. This involves reducing transactions costs and improving information flows. A recent study of the P4P pilot project in Ethiopia finds that these interventions have boosted spending by participating households by 25% – as well as sharply increased investment in children's education (Gelo et al. 2020). This effort has benefited not only short-term resilience, but also long-term development and poverty reduction objectives.

4 Conclusions

While there are many different avenues to obtain greater food system resilience, we believe that the most fundamental of these is diversification, which can occur at many different levels and across components of the food system. This comment has focused on diversification of agricultural production and trade and on household-related responses. However, equally important for food system resilience will be diversification along the entire value chain as well as in consumption. Diversity in diets is a critical element for ensuring healthy consumer outcomes, while also carrying important implications for patterns of production and trade.

In closing, it should also be noted that many of the elements discussed in this comment interact in important ways. For example, while increased production risk will encourage farmers to diversify, greater market integration encourages specialization in production in order to increase expected household income (Keenan et al. 2021). Clearly, the relationships among diversification of production and other parts of the food system, particularly diversification of diets and markets including market access, are not straightforward and need more attention (Keenan et al. 2021). Food system modeling frameworks to assess resilience are at an early stage of development (Müller et al. 2020) but can be helpful in integrating the complex interactions between food, ecology, economy and society, thereby providing advice on critical trade-offs when diversifying food systems to improve their resilience.

Acknowledgements TH acknowledges support by the National Science Foundation (CBET 1855937 and OISE-2020635) and FE acknowledges support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2070 – 390732324). This chapter was published in Nature Food, 2 832-834 (2021).

References

Burgess R, Donaldson D (2010) Can openness mitigate the effects of weather shocks? Evidence from India's Famine Era. Am Econ Rev 100:449–453

Correa JS, Daidone S, Sitko N (2021) The missing link: understanding the role of social protection in fostering sustainable food system transformation in Africa. In: African Agriculture Status Report, AGRA

Dainese M et al (2019) A global synthesis reveals biodiversity-mediated benefits for crop production. Sci Adv 5:eaax0121

Deshingkar P (2006) Internal migration, poverty and development in Asia: including the excluded. IDS Bull 37:88–100

FAO, UNDP, UNEP (2021) A multi-billion-dollar opportunity – repurposing agricultural support to transform food systems. FAO

Gelo D, Muchapondwa E, Shimeles A, Dikgang J (2020) Aid, collective action and benefits to smallholders: evaluating the World Food Program's purchase for progress pilot. Food Policy 97: 101911

GIZ (2021) Innovations and emerging trends in agricultural insurance: an update

Hazell PBR et al (2010) The potential for scale and sustainability in weather index insurance for agriculture and rural livelihoods. IFAD-WFP

Hertel TW, Elouafi I, Ewert F, Tanticharoen M (2021) Building resilience to vulnerabilities, shocks and stresses. A paper on Action Track 5. https://doi.org/10.48565/scfss2021-cz84

Hufnagel J, Reckling M, Ewert F (2020) Diverse approaches to crop diversification in agricultural research. A review. Agron Sustain Dev 40:14

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Jansen M (2020) COVID-19 and the global economy. In: COVID-19 and the global economy

Keenan M, Karanja S, Pamuk H, Ruerd R (2021) Smallholder farming households' make-or-buy decisions: linking market access, production risks, and production diversity to dietary diversity. In: CGIAR Research Program on Climate Change Agriculture and Food Security

Martin W, Anderson K (2012) Export restrictions and price insulation during commodity price booms. Am J Agric Econ 94:422–427

Müller B et al (2020) Modelling food security: Bridging the gap between the micro and the macro scale. Glob Environ Change 63:1

Naylor RL et al (2021) A 20-year retrospective review of global aquaculture. Nature 591:551–563

Pace N et al (2021) Cash transfers' role in improving livelihood diversification strategies and well-being: short- and medium-term evidence from Zimbabwe. Revis

Rosa-Schleich J, Loos J, Mußhoff O, Tscharntke T (2019) Ecological-economic trade-offs of Diversified Farming Systems – A review. Ecol Econ 160:251–263

Tamburini G et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6

Tscharntke T, Grass I, Wanger TC, Westphal C, Batáry P (2021) Beyond organic farming – harnessing biodiversity-friendly landscapes. Trends Ecol Evol **36**:919–930

UN Office for Disaster Risk Reduction (2019) Global assessment report on disaster risk reduction, UN Office for Disaster Risk Reduction

Wezel A et al (2014) Agroecological practices for sustainable agriculture. A review. Agron Sustain Dev 34:1–20

World Bank (2020) COVID-19 crisis through a migration lens. https://openknowledge.worldbank.org/handle/10986/33634

Addressing Food Crises in Violent Conflicts

Birgit Kemmerling, Conrad Schetter, and Lars Wirkus

Recommendations

- **Respect access to food as a human right:** Any policy action needs to be based on the common understanding that access to food is a human right. Providing safe, continuous and sufficient access to food is foremost the respective government's role. Every government should pursue preventive policies and take emergency measures to secure food equally for all segments of its population. If a government lacks the capacity to prevent or mitigate a food crisis, it should allow and facilitate relief operations as demanded by humanitarian law. Any government or warring faction that prohibits parts of the population from access to food needs to be sanctioned.
- **Build bridges linking humanitarian assistance, development and peacebuilding:** Food assistance, if implemented well, plays a key role in mitigating the devastating effects of conflicts and contributing to peace. While short-term assistance needs to be based on sound conflict analysis and a better understanding of the structural factors that determine vulnerabilities, long-term food assistance should actively integrate peacebuilding approaches. In line with current debates regarding the humanitarian–development–peace (HDP) nexus, improving food security requires greater cooperation and coordination among actors in humanitarian assistance, development cooperation and peacebuilding.
- **Integrate local capacities and perceptions:** Conflict-affected populations adopt multiple strategies to secure food, and these depend on a multitude of factors, such as the context, intensity and duration of the conflict, an individual's situation, access to resources and support, and governance. At the same time, local perceptions of terms such as "peace" and conflict narratives need to be taken into account, since they can differ from one place to another. Local capacities and

B. Kemmerling (✉) · C. Schetter · L. Wirkus
Bonn International Centre for Conflict Studies (BICC), Bonn, Germany
e-mail: birgit.kemmerling@bicc.de; conrad.schetter@bicc.de; lars.wirkus@bicc.de

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_12

response mechanisms to food crises and conflict, as well as local perspectives, need to be better understood and best practices integrated into relief operations and national response strategies.

- **Improve the links between early warning and early action in conflict-driven food crises:** While early warning systems for famine have advanced over the past decades, the links to early action have been weak. Recent developments in anticipatory actions have improved the links and have already addressed disasters in conflict contexts or the impact of conflict itself, but little is known about their effectiveness, and challenges remain, especially in accessing conflict data and data on food security in conflict settings. The development of an integrated platform combining early warning systems for famine and violent conflict could add important data that might serve as the missing link to assess famine, drought and conflict risk more comprehensively while advancing anticipatory humanitarian action in fragile and conflict-affected settings.

1 Introduction

Food insecurity remains one of the greatest global challenges. Since 2014, the number of people affected by hunger worldwide has been rising again: In 2020, an estimated number of 720–811 million people faced hunger, and the prevalence of undernourishment, having been stable for the past 5 years, increased by 1.5–9.9% (FAO et al. 2021). 155 million people in 55 countries or territories were classified as being in crisis conditions or worse (IPC/CH Phase 3 or above[1]) – that number is 20 million more people than in 2019. Violent conflicts undoubtedly play a decisive role in current food crises. In 2020, more than 99 million people in 23 countries were affected by conflict-driven food crises (FSIN & GNAFC 2021). Violent conflicts, in particular, entail severe short- and long-term impacts on the nutrition status of children. For example, studies in different regional contexts find evidence that conflict-affected children are shorter than children born in regions not affected by conflict (Bundervoet et al. 2009; Akresh et al. 2011). Moreover, negative effects on child weight at birth were observed if the mother was exposed to conflict during pregnancy (Camacho 2008). Physical and cognitive impacts have also been found in adults who were exposed to conflict in their early years (Akresh et al. 2012).

Food insecurity and violent conflicts are mostly found in regions with a high degree of fragility. Africa is still the continent most affected by food crises: 66% of the population globally facing food crises or worse (IPC/CH Phase 3 or higher) are located in Africa (Fig. 1). In East Africa, particularly in Darfur (Sudan), South Sudan, and Tigray (North Ethiopia), armed conflicts, violent extremism, inter-communal violence and other localised tensions are the greatest threats to peace

[1] IPC/CH Phase: Integrated Phase Classification is a standardised classification system to describe the anticipated severity of food emergencies/food insecurity according to a five-phase scale: minimal, stressed, crisis, emergency, famine. (https://fews.net/IPC)

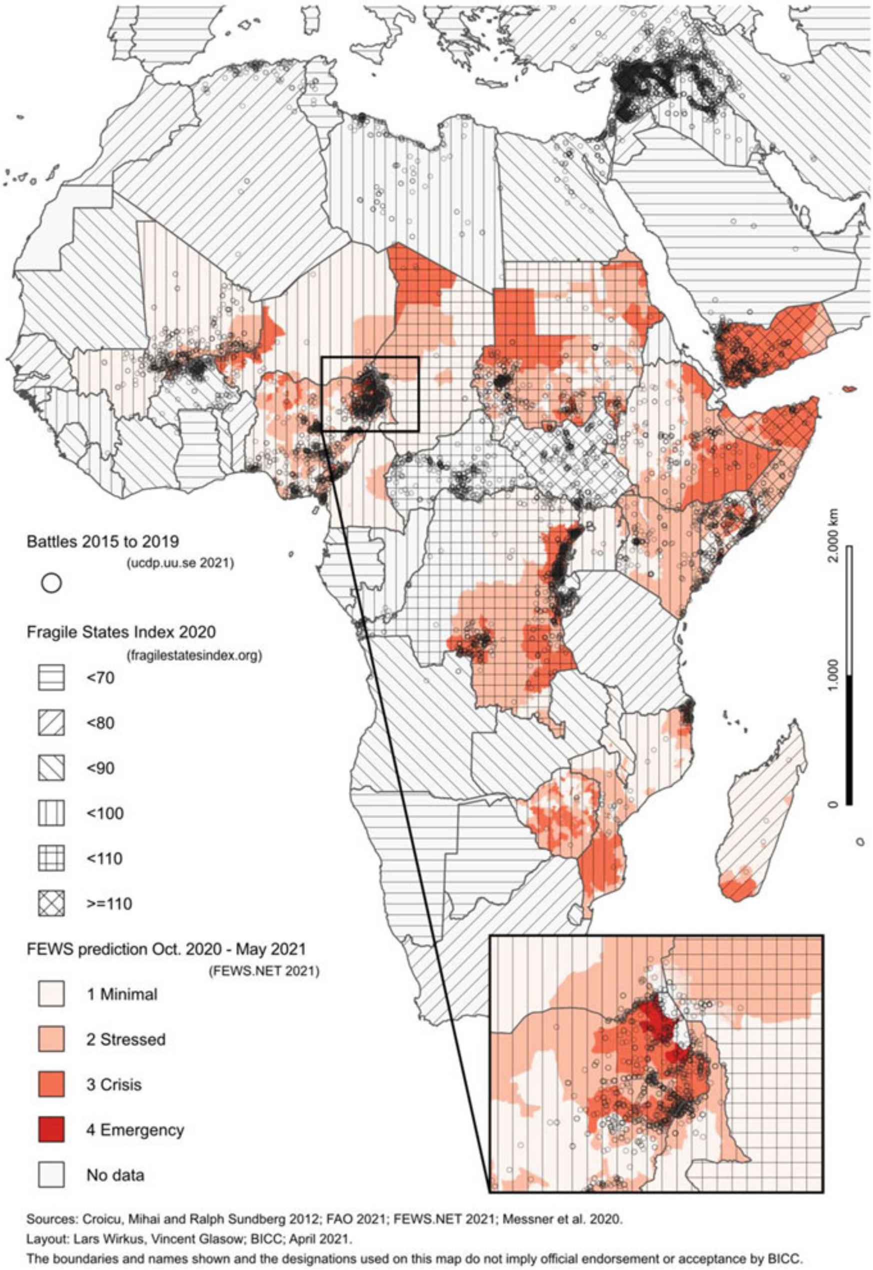


Fig. 1 Food insecurity, violent conflicts and fragility in Africa 2015–2021

and security. In Central Africa, continuous violent conflict in the Democratic Republic of Congo (DRC) and the Central African Republic has disrupted food production, as well as the food trade. Further conflict-driven food crises have emerged in two other African regions: the Lake Chad Basin, comprising the borderlands of Cameroon, Chad, Niger and northern Nigeria, and the Central Sahel, affecting Burkina Faso, Mali and Niger (FSIN & GNAFC 2021). In both areas, insecurity and jihadist groups' expansionist aspirations have led to massive violent incidents and the displacement of populations, the destruction or closure of basic social services, and the disruption or permanent breakdown of productive activities, markets and trade flows. In Asia and the Middle East region, more than 39 million people are affected by conflict-driven food crises, especially in Yemen, Afghanistan, and Syria, where political, social and economic grievances or geopolitical tensions have sparked protracted violent and armed conflicts (FSIN & GNAFC 2021).

This chapter looks at the multiple dimensions between current food crises and violent conflicts and identifies four key areas for a comprehensive response that addresses food insecurity amid such violence.

2 Multiple Dimensions of Food Crises and Violent Conflicts

Over the past decade, a growing body of research has examined the mutual impact between violent conflicts and food insecurity (for an overview, see Brück et al. 2016; Martin-Shields and Stojetz 2019) and has indicated strong correlations on multiple layers. However, food insecurity, as well as violent conflicts, are characterised by a high degree of complexity and contextualisation. Thus, discussions about the state of food insecurity and the typology of violent conflicts tend to become objectives in themselves. Criteria for determining the state of food insecurity are usually based on the four dimensions of availability, access, stability and utilisation, and encompass a range of variables covering different sectors, such as health, food prices and agricultural production, as well as different levels, from the individual to the global. Reports on the state of food security usually include a general analysis of conflicts as one of the drivers of food insecurity.

Typologies of violent conflict differentiate between the duration and intensity of said conflicts, among root causes, key drivers or ways of mobilisation, and among domestic, regional and inter-state constellations (for an overview, see Demmers 2016).[2] Each of these typologies entails a certain interpretation of violent conflicts. However, a categorisation of violent conflicts that centres on food (in)security is missing so far. To narrow this gap, we will link the logics of war to food (in)security. We will identify three dimensions of how violent conflicts have an impact on food (in)security.

[2] The question of when a violent conflict can be labelled as 'war' is still ongoing. Its definition in International Law (declaration of war) diverges from the one in Peace and Conflict Studies (e.g., number of causalities).

2.1 Destruction and Food Insecurity

The general principle of violent conflicts is that belligerent parties aim to harm, defeat or even eliminate their 'enemy'. Consequently, the emergence of frontlines, battlefields and war zones is an inevitable effect of violent conflicts, even if the current technological upgrading of modern armies and warfare (e.g., drones) aims to increase the accuracy of military attacks (Prinz and Schetter 2017). This is why, by and large, violent interactions go hand in hand with physical destruction, affecting people's vulnerabilities in various ways and leading to vicious circles of violence and hunger (Buhaug and von Uexkull 2021).

In general, Collier (1999) finds that the gross domestic product (GDP) per capita declines at an annual rate of 2.2% during civil wars. However, since the majority of people in many of today's conflict-affected countries depend on small-scale farming to provide food and income for their households, small-scale agriculture is particularly affected. The destruction (e.g., bombing) or contamination (e.g., land mines, chemical weapons) of agricultural areas, as well as infrastructure (irrigation networks, roads, bridges, buildings, etc.), might force farmers to abandon agriculture altogether. Farmers may also no longer be able to cultivate their fields for lack of access to seeds and fertiliser, credits and capital, due to the uncertainty of access to buyers and markets and the displacement or killing of people (Baumann and Kuemmerle 2016).

Especially when the expansion of war zones provokes forced migration on a large scale, the impacts on food security are direct and severe, not only in the short term, but often also in the long term. Forced migration not only leads to the collapse of agricultural production and infrastructure, but also disrupts or interrupts local and regional supply chains and increases food prices in local markets. At the same time, displaced people have to give up their livelihoods as producers of food (farmers, pastoralists, etc.), and are thus exposed to food insecurity themselves (Brück et al. 2016), especially if they become dependent on food aid from humanitarian organisations and cannot restart agricultural activities.

The rehabilitation of war zones for food production and food supply takes decades. Clearing battlefields (de-mining), re-building physical infrastructure and establishing operational governance structures is costly and takes time. Moreover, such phases of post-war reconstruction are overshadowed by fierce disputes over access to and ownership of land and water, as property rights often change hands in times of war (Van Leeuwen and Van Der Haar 2016). Thus, food insecurity, for poor populations in particular, often persist beyond the end of a violent conflict.

2.2 Food (In)security and Warring Factions

Food supply is of strategic importance to any armed group, from large-scale armies to vigilante gangs (Justino and Stojetz 2018). This is why armed groups' presence and rule directly impact local food security and the control of production areas. Historically, the supply of large armies with food went hand in hand with the plundering of food storages and the looting of civilian households and markets. Although looting is still a common strategy, the links between armed groups' presence and food security are more complex. Armed groups might show a strong interest in local food production and other goods. Combatants can take direct control over agricultural resources and livestock for sustenance or levy taxes on these products. For example, the Taliban have taken a *zakat* (Islamic tax) of 10% for any agrarian crop produced in the territory under their control in Afghanistan (Giustozzi 2019). Also, in Syria and Iraq, the agrarian zones seized by the Islamic State were maintained to a large extent, despite massive forced displacement (Eklund et al. 2017).

People in conflict-affected contexts also adjust their practices to changing politics and (local) political actors. To protect their livelihoods and food security, people might (voluntarily or under coercion) cooperate with armed groups (Martin-Shields and Stojetz 2019). On the one hand, individuals might participate in and support armed groups because they may benefit from the conflict through improved economic opportunities, such as access to food, looting and appropriation of agricultural land or livestock (Keen 1998). On the other hand, people, such as farmers in agricultural off-seasons, might be recruited as part-time fighters.

2.3 Hunger as a Weapon

When violent conflicts are directed against certain social segments, food insecurity can become "a weapon of war" (Messer and Cohen 2015), either as a direct strategy or a by-product. The goal is either to deprive a particular warring party of the population's support or eliminate entire population groups (ethnic cleansing, genocide). Direct strategies include cutting off food supplies to harm hostile armies and the population supporting them (De Waal 2018). Similarly, blocking food access and destroying food infrastructure ("scorched earth") are calculated military techniques that not only serve to ignite mass starvation, malnutrition and hunger among the population, but also to foster forced migration. Although the number of victims of mass starvation has declined in the past decades, it is still a widely used military strategy in ongoing conflict zones such as Yemen, South Sudan or the Central African Republic.

Strategies may also include preventing humanitarian access. In recent food crises, Al-Shabaab in Somalia, the Islamic State in Syria and commanders in South Sudan refused aid from humanitarian agencies. Governments themselves often violate the humanitarian principle and reject international relief operations, especially if they form part of the conflict, as could be witnessed in Syria and Yemen. The bypassing of humanitarian principle can also extend to donor governments; one reason for the delayed response to the food crisis in Somalia in 2011 was US anti-terrorist legislation, which made it difficult for humanitarian organisations to provide assistance to areas controlled by Al-Shabaab (De Waal 2018).

We have shown how the three interrelated dimensions of war logics – destruction, rule of armed groups and hunger as a weapon – have multiple effects on people's food insecurity. However, other factors, such as (conflict-related) increases in food and seed prices, as well as (changing) climatic conditions, often amplify the exposure to conflict and food insecurity (Martin-Shields and Stojetz 2019). The COVID-19 pandemic and the disruptions it caused in the global food system especially affect the food security of millions of vulnerable people (Zurayk 2020). In many of today's conflict-affected countries, smallholder farmers, who are already vulnerable in the absence of conflicts (natural hazards), represent a large portion of the population. Conflict is an additional 'shock' that affects these populations' livelihoods and well-being (Brück et al. 2016). In times of war, natural hazards affect the population much more severely and increase the difficulty of gaining access to food dramatically. As the most severe natural hazards, droughts exacerbate the effect of food (in)security. Droughts as 'creeping' or slow-onset disasters usually affect larger land areas than other types of disasters and make mitigation and adaptation strategies difficult to implement. Many of the adverse effects of drought often accumulate slowly and may persist for years after the event has ended (Wirkus and Piereder 2019).

What is less clear is whether food insecurity in turn sparks, intensifies or perpetuates conflict. While food insecurity alone is not likely to cause violent conflicts, it can increase social grievances in combination with socio-economic and political inequalities. These exclude parts of the population (particularly youths) from economic activities and participation in political decision-making processes, which ultimately can fuel civil unrest or conflicts (Brinkman and Hendrix 2011; Vestby et al. 2018). Besides structural conditions, rising food prices have been found to exacerbate the risk of political unrest and conflicts, particularly in urban settings. The dominant explanation for the vicious circle of price and violent conflict are consumer grievances: higher prices create or increase economic constraints and/or sentiments of (perceived) relative deprivation, which activate grievances that, in turn, can lead to conflict, whereas conflict is likely to increase food prices again (Raleigh et al. 2015). These grievances can be directed against the state if it fails to secure food for the population in the face of rising global food prices. In Africa, rising food prices and unrest were associated with more political repression (Berazneva and Lee 2013).

3 Addressing Food Crises and Violent Conflict

The complex relationships between food crises and violent conflicts require comprehensive and adapted policy actions. These actions must refer to the reduction of food insecurity as an effect of violent conflict and consider the reduction of violent conflict or conflict risks itself. We thus suggest four key areas for a multi-faceted response that addresses food insecurity and violent conflict.

3.1 Respect Access to Food as a Human Right During Violent Conflict

Access to food is a human right. Any government should pursue preventive policies and take emergency measures to secure food equally for all segments of its population. If a government lacks the capacity to prevent or mitigate a food crisis, it should allow and facilitate relief operations as demanded by humanitarian law (Akande and Gillard 2019). However, national governments or belligerents are often unable or unwilling to respond adequately to food crises. At the same time, international relief operations face the challenges of reaching the people most in need and avoiding exacerbation of the conflict.

Therefore, all actors must comply both with the provisions to protect the population from intended starvation and with humanitarian principles to guarantee humanitarian access. Any government or warring faction that prohibits parts of the population from access to food needs to be sanctioned. UN Security Council Resolution 2417 is a major step in this direction. The Resolution stresses the importance of compliance by belligerents with international humanitarian law and condemns the denial of humanitarian access to affected civilians (UNSC 2018). Most importantly, the Resolution stipulates that the obstruction of humanitarian access in conflict settings can result in targeted sanctions, as already used, for example, on Al-Shabaab in Somalia (Akande and Gillard 2019). Thus, the Resolution has the potential to be used by UN agencies to monitor and report robustly on human-induced food crises in conflicts and call on the Security Council and the international community to act (Zappalà 2019).

3.2 Build Bridges Linking Humanitarian Action, Development and Peacebuilding

The genuine role of international relief operations in food crises is to prevent or alleviate human suffering induced by disasters and conflicts. Short-term food assistance during conflict-driven food crises usually focuses on improving the food consumption of conflict-affected people and communities. It also aims to support the most vulnerable, such as displaced persons, children, and pregnant and nursing women. However, relief operations in conflict settings often face challenges in guaranteeing aid workers' safety and security, gaining necessary data on affected populations and reaching those people most in need in a timely and appropriate manner (see, for example, Tranchant et al. 2019). At the same time, food interventions risk becoming a source of conflict themselves, primarily because of an inadequate understanding of the conflict setting (Devereux 2000). The misappropriation of food aid in particular, such as the usurpation of food by violent actors, can fuel political grievances and perpetuate conflict. Moreover, food aid can undermine local food production and markets and affect the development of local capacity (Hendrix and Brinkman 2013). A clear and locally informed analysis of the conflict and its context, as well as increased equity and accountability, is needed to prevent negative impacts of food aid in conflict environments.

While short-term food aid focuses primarily on alleviating human suffering rather than resolving violent conflict, long-term humanitarian assistance, as particularly provided in protracted crises or post-conflict situations, can identify potential conflicts and address them, reducing the risk of conflict flare-ups. Usually, these interventions have a stronger impact than the immediate supply of food (or cash/vouchers) and already include development assistance measures. Long-term food assistance can therefore play a crucial role in building local capacity, restoring agricultural production and, ultimately, consolidating peace. However, it is crucial to initiate its provision early enough, to consider the actual needs of the most vulnerable people, and to include conflict analysis (Hendrix and Brinkman 2013; Lander and Richards 2019). Nevertheless, aid agencies need to be aware of the (globalised) food system in which local agricultural production is embedded and that the longer food aid is provided, the more it has a direct impact on the local food market and price trends. Therefore, they must avoid aid dependency, especially by affecting smallholders' livelihoods (Delgado et al. 2021).

To effectively address these challenges, long-term food assistance needs to bridge humanitarian action, development intervention and peacebuilding. Thus, food assistance is a key instrument that should be addressed in current debates on the humanitarian–development–peace (HDP) nexus, which calls for greater cooperation and coordination among actors in humanitarian aid, development cooperation and peacebuilding.

3.3 Integrate Local Capacities and Perceptions

Conflict-affected populations adopt very different strategies in order to secure food. These strategies depend on multiple factors, such as the conflict's context, intensity and duration, the individual situation, access to resources and support, and governance. For example, rather than aiming to maximise agricultural profits, farmers may change their crop production to a low-risk, low-return strategy by switching from cash crops to less profitable crops, as the latter provide food for subsistence or can be easily transferred in case of displacement. However, maintaining these low-risk-low-return strategies after conflicts end affects their recovery and can further affect their livelihoods in the long run (Arias et al. 2017; Martin-Shields and Stojetz 2019).

Similarly, pastoralists may adapt livestock production to the conflict, e.g., by selling livestock to have sufficient cash or hiding livestock from armed groups or local ruling groups (Brück et al. 2016). Furthermore, studies have shown that households increase their use of safety nets to minimise uncertainty. Support ranges from cash transfers to in-kind assistance received by the household (Brück et al. 2019). Remittances are also an important safety net in responding to food crises and conflict, but much still needs to be learned about its role for affected people (Haan et al. 2012). Therefore, local response mechanisms to food crises and conflicts need to be better understood and successful practices incorporated into relief efforts and national response strategies while, at the same time, striving to avoid potential harm. At the same time, local perceptions of terms such as "peace" need to be taken into account, since they can differ from one place to another and, most importantly, differ from (Western) academic concepts (Ejdus 2021). It is important to understand local perspectives and to strengthen existing potentials for peace in order to integrate a peacebuilding perspective into food assistance interventions.

3.4 Improve the Links Between Early Warning and Early Action in Conflict-Driven Food Crises

Early warning mechanisms for famine such as FEWS NET have advanced over the past decades towards a better model for predicting and managing food crises. They provide decision-makers and relief organisations with a rigorous, evidence- and consensus-based analysis of food insecurity and acute malnutrition situations. Recent developments in anticipatory action aim to close the gap between forecasting tools and delayed response, but still face multiple challenges in adjusting these to conflict settings (Wagner and Jaime 2020).

First, in violent conflicts, access to data needed for comprehensive analysis and timely warning is often unavailable or out-of-date. Second, the announcement of a food emergency is highly political and often challenged by claims of sovereignty (Lander and Richards 2019). Third, even if warnings are timely and allow for careful planning, adequate finance mechanisms need to be in place, capacities of organisations built, and access to conflict-affected regions guaranteed. Fourth, a knowledge gap still exists between data that is available to assess the food security situation and data on conflict early warning. Accurate conflict early warning seems to be more challenging, especially when it comes to predicting the impact of conflicts (Maxwell and Hailey 2020). Conflict early warning and forecasting systems such as UCDP ViEWS, ACLED Pulse might have the potential to close the "conflict assessment gap" of current food crisis warning systems (Wirkus and Piereder 2019).

While the use of conflict analysis is politically sensitive and needs to be considered carefully (Maxwell and Hailey 2020), an integrated platform developed to combine early warning data sets for famines and violent conflicts could provide a better basis for a more comprehensive assessment of famine, drought and conflict risk and advance anticipatory humanitarian action in fragile and conflict-affected settings.

Accounting for these four key areas could help national governments and international humanitarian and development organisations to take effective preventive, anticipatory and emergency action against food crises during violent conflict, while, at the same time, integrating peacebuilding approaches into long-term food interventions to address hunger and conflict.

References

Akande D, Gillard E (2019) Conflict-induced food insecurity and the war crime of starvation of civilians as a method of warfare: the underlying rules of International Humanitarian Law. BSG Working Paper 2019/030. https://www.bsg.ox.ac.uk/sites/default/files/2019-11/BSG-WP-2019-030.pdf

Akresh R, Verwimp P, Bundervoet T (2011) Civil war, crop failure, and child stunting in Rwanda. Econ Dev Cult Chang 59(4):777–810

Akresh R, Bhalotra S, Leone M, Osili UO (2012) War and stature: growing up during the Nigerian civil war. Am Econ Rev 102(3):273–277. https://doi.org/10.1086/660003
Arias MA, Ibáñez AM, Zambrano A (2017) Agricultural production amid conflict: separating the effects of conflict into shocks and uncertainty. HiCN Working Paper 245
Baumann M, Kuemmerle T (2016) The impacts of warfare and armed conflict on land systems. J Land Use Sci 11:672–688. https://doi.org/10.1080/1747423X.2016.1241317
Berazneva J, Lee DR (2013) Explaining the African food riots of 2007-2008: an empirical analysis. Food Policy 39:28–39. https://doi.org/10.1016/j.foodpol.2012.12.007
Brinkman HJ, Hendrix CS (2011) Food insecurity and violent conflict: causes, consequences, and addressing the challenges. Occasional Paper no. 24. Accessed at https://www.wfp.org/publications/occasional-paper-24-food-insecurity-and-violent-conflict-causes-consequences-and-addressing-
Brück T, Habibi N, Martin-Shields C, Sneyers A, Stojetz W, van Weezel S (2016) The relationship between food security and violent conflict. Report to the Food and Agriculture Organization. Final Report to FAO. Accessed at https://isdc.org/wp-content/uploads/2019/08/Food-Security-and-Conflict-2016-12-22.pdf
Brück T, d'Errico M, Pietrelli R (2019) The effects of violent conflict on household resilience and food security: evidence from the 2014 Gaza conflict. World Dev 119:150–164
Buhaug H, von Uexkull N (2021) Vicious circles: violence, vulnerability, and climate change. Annu Rev Environ Resour 46:545–568. https://doi.org/10.1146/annurev-environ-012220-014708
Bundervoet T, Verwimp P, Akresh R (2009) Health and civil war in rural Burundi. J Hum Resour 44(2):536–563
Camacho A (2008) Stress and birth weight: evidence from terrorist attacks. Am Econ Rev 98(2): 511–515. https://doi.org/10.1257/aer.98.2.511
Collier P (1999) On the economic consequences of civil war. Oxford Economic Papers 51
De Waal A (2018) The end of famine? Prospects for the elimination of mass starvation by political action. Polit Geogr 62:184–195. https://doi.org/10.1016/j.polgeo.2017.09.004
Delgado C, Murugani V, Tschunkert K (2021) Food systems in conflict and peacebuilding settings. Pathways and interconnections. Stockholm International Peace Research Institute, Stockholm. Accessed at https://www.sipri.org/publications/2021/other-publications/food-systems-conflict-and-peacebuilding-settings-pathways-and-interconnections
Demmers J (2016) Theories of violent conflict: an introduction. Routledge, London
Devereux S (2000) Famine in the twentieth century. IDS working papers issue 105
Ejdus F (2021) Revisiting the local turn in peacebuilding. In: Kustermans J, Sauer T, Segaert B (eds) A requiem for peacebuilding? Palgrave Macmillan, Cham, pp 41–58
Eklund L, Degerald M, Brandt M, Prishchepov AV, Pilesjö P (2017) How conflict affects land use: agricultural activity in areas seized by the Islamic State. Environ Res Lett 12(5):1–10. https://doi.org/10.1088/1748-9326/aa673a
FAO, IFAD, UNICEF, WFP & WHO (2021) The state of food security and nutrition in the world 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. FAO, Rome. Accessed at https://www.fao.org/publications/sofi/2021/en/
FSIN & GNAFC (2021) Global report on food crises. Joint analysis for better decisions. Accessed at https://www.wfp.org/publications/global-report-food-crises-2021
Giustozzi A (2019) The Taliban at war 2001–2018. Hurst, London
Haan N, Devereux S, Maxwell D (2012) Global implications of Somalia 2011 for famine prevention, mitigation and response. Glob Food Sec 1(1):74–79. https://doi.org/10.1016/j.gfs.2012.09.003
Hendrix C, Brinkman H (2013) Food insecurity and conflict dynamics: causal linkages and complex feedbacks. Stab Int J Secur Dev 2(2):1–18. https://doi.org/10.5334/sta.bm
Justino P, Stojetz W (2018) On the legacies of wartime governance. HiCN Working Paper 263
Keen D (1998) The economic functions of violence in civil wars. Oxford University Press for the International Institute for Strategic Studies

Lander B, Richards RV (2019) Addressing hunger and starvation in situations of armed conflict – laying the foundations for peace. J Int Crim Justice 17(4):675–698. https://doi.org/10.1093/jicj/mqz055

Martin-Shields CP, Stojetz W (2019) Food security and conflict: empirical challenges and future opportunities for researchand policy making on food security and conflict. World Dev 119:150–164. https://doi.org/10.1016/j.worlddev.2018.07.011

Maxwell D, Hailey P (2020) Towards anticipatory information systems and action: notes on early warning and early action in East Africa. Feinstein International Center and Centre for Humanitarian Change, Boston/Nairobi. Accessed at https://fic.tufts.edu/publication-item/towards-anticipatory-information-systems-and-action/

Messer E, Cohen MJ (2015) Breaking the links between conflict and hunger redux. Special Issue: Glob Food Sec 7(3):211–233. https://doi.org/10.1002/wmh3.147

Prinz J, Schetter C (2017) Conditioned sovereignty: the creation and legitimation of spaces of violence in counterterrorism operations of the "war on terror". Alternatives 41(3):119–136

Raleigh C, Choi HJ, Kniveton C (2015) The devil is in the details: an investigation of the relationships between conflict, food price and climate across Africa. Glob Environ Chang 32:187–199. https://doi.org/10.1016/j.gloenvcha.2015.03.005

Tranchant JP, Gelli A, Bliznashka L, Diallo AS, Sacko M, Assima A, Siegel EH, Aurino E, Masset E (2019) The impact of food assistance on food insecure populations during conflict: evidence from a quasi-experiment in Mali. World Dev 119:185–202. https://doi.org/10.1016/j.worlddev.2018.01.027

UNSC (2018). Security Council resolution 2417 (2018) [on conflict-induced food insecurity]/ adopted by the Security Council at its 8267th meeting, on 24 May 2018. Accessed at https://digitallibrary.un.org/record/1627380?ln=en

Van Leeuwen M, Van Der Haar G (2016) Theorizing the land–violent conflict nexus. World Dev 78:94–104. https://doi.org/10.1016/j.worlddev.2015.10.011

Vestby J, Rudolfsen I, Buhaug H (2018) Does hunger cause conflict? Peace Research Institute Oslo – Climate & Conflict, 18 May 2018. Accessed at https://blogs.prio.org/ClimateAndConflict/2018/05/does-hunger-cause-conflict/

Wagner M, Jaime C (2020) An agenda for expanding forecast-based action to situations of conflict. GPPi Working Paper. Accessed at https://www.gppi.net/media/Wagner_Jaime_2020_Forecast-Based-Action-in-Conflicts.pdf

Wirkus L, Piereder J (2019) Early warning systems for drought and violent conflict – toward potential cross-pollination. In: Mapedza E, Tsegai D, Bruntrup M, Mcleman R (eds) Drought challenges: policy options for developing countries, Current directions in water scarcity research, vol 2. Elsevier, Amsterdam, pp 165–181

Zappalà S (2019) Conflict related hunger, 'starvation crimes' and UN Security Council Resolution 2417 (2018). J Int Crim Justice 17(4):881–906. https://doi.org/10.1093/jicj/mqz047

Zurayk R (2020) Pandemic and food security: a view from the Global South. J Agric Food Syst Community Dev 9(3):17–21. https://doi.org/10.5304/jafscd.2020.093.014

In Brief: The White/Wiphala Paper on Indigenous Peoples' Food Systems

Pablo Arigita Baena, Anne Brunel, Yon Fernández-de-Larrinoa, Tania Eulalia Martinez-Cruz, Charlotte Milbank, and Mikaila Way

Acronyms

CINE	Centre for Indigenous Peoples' Nutrition and Environment
COP	Conference of Parties
FAO	Food and Agriculture Organization of the United Nations
FPIC	Free, Prior and Informed Consent
GHG	Greenhouse Gases
HDP	Humanitarian Development Peace
ICC	Inuit Circumpolar Council
IFAD	International Fund for Agricultural Development
ILO	International Labour Organization
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPFS	Indigenous Peoples' food systems
IPR	Intellectual Property Rights
LCIPP	Local Communities and Indigenous Peoples' Platform
PSUI	Indigenous Peoples Unit (FAO)
SDG	Sustainable Development Goal
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNFSSS	United Nations Food Systems Summit
UNDPI	United Nations Department of Public Information

The Complete list of contributors is in Annex 2 of this chapter.

FAO. 2021. *The White/Wiphala Paper on Indigenous Peoples' food systems*. Rome. https://doi.org/10.4060/cb4932en
The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

P. A. Baena · A. Brunel · Y. Fernández-de-Larrinoa (✉) · T. E. Martinez-Cruz · C. Milbank
M. Way
FAO, Indigenous Peoples Unit, Rome, Italy
e-mail: Yon.FernandezLarrinoa@fao.org

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_13

UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
UNPFII	United Nations Permanent Forum on Indigenous Issues

1 Purpose of This Brief

This brief version of the White/Wiphala paper on Indigenous Peoples' Food Systems summarises some of the key messages and conclusions from the full publication. The White/Wiphala paper was written at a time when the UN Food Systems Summit (UNFSS) discussions followed 'Five Action Tracks.' While the White/Wiphala paper policy recommendations are laid out according to these five Action Tracks, the authors acknowledge that these themes cannot be looked at in isolation, and that any single strategy must be implemented within a broader context of supportive governance and an open-minded legislative environment.

Since the White/Wiphala paper was published, the UNFSS has replaced the five Action Tracks with five Action Areas. Contrastingly, this short brief is aligned with newly identified Action Areas and thirty (non-exhaustive) different coalitions emanating from the September 2021 Food Systems Summit.

The objective of this brief version, through the work of the Coalition on Indigenous Peoples' Food Systems and under the 'do no harm' principle, is to support the two goals of the Indigenous Peoples' Coalition. This is: to ensure the recognition, respect, protection, and support of Indigenous Peoples' food systems; and to upscale valid lessons learned from Indigenous Peoples' food systems capable of informing the transformation of other food systems towards sustainability and resilience. The overarching goal remains to promote the UN Declaration on the Rights of Indigenous Peoples (UNDRIP). This is particularly relevant within the context of the UN Decades of Ecosystem Restoration and the Decade of Indigenous Peoples Languages.

After the significant concerns experienced during the Summit with the rejection of the demands expressed by Indigenous Peoples, particularly on the Coalition on Indigenous Peoples' Food Systems as game-changers and the creation of an Indigenous Peoples' fund, we saw clear opportunities for a way forward with the overwhelming support from countries for a new and reinvigorated Coalition on Indigenous Peoples' Food Systems.

This paper presents clear lessons that can be learned from Indigenous Peoples' approach to food and natural resources, which will contribute to the resilience and sustainability of food systems worldwide while supporting the wellbeing of Indigenous Peoples. It provides evidence on the sustainable characteristics and diversity of Indigenous Peoples' food systems, including how they have proven their resilience over time. The White/Wiphala paper brief will serve as a base for other documents that will support the Coalition on Indigenous Peoples and the different strategies that will be implemented to achieve the goals and objectives of the Coalition, resulting in more evidence-based recommendations.

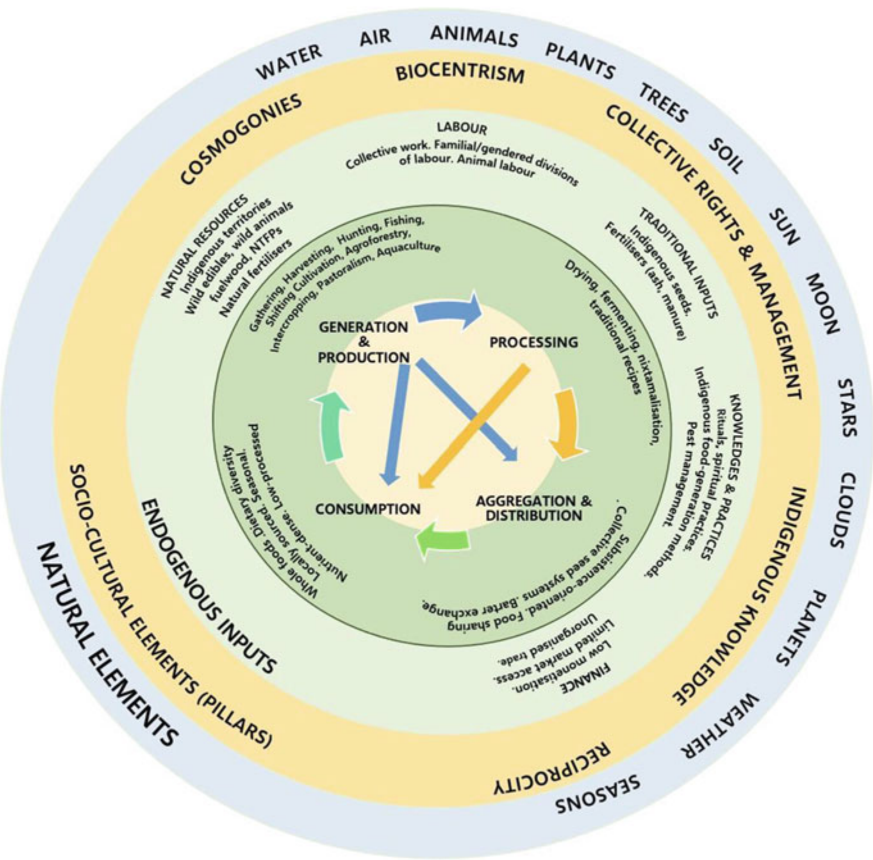


Fig. 1 Circular representation of the relations in Indigenous Peoples' food systems

While the extended version of the White/Wiphala paper was written with scientists and food system experts in mind, this chapter is aimed at media, member countries, policy-makers, and the general public (Fig. 1).

Key Messages

– The current global food system is unsustainable; while we will need to double food production by 2050 to satisfy food demands, we also must reduce the contribution of the current food system to climate change, which accounts for about 30% of total GHG emissions, with 30% of that 30% being caused by food waste. Unmitigated, our food systems result in radically modified ecosystems, environments, coastlines, mountain tops, glaciers, water bodies, and weather patterns, with consequences for human wellbeing and life on earth. At COP26, the discussions indicated that, rather

(continued)

than mitigating, we need to think about adaptation, and Indigenous Peoples have shown us for centuries how to adapt to a changing world. Their Indigenous core values and principles of reciprocity, community-solidarity, balance, reutilisation and not wasting food are being progressively understood and incorporated into other contexts about food.

– Indigenous Peoples' foods systems are well placed to contribute to global debates about food. Despite this, Indigenous Peoples, their food and knowledge systems, and their ancestral territorial management practices continue to be marginalised in policy and decision-making and their Human and Indigenous Peoples Rights not respected. Numbering over 476 million worldwide, Indigenous Peoples live across over 90 countries and seven socio-cultural regions (ILO, 2019). They live in areas of rich biodiversity and sustain and enhance immense biocultural diversity and knowledge that has been carried on for generations. Their participation in the drafting and implementation of food policies is paramount in actualising their human rights and continuing their livelihoods, cosmogonies, cultures, and traditional knowledge systems, as well as the planet's ecological health.
– As guardians of 80% of the worlds' remaining biodiversity in their territories (Sobrevilla, 2008), Indigenous Peoples are fundamental knowledge holders in any global effort to make current food systems sustainable and resilient.
– Indigenous Peoples' food systems have been providing nourishment and healthy diets for hundreds of years through food generation and food production practices rooted in a comprehensive understanding of the environment and tailored territorial management. They make use of several hundred species of edible and nutritious flora and fauna, including traditionally cultivated crops, crop wild relatives, and animal wildlife (including bush meat, insects, fish, and aquatic species).
– Indigenous Peoples' food systems promote the equitable distribution of resources and power and support Indigenous identities and values, ensuring that no one is left behind. Indigenous Peoples' knowledge, cosmogony, practices, and worldviews differ from dominant mainstream science. Their food and knowledge systems are embedded with a biocentric approach that is intimately tied to nature and related to their cosmogonies.
– Indigenous Peoples' food systems cannot be characterised according to dominant conceptualisations of food systems presented as linear value chains.
– The Scientific group participating in the July 2021 UNFSS Pre-Summit acknowledged that, on the other hand, Indigenous Peoples' food systems constitute game-changing solutions, with a systemic approach to sustainability and resilience.

(continued)

- Indigenous Peoples' food and knowledge systems are eroding, and their traditional knowledge is disappearing. Urgent actions are needed to guarantee the survival of Indigenous Peoples' food systems and the preservation of biodiversity on the planet.
- Efforts to protect and strengthen their food systems must be prioritised. However, Indigenous Peoples, their food systems, knowledge, and practices have been and continue to be marginalised in policy, science, and funding.
- Indigenous Peoples from the seven socio-cultural regions contributed actively to the 2021 UNFSS and to the global debates on transforming food systems towards sustainability and resilience and climate change mitigation and adaptation strategies.
- At the September 2021 Summit, Indigenous Peoples from the seven socio-cultural regions, the UNPFII, Canada, the Dominican Republic, Finland, Mexico, New Zealand, Norway, Spain, and FAO represented the Indigenous Peoples' food systems Coalition.
- The Coalition has two main goals: 1. Respect, recognise, protect and strengthen Indigenous Peoples' food systems across the world; and 2. Disseminate and scale-up traditional knowledge and good practices from Indigenous Peoples' food systems with the potential to transform global food systems across the board.

What is the problem?

1. **Indigenous Peoples, their food systems, knowledge and practices, have been and continue to be marginalised in policy-making**. Numbering over 476 million worldwide, Indigenous Peoples live across over 90 countries and seven socio-cultural regions (ILO, 2019). They often reside in sites of rich biodiversity and possess rich biocultural diversity and knowledge that has been preserved for generations. Their participation in the drafting and implementation of food policy is crucial to the future continuation of their livelihoods.
2. **Indigenous Peoples' food systems cannot be characterised according to dominant conceptualisations of food systems that are presented as linear value chains**. Indigenous Peoples' food systems do not follow linear value chains, comprising different values, systems of governance, and cultural relations to food compared to value-chain-oriented food systems. Indigenous Peoples' food systems emphasise circularity and include many ways of obtaining, preparing, storing and sharing food.

What are the main characteristics of Indigenous Peoples' food systems, and what they can bring to the debate?

3. **Indigenous Peoples' food systems are embedded in a biocentric approach intimately tied to nature.** Compared to specialised, input-intensive systems of conventional food production, Indigenous Peoples

(continued)

generate a diversity of foods with minimal intervention on the ecosystems and use inputs endogenous to the local system. Indigenous Peoples' food systems are efficient in resource use, with little waste and wide circulation of resources. Material inputs tend to be fully used and recycled locally while also promoting biodiversity preservation, as they respect the seasonality of the systems.

4. **Indigenous Peoples' food systems promote the equitable distribution of resources and power and support Indigenous identities and values**. Food generative practices are often localised, using communal resources and supporting traditional governance systems. Exchange is often barter-based or based on reciprocal agreements. Indigenous Peoples' lands, waters and resources are often used, managed or governed collectively as a common resource under community-based management. Indigenous Peoples' systems of collective ownership of resources and food-sharing can thus support inter- and intra-community cooperation, the cultivation and maintenance of shared identities, and healthy, resilient and culturally appropriate food systems.
5. **Indigenous Peoples' knowledge, practices and worldviews differ from western science and provide a valuable contribution to current debates on sustainable food systems.** While the value of Indigenous Peoples' traditional knowledge has been recognised, Indigenous Peoples' views, cosmovisions, time-tested practices and relational values continue to be excluded in science and policy. The contribution of systemic observation carried by Indigenous Peoples' traditional knowledge is a time-tested scientific approach. The sensitive inclusion of Indigenous Peoples' traditional knowledge in policy will support the sustainable management of natural resources and the transformation of food systems for all.
6. **Indigenous Peoples occupy over a quarter of the world's land, and their food systems can help preserve global biodiversity.** There is evidence that lands and forests managed and governed by Indigenous Peoples can resist forest loss and experience lower rates of land conversion than forests within protected areas and undefined national forests. Indigenous Peoples' communities have persisted as custodians of the planet's food and genetic resources.
7. **Indigenous Peoples' food systems provide nourishment and healthy diets.** Indigenous Peoples' food systems make use of several hundred species of edible and nutritious flora and fauna, including traditionally cultivated crops, crop wild relatives and animal wildlife (including bushmeat, marine mammals, insects and fish). Indigenous Peoples' communities are feeling the effects of the dietary transition, with increasing consumption of highly processed foods becoming a growing public health concern. With Indigenous Peoples already suffering higher malnutrition

(continued)

rates worldwide than their non-Indigenous counterparts, supporting the continuation of Indigenous Peoples' food practices is essential to future nutritional health.

What is needed to protect and strengthen Indigenous Peoples' food systems?

8. **Indigenous Peoples' food systems are themselves a game-changing solution.** The speed at which Indigenous Peoples' food systems are eroding and their traditional knowledge systems disappearing requires urgent actions to guarantee the survival of Indigenous Peoples. Indigenous Peoples' food systems are intimately tied to the natural world and can provide food and nutritional security while restoring ecosystems and maintaining biodiversity. Such protection and preservation are fundamentally aligned with the human and cultural rights that guarantee the survival of Indigenous Peoples.

Indigenous Peoples' Food Systems Coalition: Supporting Indigenous Peoples' food systems

9. **The Coalition on Indigenous Peoples' Food Systems builds upon the White/Wiphala Paper, establishing the objective of ensuring the understanding, respect, recognition, inclusion, and protection of Indigenous Peoples' food systems while providing evidence about their 'game-changing and systemic' nature**. To support this objective, the Coalition organises its work around two main goals: Goal 1: Respect, recognise, protect and strengthen Indigenous Peoples' food systems across the world; and Goal 2: Disseminate and scale-up traditional knowledge and good practices from Indigenous Peoples' food systems with the potential to transform global food systems across the board.

2 Coalitions from the United Nations Food Systems Summit and the Coalition on Indigenous Peoples' Food Systems

In September 2021, at the UN Food Systems Summit, 30 coalitions organised into five Action Areas were announced, among them, the Coalition on Indigenous Peoples' Food Systems that falls within the Action Area of "Advance equitable livelihoods, decent work, and empowered communities." The Coalition on Indigenous Peoples' Food Systems was endorsed by seven member countries: Canada, the Dominican Republic, Finland, Mexico, New Zealand, Norway, and Spain.

The Coalition on Indigenous Peoples' Food Systems builds upon the White/Wiphala Paper, establishing the objective of ensuring the understanding, respect, recognition, inclusion, and protection of Indigenous Peoples' Food Systems while providing evidence about their game-changing and systemic nature. Table 1 summarises the objective and goals of the Coalition on Indigenous Peoples' Food

Table 1 Summary of Action areas vis-à-vis the Indigenous Peoples' Food Systems Coalition's goals

Specific goals and actions recommended per Action Area	**Action Area 1**: Nourish all people	**Action Area 2:** Boost nature-based solutions of production	**Action Area 3:** Advance Equitable Livelihoods, Decent Work, & Empowered Communities	**Action Area 4:** Build resilience to vulnerabilities, shocks, and stresses	**Action Area 5:** Support Means of Implementation
Main objective of the Coalition on Indigenous Peoples' Food Systems: Ensure understanding, respect, recognition, inclusion and protection of Indigenous Peoples' Food Systems (IPFS) post-UNFSS, providing evidence about their "game-changing and systemic" aspects.					
Goal 1: Respect, recognise, protect and strengthen Indigenous Peoples' food systems across the world. 1. Strengthen policy and regulations to ensure that intensive and transformed food systems do not harm indigenous Peoples' food systems. 2. Work with national governments and international agencies to secure funding. 3. Support interculturality at all levels. 4. Support the drafting of national policies, research, and programmes to protect and strengthen Indigenous Peoples' food systems, including them in decision-making, and focusing on Indigenous women, youth and elders.	Engaging Indigenous leaders in policy discussions and devising strategies for accessing safe and nutritious foods. Develop new standards and legal frameworks to drive private sector change and hold companies accountable.	Proposals to increase agro-biodiversity for improved production and resilience Include policies that promote agro-biodiversity preservation and specific actions at the field level.	Establishing forums that bring together government representatives, trade unions and employers' associations, as well as other key stakeholders and organisations, to set guidelines for equitable food systems.	Indigenous Peoples' perspectives and leadership must be incorporated within risk analysis and management Blended financing mechanisms for small projects Universal food access	Co-creation of platforms on which mutual respect for knowledge is ensured and that foster the inclusive and effective development of sustainable food systems Innovative financing and investments for sustainable land management practices
	Crosscutting				
	Indigenous Peoples' rights to self-determination, self-development, land tenure, self-governance and sovereignty must be respected to achieve the goals of each Action Area. The participation of Indigenous Peoples at the policy level is crucial for the success of Action Areas; they must have an active voice in designing and implementing policies and managing bodies and institutions that affect them. Intercultural policies in different areas must be developed and implemented to ensure that Indigenous Peoples' knowledge, food systems, languages, values and factors that have made them resilient can continue and be passed to younger generations				

5. Support processes of inter- and intra-generational transmission of knowledge and horizontal capacity-building on Indigenous Peoples' food systems. 6. Strengthen the leadership of Indigenous youths for innovative intercultural approaches, integrating Indigenous Peoples' traditional knowledge, science, technology and management. **7.** Promote seed security to ensure Indigenous Peoples' access to seeds and planting material that meets their preferences.	who will be the stewards of all this knowledge and strategy. This includes policies linked to education, health, social development, environment, agriculture/food, etc.				
Goal 2: Disseminate and scale-up traditional knowledge and good practices from Indigenous Peoples' food systems with the potential to transform global food systems across the board 1. Scale-up Indigenous Peoples' food systems by strengthening scientific and empirical research and intercultural co-creation processes.	The establishment of a zero-hunger fund. Expansion of coverage of social protection systems	Scaling-out agroecological production systems and adopting regenerative agricultural practices for resilient landscapes at scale	Promoting labelling and certification schemes for Indigenous Peoples, driven forward by Indigenous Peoples. Creating a global matching investment fund for small-scale producers' organisations	Indigenous Peoples' perspectives, local knowledge, and leadership must be incorporated in risk analysis and management. Supporting biodiversity conservation strategies, such as the creation of biocentric centres.	Create a fund to research the potential of many Indigenous Peoples' food and support the use of funds by Indigenous-led researchers

(continued)

Table 1 (continued)

Main objective of the Coalition on Indigenous Peoples' Food Systems:
Ensure understanding, respect, recognition, inclusion and protection of Indigenous Peoples' Food Systems (IPFS) post-UNFSS, providing evidence about their "game-changing and systemic" aspects.

Specific goals and actions recommended per Action Area	**Action Area 1**: Nourish all people	**Action Area 2:** Boost nature-based solutions of production	**Action Area 3:** Advance Equitable Livelihoods, Decent Work, & Empowered Communities	**Action Area 4:** Build resilience to vulnerabilities, shocks, and stresses	**Action Area 5:** Support Means of Implementation
2. Increase food systems' resilience and risk management by incorporating Indigenous Peoples' knowledge about ecosystems. 3. Promote Indigenous Peoples' leadership in food systems by sharing their food management, production, and processing models. 4. Provide evidence about Biocentric-Biocultural considerations in food for policy discussions. **5.** Work with other coalitions to ensure the protection of Indigenous Peoples' food systems under the 'do no harm' principle and promote the implementation of the UN Declaration on the Rights of Indigenous Peoples and other related UN Declarations.					

Systems and how it overlaps with the Action Areas of the UNFSS2021 (More details on the Coalition are available in Annex 1).

3 Action Area 1: Nourish All People

This Action Area could help countries connect to coalitions, initiatives, and resources around i. zero hunger, ii. healthy diets from sustainable food systems, iii. universal school meals, iv. food is never waste, v. the Food Coalition, vi. One Health, and beyond.

Key Contributions from Indigenous Peoples

1. Indigenous Peoples have developed unique territorial management practices to generate food while preserving biodiversity.
2. The biodiversity maintained by Indigenous Peoples supports a broad food base, which, in some cases, exceeds 250 edibles for food and medicinal purposes in a single food system, consisting of different species, varieties and breeds, including wild, semi-domesticated and domesticated species of plants, animals, and fish.
3. Despite the reported weather variability associated with climate change, the integration of seasonality into Indigenous Peoples' food practices is an important characteristic of their food system. This seasonality contributes to their resilience and self-sufficiency, ensuring numerous foods that guarantee dietary diversity. The combination of territorial management and generation techniques results in food systems that provide a broad base of foods from fields, forests, pastures, and waterways. At COP26, the need to invest in adaptation and mitigation strategies was highlighted. Indigenous Peoples are champions at adapting to their environment, and do not seek to adapt their environments to them, as conventionally happens with other societies. Indigenous Peoples' game-changing solutions can be scaled out as provably sustainable and resilient.
4. Indigenous Peoples' governance systems and solid social cohesion enable the maintenance of solid social bonds and solidarity within their communities, based on values of reciprocity and caring for each other, i.e., not leaving anyone behind. Indigenous trade and sharing networks are based on trusted relationships for acquiring and sharing foods from and with other communities.
5. Indigenous Peoples' land tenure and sovereignty are prerequisites to biodiversity conservation and adaptive capacity in confronting climate change and addressing global sustainability. There is strong evidence of the positive and central role of traditional governance practices and Indigenous Peoples' knowledge systems in maintaining and enhancing biodiversity in Indigenous Peoples' lands and territories while supporting the generation of healthy food. (ICC -Alaska, 2015)

Recommendations for Action Area 1

6. Leaving no one behind can only be achieved by the overarching recommendation of **engaging Indigenous leaders in policy discussions and devising strategies to access safe and nutritious foods**. At the global level, the inclusion

of Indigenous Peoples and recognition of their knowledge in platforms, mechanisms and processes that affect their food systems should be promoted, such as (i) UNFSS and outcomes; (ii) the Local Communities and Indigenous Peoples Platform (LCIPP); (iii) The Treaty on Genetic Resources for Food and Agriculture; and (iv) the Committee on World Food Security.

7. **The establishment of a zero-hunger fund**, proposed by the Summit, should not be done at the expense of Indigenous Peoples. Therefore, it is recommended that this global fund include a sub-fund allocated to and led by Indigenous Peoples to protect and preserve their food systems and that considers the wide variety of food systems, from the arctic region, to the rainforest, to the deserts. At COP26, a fund that will support degradation loss and reverse forest loss was announced. It is important to note that funds like this should consider a holistic approach and the wide range of landscapes and environments where Indigenous Peoples live other than the forest, e.g., include the complexity of food systems and their multipurpose nature, as well as consider environments from deserts to fishing landscapes.
8. The **expansion of coverage of social protection systems** proposed by the Summit is essential for Indigenous Peoples and must resolve the lack of recognition by governments of the Indigenous Peoples' populations living in their countries.
9. **Develop new standards and legal frameworks to drive private sector change and hold companies accountable**. This is fundamental to ending displacement situations, the expansion of the agriculture frontier into ecosystems, and the pollution and destruction of the environment undertaken by the private sector, often under state-run concession systems. During COP26, countries of the Global North committed to supporting the disproportionate effects of climate change, including Indigenous Peoples. If the Glasgow Climate Pact is committed to climate justice, Indigenous Peoples should receive investment to support their resilience and adaptation strategies.
10. In the case of Indigenous Peoples' food systems, **the principle of self-determination and self-determined development** is fundamental in critical areas such as intellectual property rights, harvesting rights, access to plant genetic resources, territorial rights, and the right to self-determination and self-governance.
11. The influence of predominant cultures and school education curricula that are not rooted in Indigenous Peoples' knowledge systems have been linked to elevated rates of food insecurity, cultural degradation, erosion of traditional knowledge and loss of language in many Indigenous Peoples' communities. Therefore, Indigenous Peoples must be **leaders in devising and implementing intercultural education, policies and strategies for sustaining their food systems and creating cultural security in education, health services, policies, programmes, and decision-making.** It is also vital to protect and strengthen Indigenous Peoples' connections to their knowledge and food systems, languages, values, and cultures, beginning with school children and community leadership.
12. **Building interventions to restore and sustain local food systems using locally preferred methods.**

4 Action Area 2: Boost Nature-Based Solutions of Production

This Action Area could help countries connect to coalitions, initiatives, and resources around i. agroecology and regenerative agriculture, ii. blue and aquatic foods, iii. sustainable livestock, iv. AIMs for limate, v. a global soil hub, vi. efforts to stop and reverse biodiversity loss, and beyond.

Key Contributions from Indigenous Peoples

1. Indigenous Peoples are custodians of the majority of the planet's food and genetic resources and are stewards for the territories and biocultural processes that shape and support genetic diversity (Hunter et al., 2015; Garnett et al., 2018; Díaz et al., 2019; Hunter et al., 2020).
2. For thousands of years, Indigenous Peoples have managed their territories and natural resources in sustainable and dynamic ways that have allowed them to inhabit the same territories and preserve the natural resources, making them available for future generations.
3. Indigenous Peoples' food systems typically involve the generation of food from multiple distinct areas of the landscape and from a rich diversity of species, varieties and breeds, which diffuses the risk associated with any single resource and allows Indigenous Peoples to benefit from the diversity of resources from different ecological zones through the year. Biodiversity-rich practices contribute to resilience by providing insurance against resource failures, enabling adaptation of food resources over longer time frames through evolutionary processes, encouraging positive symbiotic interactions between species and areas in the landscape that support nutrient cycling, control pests and disease, and facilitate pollination, and sheltering the food system from the impact of ecological shocks. (Mijatović et al., 2013).
4. Indigenous youths are the future knowledge keepers of Indigenous Peoples' food systems, languages, knowledge, cultures, and lifeways. Their opportunities and decisions now will determine the future existence or extinction of Indigenous Peoples' food systems and territories across the world. To sustain their lifeways and cultures, Indigenous youths need to have opportunities for the intergenerational transfer of knowledge with their elders and be empowered, informed decision-makers in their communities, as well as regionally and globally. The health and empowerment of Indigenous youths are crucial for Indigenous Peoples' resilience and the planet's health.

Recommendations for Action Area 2

5. Proposals **to increase agro-biodiversity for improved production and resilience** are critical to future nature-positive production in which Indigenous Peoples can play a significant role. Not only are Indigenous Peoples'

communities the custodians for significant proportions of the world's genetic resources, but their territories also encompass unique dynamic biocultural spaces that enhance and allow these resources to continue to evolve and adapt further to ongoing climate variability and other challenges. Also, Indigenous Peoples' intellectual property rights and leadership in policy work, such as the International Treaty on Plant and Genetic Resources and Convention on Biological Diversity, have a crucial role in preserving agrobiodiversity.

6. Scaling**-out agroecological production systems and adopting regenerative agricultural practices for resilient landscapes at scale** have the potential to conserve and promote nature-positive production. Indigenous Peoples' communities and farmers can make numerous contributions in this effort, given their rich knowledge, agroecological practices and access to a diversity of crop genetic resources.

5 Action Area 3: Advance Equitable Livelihoods, Decent Work, & Empowered Communities

This Action Area could help countries connect to coalitions, initiatives, and resources around i. Decent Work and Living Incomes, ii. More and Better Jobs for Youths, iii. Making Food Systems Work for Women and Girls, iv. Indigenous Peoples Food Systems, and beyond.

Key Contributions from Indigenous Peoples

1. Indigenous Peoples' food systems are based on inclusive agroecological networks that lead to equitable and sustainable livelihoods.
2. Indigenous Peoples' food systems have traditionally relied on sharing and barter exchange. Further, examples of small farmers and Indigenous Peoples' inclusive and sustainable agroecological networks advance equitable livelihoods for the communities involved in these exchange networks. The food that they produce and their exchange systems rely on diversified and low-input agriculture and short, domestic, and equitable value chains that ensure transparency and trust between producers and consumers, along with cultural security and preserving cultural values, such as sharing and reciprocity.

Recommendations for Action Area 3

3. **The establishment of forums that bring together representatives of government, trade unions and employers' associations, and other key stakeholders and organisations,** such as cooperatives, small business organisations, women's groups, peasants' and Indigenous Peoples' organisations, has been proven to be an effective way of jointly designing and implementing common

strategies to promote decent work in the agri-food sector and economic development.

4. Labelling **and certification schemes for Indigenous Peoples' food, driven forward by Indigenous Peoples** to ensure their rights to self-determination and intellectual property rights. The integration of Indigenous Peoples' biocultural products in public procurement programmes and the creation of supportive infrastructure will facilitate physical access to markets and promote value chains for traditional food varieties.
5. **Investing** in **the intercultural education of Indigenous Peoples** to reach positions within research, policy-making and decision-making on matters that affect their livelihoods, territories and peoples. At COP26, examples of how intercultural education and research led by Indigenous Peoples can have a positive impact on their lives were presented, but more investment is needed to support intercultural education.
6. **The creation of a global matching investment fund for small-scale producers' organisations** to ensure decent and fair incomes, livelihoods and equitable development opportunities for local communities, especially for rural youths, women and Indigenous Peoples. All investments must respect the rights of Indigenous Peoples to their territories and ancestral domains, cultural heritage and landscapes, and traditional knowledge and practices.

6 Action Area 4: Build Resilience to Vulnerabilities, Shocks, and Stresses

This Action Area could help countries connect to coalitions, initiatives, and resources around i. Local food supply chains, ii. Climate-resilient development pathways, iii. The Humanitarian Development Peace (HDP) Nexus, iv. Safety nets, and beyond.

Key Contributions from Indigenous Peoples

1. As knowledge keepers of intergenerational traditional knowledge and experts on their local environments, Indigenous Peoples' leadership and expertise are critical to the global efforts to mitigate and adapt to climate change. Indigenous Peoples' perceptions of change, observational histories, and use of modern technologies with traditional practices position them to develop risk analysis and innovative strategies for climate change and safeguard food systems within their territories. Indigenous researchers and communities globally have developed their climate adaptation plans utilising technical data paired with value-based evidence to design more responsive solutions to community priorities. Many Indigenous Peoples are ahead of other entities in their planning and response to the climate crisis. Further, many Indigenous Peoples' communities and territories are among the most heavily impacted and vulnerable to climate change impacts.

Their territories and lands are priority areas for preserving ecosystems with endemic plants, animals, seeds, crops (wild and cultivated), and other food diversity elements essential for sustainable and resilient food systems.

2. Occasional gene flow between domesticated and wild species also contributes to the generation of unique genetic diversity. Indigenous Peoples frequently source new diversity from nearby communities or further afield and exchange materials with friends and relatives (Maxted et al., 2020).
3. Beyond simply the preservation of biological diversity, the vast biocultural diversity of Indigenous Peoples' food systems contributes a broad knowledge base that can inform and expand the set of possibilities and resources that humanity can draw upon in facing environmental uncertainty. Indigenous Peoples often possess rich environmental knowledge, encompassing a breadth of topics, including climate, botany, ecology, and spirituality, that guide resource use and land management practices.
4. Indigenous beliefs, rituals and values, in many cases, underpin collective action by enabling processes that gather and reconcile different viewpoints on how to respond to environmental issues (Ford et al., 2020).
5. Food-sharing is a norm in many Indigenous Peoples' communities, which helps buffer food availability and diversity during periods of stress (Zavaleta-Cortijo et al., 2020). Indigenous Peoples place significant value on learning by adopting and modifying existing practices and abandoning practices that no longer serve them. Learning is supported by the intergenerational exchange between Indigenous youths and elders and supports the continual adaptation of food systems in response to environmental change (Van Uffelen et al., 2021); most of this knowledge is passed through orality, and therefore Indigenous languages play a crucial role in maintaining the learning loop.

Recommendations for Action Area 4

6. **Indigenous Peoples' perspectives and leadership must be incorporated within risk analysis and risk management** strategies to monitor, prevent and mitigate environmental shocks and change. During COP26, Indigenous Peoples demonstrated different strategies and innovations that they are using in monitoring and adapting to climate change, e.g., GIS and Indigenous knowledge to monitor the rise of rivers and oceans, land-use change and how it affects food seasonality, warning mechanisms for flooding, etc. Funds to support these monitoring and adaptation strategies should be promoted.
7. **Indigenous Peoples' land tenure and sovereignty** are prerequisites to adaptive capacity in confronting climate change and addressing global sustainability. That includes the right to access and manage traditionally occupied or used land, territories and resources, as well as the rights to mobility and passage to access food system resources.
8. Long-term conservation on food diversity in gene banks and the field, and sustained diversification of the food basket. **Creation of biocentres that ensure food for all** in a sustainable way.

9. **Blended financing mechanisms for small projects/initiatives** locally owned by women and youths to empower women's agency and leadership in developing resilience solutions. In COP26, Indigenous women and youths showcased their different climate change adaptation strategies and highlighted their role as knowledge holders of these strategies. Investment funds for ongoing projects and supporting alliances among different stakeholders should be promoted to reinforce their work and success.
10. **Universal food access**: enacting food as a public good. Indigenous Peoples perceive food as a concept beyond the nutritional and physical aspects that embodies culture, cosmogony, and territorial management.
11. **Intercultural education systems** that allow Indigenous Peoples to reclaim, preserve and restore their knowledge systems and their languages; these actions are crucial for supporting their resilience and the planet's.
12. **Intercultural health services and the institutionalisation of cultural security in health services:** To ensure quality and equitable health care provided to Indigenous Peoples and recognise the centrality of nutrition and culturally aligned foods and medicinal practices to support and sustain the health of Indigenous Peoples.

7 Action Area 5: Support Means of Implementation

This Action Area could help countries connect to coalitions, initiatives, and resources around i. Finance, ii. Governance, iii. Science and Knowledge (e.g., True Value of Food; Indigenous Food Systems), iv. Innovation, Technology, & Data, v. Capacity, v. Human Rights, and beyond.

Key Contributions from Indigenous Peoples

1. Indigenous Peoples are crucial for the planet's sustainability, and both their food systems and they themselves are game-changers for the current food security and climate challenges and for achieving the SDG2030. However, they face structural racism and marginalisation that also force them to face economic poverty that stands in sharp contrast to Indigenous societies' cultural and ecological richness. Therefore, it is not possible to imagine world leaders meeting and trying to discuss and implement measures about sustainability and resilient food systems without including Indigenous Peoples, because they have been practising many sustainable and resilient strategies successfully in their communities and ecosystems before these terms were even conceptualised.

Recommendations for Action Area 5

2. **The overarching rights to land, territories and natural resources, and the right to self-determination and cultural rights, are preconditions for the full and effective exercise and realisation of other rights.** During COP26, the pressure and forced displacement Indigenous Peoples face were highlighted; thus, to achieve the goals of the SGD2030, Indigenous Peoples' rights to land,

territories and resources must be fully respected and recognised, including their capacity for the management and co-management of resources that are at the heart of their food systems. The right to self-determination under the principle of "Nothing for or about Indigenous Peoples without Indigenous Peoples" is relevant for any external entity whose actions involve or impact Indigenous Peoples in any way that could affect their livelihoods, food systems, or territories. The implementation of the UN Declaration on the Rights of Indigenous Peoples and the right to Free, Prior, and Informed Consent are the international standard for the rights-based approach with Indigenous Peoples.

3. **Policy-making and decision-making concerning food resources must start and end with Indigenous Peoples and their management and co-management of institutions and bodies** and, where relevant, in collaboration and cooperation with state government bodies that support such Indigenous-driven decisions. Any and all relationships with non-Indigenous Peoples at all levels require trust, respect, sharing and cooperation, as well as education to support Indigenous Peoples' food systems, thereby guiding and protecting the cultural integrity of Indigenous Peoples and their communities now and into the future.
4. **Indigenous Peoples should be leaders in devising strategies for developing their food systems based on their insights and priorities** for their communities. Policies must be created to be intercultural, and thus strengthen (not erode) Indigenous Peoples' values, foods and traditional knowledge.
5. **Create a fund to research and support the potential of Indigenous Peoples' food systems and resilience strategies supporting Indigenous-led researchers' use of funds**. Ensuring Indigenous Peoples' data sovereignty and governance are upheld and intellectual property rights are not violated.
6. The co-creation of **platforms within which mutual respect for knowledge is ensured and fosters inclusive and effective sustainable food system developmen**t. There is a need to preserve, value, and respect the richness of Indigenous Peoples' knowledge systems and further identify ways that bring together the synergistic strengths of scientific knowledge and Indigenous Peoples' knowledge systems. The process of knowledge co-creation fostered by the Global-Hub on Indigenous Peoples' Food Systems is similar to that followed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and regards Indigenous Peoples' traditional knowledge systems and non-Indigenous scientific knowledge with equal respect and consideration. This process of co-creating knowledge identifies and builds synergies between Indigenous Peoples' knowledge systems and scientific knowledge systems.
7. **Innovative financing and investments for sustainable land management practices** (for example, economic incentive systems such as payment for ecosystem services and carbon credits) offer ways for Indigenous Peoples to continue safeguarding and managing their territories in sustainable ways for the land and their food systems, with positive side effects such as sequestering carbon, maintaining carbon in ecosystems and preserving biodiversity while

also earning an income that sustains their communities' economic needs. However, these funds should be allocated directly to Indigenous communities, such as the investment announced at COP26 last November first, 2021, that will support Indigenous Peoples and Local Communities.

Annexes

Annex 1: Coalition on Indigenous Peoples' Food Systems

Indigenous Peoples' Food Systems Coalition
Main objective of the Coalition:
Ensure understanding, respect, recognition, inclusion, and protection of Indigenous Peoples' Food Systems (IPFS) post-UNFSS, providing evidence about their ¨game-changing and systemic¨ aspects. ***Goal 1: Respect, recognise, protect, and strengthen Indigenous Peoples' food systems across the world*** 1. Strengthen policy and regulations to ensure that Indigenous Peoples' food systems are not harmed by intensive and transformed food systems. 2. Work with national governments and international agencies to secure funding. 3. Support interculturality at all levels. 4. Support the drafting of national policies, research, and programmes to protect and strengthen Indigenous Peoples' Food Systems, including them in decision-making, with a special focus on Indigenous women, youths and elders. 5. Support processes of inter- and intra-generational transmission of knowledge and horizontal capacity building in regard to Indigenous Peoples' food systems. 6. Strengthen the leadership of Indigenous youths for innovative intercultural approaches, integrating indigenous peoples' traditional knowledge, science, technology and management. 7. Promote seed security to ensure Indigenous Peoples' access to seeds and planting material that meets their preferences. ***Goal 2: Disseminate and scale-up traditional knowledge and good practices from Indigenous Peoples' food systems with the potential to transform global food systems across the board*** 1. Scale-up Indigenous Peoples' food systems by strengthening scientific and empirical research and intercultural co-creation processes. 2. Increase food systems' resilience and risk management by incorporating Indigenous Peoples' knowledge about ecosystems. 3. Promote Indigenous Peoples' leadership in food systems by sharing their models of food management, production, and processing. 4. Provide evidence about Biocentric-Biocultural considerations in food for policy discussions. 5. Work with other coalitions to ensure the protection of Indigenous Peoples' food systems under the 'do no harm' principle and promote the implementation of the UN Declaration on the Rights of Indigenous Peoples and other related UN Declarations.
Science-based evidence to prioritise this Coalition (scientific references):
The Scientific-Committee included the Wiphala paper as a reference document and recognised Indigenous Peoples' food systems as game-changers at the Pre-Summit. This Coalition builds on the Wiphala Paper and other research and scientific publications: • FAO and Alliance of Bioversity International and CIAT. 2021. *Indigenous Peoples' food systems: Insights on sustainability and resilience in the front line of climate change*. Rome. https://doi.org/10.4060/cb5131en

(continued)

• Settee and Shukla. 2020. *Indigenous Food Systems: Concepts, Cases and Conversations*. Canadian Scholars an Imprint of CSP Books, Inc. • Jackson, G., McNamara, K.E., Witt, B. 2020. "System of hunger": Understanding causal disaster vulnerability of indigenous food systems, *Journal of Rural Studies*, Vol 73, Pages 163–175, doi.org/10.1016/j.jrurstud.2019.10.042. • Dawson, N. M., B. Coolsaet, E. J. Sterling, R. Loveridge, N. D. Gross-Camp, S. Wongbusarakum, K. K. Sangha, L. M. Scherl, H. Phuong Phan, N. Zafra-Calvo, W. G. Lavey, P. Byakagaba, C. J. Idrobo, A. Chenet, N. J. Bennett, S. Mansourian, and F. J. Rosado-May. 2021. The role of Indigenous peoples and local communities in effective and equitable conservation. *Ecology and Society* 26(3):19. https://doi.org/10.5751/ES-12625-260319. • Rosado-May, F., Urrieta, L. Jr., Dayton, A., Rogoff, B. 2020. *Handbook of the Cultural Foundations of Learning Innovation as a Key Feature of Indigenous Ways of Learning*. Routledge • Jackson, G. 2019. The influence of emergency food aid on the causal disaster vulnerability of Indigenous food systems. *Agriculture and Human Values,* 37, 761–777. https://doi.org/10.1007/s10460-019-10006-7 • Kuhnlein, H.V., Erasmus, B. &Spigelski, D. 2009. Indigenous Peoples' Food Systems: The Many Dimensions of Culture, Diversity and Environment for Nutrition and Health. Food and Agriculture Organization of the United Nations, Rome. 339 pp. • Kuhnlein, H.V., Erasmus, B., Spigelski, D. &Burlingame, B. 2013. Indigenous Peoples' Food Systems and Wellbeing: Interventions and Policies for Healthy Communities. Food and Agriculture Organization of the United Nations, Rome. 398 pp. • Turner, N., Berkes, F., Stephenson, J., Dick, J. 2013. Blundering Intruders: Extraneous Impacts on Two Indigenous Food Systems, *Human Ecology*, Vol. 41, No 4, pp. 563–574. https://www.jstor.org/stable/24017347
Mechanisms of implementation (Global to National levels):
The Coalition's working groups, supported by the Global-Hub on Indigenous Peoples' food systems, Indigenous Peoples' forums and experts mechanisms, will work on: **1. Intercultural Co-Creation of Knowledge and Research:** To establish a research agenda on Indigenous Peoples' food and knowledge systems, support policy-making, improve national-global programmes, and include interculturality in school meals, school-university curricula, and scientific dialogues. **2. Financing the Strengthening of Indigenous Food Systems and Knowledge:** To collaborate with IFIs and development agencies to improve donor coordination and funding towards creating an Indigenous Peoples' Food Systems Global-Fund. **3. Coordination at the Rome Level:** To facilitate coordination among member states, RBAS and Indigenous Peoples. **4. National and Regional Dialogues:** To work with countries on national and regional dialogues on strengthening Indigenous Peoples' food systems. **5. Monitoring, Reporting and Accountability:** To monitor post-UNFSS efforts to transform unsustainable and inequitable food systems and safeguard against harm to Indigenous Peoples. **6. Support other UNFSS Coalitions:** To integrate Indigenous Peoples' views on sustainability. **7. Inclusion in other Platforms:** To promote the inclusion of Indigenous Peoples and the recognition of their knowledge and food systems in platforms, mechanisms and processes that affect them.
Strategic partners (members, private sector, civil society, academia):
The following Member States have expressed interest in the Coalition; the formal structure of this group, including membership, will be determined after the Summit: *Mexico, New Zealand, Canada, Finland, Norway, the Dominican Republic, Spain, UNPFII, Global-Hub, FAO, WFP, IFAD.* *Indigenous Organizations/Communities from seven socio-cultural regions at the country and regional levels.*

(continued)

Monitoring and Evaluation (clear quantifiable indicators and targets linked to SDGs)
Post-UNFSS activities must be guided by UNDRIP's rights of Indigenous Peoples and monitored through disaggregated data and Indigenous Peoples' sensitive indicators. This Coalition will work with other coalitions, identifying measurable outcomes and indicators, such as: land and resource rights; support for Indigenous Peoples' institutions, knowledge and food systems; participation by Indigenous Peoples in decision and policy-making; states' efforts to commit to non-discrimination in international conventions and in adopting laws and policies. This Coalition will oversee the election of Indigenous Peoples' representatives to the Advisory Group to the RBAs coordination food systems hub, and will participate in the SGs Two-year Stocktake of this process and of the 2030 Agenda, contributing at the national level to Resident Coordinators and UN Country Teams' reports.

Annex 2: The White/Wiphala Paper on Indigenous Peoples' Food Systems

Contributors

Members of Global-Hub and the Technical Editorial Committee Danny Hunter (Alliance of Bioversity International and CIAT)**;** Gam Shimray (Asian Indigenous Peoples Pact); Thomas Worsdell; (Asian Indigenous Peoples Pact); Anne Brunel (FAO Indigenous Peoples Unit); Gennifer Meldrum (FAO Indigenous Peoples Unit); Ida Strømsø (FAO Indigenous Peoples Unit); Luisa Castañeda (FAO Indigenous Peoples Unit); Mariana Estrada (FAO Indigenous Peoples Unit); Mikaila Way (FAO Indigenous Peoples Unit); Yon Fernandez de Larrinoa (FAO Indigenous Peoples Unit); Charlotte Milbank (FAO Indigenous Peoples Unit, University of Cambridge); Pablo Arigita Baena (FAO Indigenous Peoples Unit); Tania Martinez (Greenwich University, Natural Resources Institute); Harriet Kuhnlein (McGill University, Centre for Indigenous Peoples' Nutrition and Environment); Bhaskar Vira (University of Cambridge).

Members of Global-Hub Amparo Morales (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Dennis Mairena (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Ernesto Marconi (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Gabriel Muyuy (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Luis Alfredo Rojas (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Myrna Cunningham Kain (Fondo para el Desarrollo de los Pueblos Indígenas de América Latina y El Caribe); Carolina Herrera (Fundación Gaia Amazonas); Juliana Sanchez (Fundación Gaia Amazonas); Julieth Rojas (Fundación Gaia Amazonas); Maria Isabel Valderrama (Fundación Gaia Amazonas); Pamela Katic (Greenwich University, Natural Resources Institute); Julie Brimblecombe (Monash University); Tero Mustonen (Snowchange Cooperative); Bhogtoram Mawroh (The Indigenous Partnership on

Agrobiodiversity and Food Sovereignty); Lukas Pawera (The Indigenous Partnership on Agrobiodiversity and Food Sovereignty); Phrang Roy (The Indigenous Partnership on Agrobiodiversity and Food Sovereignty).

Contributors from Africa Boris Ibela (Association pour le devenir des autochtones et de leur connaissance originelle); Davy Pouaty Nzembialela (Association pour le devenir des autochtones et de leur connaissance originelle); Pierre Mondjo (Association pour le devenir des autochtones et de leur connaissance originelle); Sandrine Moughola (Association pour le devenir des autochtones et de leur connaissance originelle); Bakari Chaka (Maasai Mara University); Charity Konana (Maasai Mara University, Individual Expert from the Maasai Community); Mariam Wallet Aboubacrine (Tin Hinan, women's association); Abdallah Marjan (Maasai Mara University); Osano Aloys (Maasai Mara University); Morompi Ole Masago (Maasai Mara University).

Contributors from the Arctic Dalee Sambo (Inuit Circumpolar Council, Individual contribution); Vera Metcalf (Inuit Circumpolar Council, Individual contribution); Vernae Angnaboogok (Inuit Circumpolar Council, Individual contribution); Carolina Behe (Inuit Circumpolar Council, Individual contribution).

Contributors from Asia Pradeep Metha (Central Himalayan Institute for Nature & Applied Research); Lalita Bhattacharjee (Meeting the Undernutrition Challenge, FAO); Fidel Rodriguez (FAOPH, FAO Representation Office in the Philippines); Jeffrey Oliver (FAOPH, FAO Representation Office in the Philippines); Jasmine Magtibay (FAOPH, FAO Representation Office in the Philippines); Kathleen Ramilo (FAOPH, FAO Representation Office in the Philippines); Melanie Sison (FAOPH, FAO Representation Office in the Philippines); Virginia Agcopra (FAOPH, FAO Representation Office in the Philippines); Dharmen G. Momin (Garo tribe, Individual contribution); Neelam Kerketta (Oraon tribe, India, Jawaharlal Nehru University, New Delhi); Mardha Tillah (Indonesian Institute for Forest and Environment); Basavi Kiro (Torang Trust).

Contributors from Latin America Samuel Cauper Pinedo (Asociación Centro Indígena para el Desarrollo Sostenible); Gloria Amparo Miranda Zambrano (Departamento de Estudios Culturales, Demográficos y Políticos. División de Ciencias Sociales y Administrativas, Campus Celaya-Salvatierra. Universidad de Guanajuato, Mexico); Liseth Escobar (National University of Colombia, Amazonia Campus); Olga Lucía Chaparro Africano (National University of Colombia, Amazonia Campus. Honorary Fellow Researcher in the Latin American, Caribbean and Iberian Studies Program (LACIS) at the University of Wisconsin-Madison); Jenny Chicaiza (pueblo Kayambi, Red de jóvenes Wambra Páramo); Carmen Laura Paz Reverol (pueblo wayuu, Fundación Indígena Lumaa, Universidad del Zulia).

Contributors from North America Hannah Tait Neufeld (Indigenous Health Wellness and Food Environments, School of Public Health and Health Systems, Faculty of Health, University of Waterloo); Steven Holley (Dena'ina (the Many People), Alaska Village initiative, Alaska Carbon Exchange); Erin Riley (Division of Community and Education, Institute of Youth, Family and Community-IYFC USDA|National Institute of Food and Agriculture-NIFA); Kellyann Jones-Jamtgaard (Division of Community and Education, Institute of Youth, Family and Community-IYFC, USDA|National Institute of Food and Agriculture-NIFA); Jamie Betters (Oneida Nation); Debra Nkusi (First Nations and Inuit Health Branch, Indigenous Services Canada); Lesya Marushka (First Nations and Inuit Health Branch, Indigenous Services Canada); Andrea Carmen (International Indian Treaty Council, Yaqui Nation); Joseph Gazing Wolf (Lakota, Standing Rock Sioux Nation, Arizona State University, USA); Tara Maudriez (Johns Hopkins Bloomberg School of Public Health, Sault Ste. Marie Tribe of Chippewa Indians, Individual contribution); Sara Moncada (The Culture Conservancy, Yaqui Nation); Robert Brown (Oneida Nation); Vicki Hebb (University of Nevada Reno, Community Services – Extension Mineral County, Cheyenne River Sioux Tribe); Jonathan Long (US Forest Service); Tracy Morgan (Washington State University, FRTEP Tribal Extension under the Kalispel Tribe of Indians; Friend of Kalispel Tribe).

Contributors from the Pacific Jane Lokomaika'ikeakua Au (Kānaka 'Ōiwi (Native Hawaiian) 'Āina Momona); Dr Kamana Beamer (Kānaka 'Ōiwi (Native Hawaiian), Center for Hawaiian Studies in the Hui 'Āina Momona Program at the University of Hawai'i at Mānoa).

Contributors on COVID-19 and Resilience Carol Zavaleta-Cortijo (Quechua from Peru, Unidad de Ciudadania Intercultural y Salud Indígena (UCISI), Facultad de Salud Pública y Administración, Universidad Peruana Cayetano Heredia; Eranga K. Galappaththi (Individual (expert) contribution).**General contributions.** Amy Ickowitz (Center for International Forestry Research); Alexandre Meybeck (Center for International Forestry Research (CIFOR) and the Forests, Trees and Agroforestry research programme of the CGIAR); Vincent Gitz (Center for International Forestry Research, the Forests, Trees and Agroforestry (FTA) research programme of the CGIAR); Junko Nakai (FAO, Natural Resources Management Officer); Francesco N. Tubiello (FAO, FAOSTAT); Alvaro Toledo (FAO, International Treaty on Plant Genetic Resources); Daniele Manzelaa (FAO, International Treaty on Plant Genetic Resources); Francisco Lopez (FAO, International Treaty on Plant Genetic Resources); Kent Nnadozie (FAO, International Treaty on Plant Genetic Resources); Mario Marino, Technical Officer (FAO, International Treaty on Plant Genetic Resources); Mary Jane Ramos De la Cruz (FAO, International Treaty on Plant Genetic Resources); Olivier Rukundo (FAO, International Treaty on Plant Genetic Resources); Rodica Leahu (FAO, International Treaty on Plant Genetic Resources); Tobias Kiene (FAO, International Treaty on Plant Genetic Resources); Anneleen Van Uffelen (FAO, Office of Climate Change, Biodiversity and Environment); Ghislaine Gill (FAO, Office of Climate Change, Biodiversity and Environment); Irene Hoffmann (FAO, Office of Climate Change, Biodiversity and Environment); Monika Kobayashi (Office of Climate Change, Biodiversity and Environment) Preetmoninder Lidder (FAO, Office of the Chief Scientist); Jessica Vega Ortega (Global Indigenous Youth Caucus); Ajay Rastogi and Lok Chetna Manch (IIED and members of the Biocultural Heritage Working Group); Alejandro Argumedo (IIED

and members of the Biocultural Heritage Working Group); Dr. Chemuku Wekesa (Kenya Forestry Research Institute, IIED and members of the Biocultural Heritage Working Group); Dr. Philippa Ryan (RBG Kew, IIED and members of the Biocultural Heritage Working Group); Dr. Yiching Song (Farmer Seed Network (China), IIED and members of the Biocultural Heritage Working Group); Krystyna Swiderska (IIED and members of the Biocultural Heritage Working Group); Gina Kennedy USAID Advancing Nutrition, IUNS Task Force on Traditional and Indigenous Food Systems and Nutrition, Individual contribution); Rosalaura Romeo (Mountain Partnership Secretariat in FAO); Samantha Abear (Mountain Partnership Secretariat in FAO); Sara Manuelli (Mountain Partnership Secretariat in FAO); Valeria Barchiesi (Mountain Partnership Secretariat in FAO); Yuka Makino (Water and Mountains, Mountain Partnership Secretariat in FAO); Angus W. Naylor and Prof. James D. Ford (Priestley International Centre for Climate, University of Leeds, Leeds, Arctic/Canadian Arctic Individual contributions); Lev Neretin (Safeguards, Climate Risks and Bioeconomy Team of FAO).

Glossary

Biocentrism An ethical approach that holds that all life deserves equal consideration and has, therefore, rights of existence and standing.

Biodiversity conservation The practice of protecting and preserving the abundance and variety (biodiversity) of all species, regardless of classification, ecosystems and genetic diversity, on the planet (IFAD, 2015 and Convention on Biological Diversity).

Bushmeat Meat for human consumption derived from wild animals (IPBES Glossary).

Communal resources or "common property" Rights held by members of a community to land and other natural resources (e.g., pastures) that members can use independently of one another (FAO Glossary). Common property is characterised by the following elements: overarching ritual and cosmological relations with traditional lands; community "rights" of control over land disposal (sometimes delegated to traditional leaders); kinship or territory-based criteria for land access; community-based restrictions on dealings in land with outsiders; and principles of reversion of unused land to community control (IFAD, 2015).

Community-based natural resource management An approach to natural resource management that involves the full participation of Indigenous Peoples, local communities and resource users in decision-making activities, and the incorporation of local institutions, customary practices and knowledge systems in management, regulatory and enforcement processes. Under this approach, community-based monitoring and information systems are initiatives by Indigenous Peoples and local community organisations to monitor their community's wellbeing and the state of their territories and natural resources, applying a mix of traditional knowledge and innovative tools and approaches (IPBES Glossary).

Conservation Includes protection, maintenance, rehabilitation, restoration and enhancement of populations and ecosystems. This implies sound biosphere management within given social and economic constraints, producing goods and services without depleting natural ecosystem diversity.

Co-creation (of knowledge) The collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem (Armitage et al., 2011).

Cosmogonies A vision of reality that places the highest importance or emphasis on the universe or nature, as opposed to an anthropocentric vision, which strongly focusses on humankind as the most important element of existence (IPBES Glossary).

Customary tenure Rules and norms that communities devise and uphold to regulate how their lands are acquired, owned, used and transferred. Many rules and norms are tested over generations (hence, "traditions" or "customs"). IFAD Glossary

Customary use of biological resources Uses of biological resources in accordance with traditional cultural practices that are compatible with conservation and sustainable use requirements (Convention on Biological Diversity, CBD).

Ecosystem services The benefits people obtain from ecosystems. These include provisioning services such as food and water; the pollination of crops; regulating services such as flood and disease control; cultural services such as spiritual, recreational and cultural benefits; and supporting services, such as the nutrient cycling that maintains the conditions for life on Earth (IPBES Glossary).

Empowerment (of Indigenous Peoples) The process of increasing the opportunity of Indigenous Peoples to take control of their own lives (IFAD, 2015).

Endemism The ecological state of a species being unique to a defined geographic location, such as an island, nation, country or other defined zone, or habitat type; organisms that are indigenous to a place are not endemic to it if they are also found elsewhere (IPBES Glossary).

Equitable benefit-sharing Equitable distribution of benefits among stakeholders (modified from IPBES).

Food generation Viewed in contrast to food production, food generation relates to consumptive activities involving minimal human intervention within the ecosystem. Food generation includes hunting, fishing and gathering activities, which traditionally rely on a deep understanding of the seasonality of ecosystems, the availability of food sources, and knowledge that supports the recollection of food spontaneously generated by the system.

Free, Prior and Informed Consent (FPIC) Operational principle empowering local communities to give or withhold their consent to proposed investment and development programmes that may affect their rights, access to lands, territories and resources, and livelihoods. Defined by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).

Holism Holistic perspectives consider a large number of variables qualitatively, while science tends to concentrate on a small number of variables quantitatively (adapted from Berkes and Berkes, 2009).

Hunter-gatherers (present-day) A term used to refer to small-scale, mostly egalitarian, societies that subsist primarily on food that has been obtained directly from the environment – through hunting animals, gathering plant food, fishing or scavenging. A more general term for this is "foraging," and such peoples are also sometimes referred to as "foragers" – or often "post-foragers," given that most such societies no longer survive through these subsistence techniques alone. They constitute a tiny fraction (less than 1 percent) of the 476 million peoples referred to as Indigenous (Lee et al., 1999).

Indigenous food Foods from the natural environment that became included in the cultural food use patterns of a group of Indigenous Peoples (FAOTERM).

Indigenous language Not only methods of communication, but also extensive and complex systems of knowledge that have developed over millennia. They are central to the identity of Indigenous Peoples, the preservation of their cultures, worldviews and visions and an expression of self-determination. Indigenous languages are critical markers of the cultural health of Indigenous Peoples. When Indigenous languages are under threat, so too are Indigenous Peoples themselves (UNDPI, 2018)

Indigenous Peoples In accordance with international consensus, the four following criteria apply when considering Indigenous Peoples: priority in time, with respect to occupation and use of a specific territory; the voluntary perpetuation of cultural distinctiveness, which may include the aspects of language, social organisation, religion and spiritual values, modes of production, laws and institutions; self-identification, as well as recognition by other groups, or by state authorities, as a distinct collectivity; and an experience of subjugation, marginalisation, dispossession, exclusion or discrimination, whether or not these conditions persist (FAO, 2010).

Indigenous Peoples' traditional knowledge Cumulative body of knowledge (for example, know-how), practices and manifestations maintained and developed by Indigenous Peoples with long histories of interaction with their natural environment. Indigenous Peoples' knowledge is adapted to the local culture and transmitted orally from generation to generation (adapted from FAOTERM).

Knowledge system A body of propositions that are adhered to, whether formally or informally, and are routinely used to claim truth. They are organised structures and dynamic processes (a) generating and representing content, components, classes or types of knowledge, that are (b) domain-specific or characterised by domain-relevant features as defined by the user or consumer, (c) reinforced by a set of logical relationships that connect the content of knowledge to its value (utility), (d) enhanced by a set of iterative processes that enable evolution, revision, adaptation and advances, and (e) subject to criteria of relevance, reliability and quality (IPBES Glossary).

Land rights Property rights pertaining to land. There are three principal rights linked to the spatial dimension of land: use rights, control rights and transfer rights (FAOTERM).

Land tenure The relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land. More than one person may hold rights to a parcel of land, which gives rise to the concept of a "bundle of rights" (adapted from FAOTERM).

Linguistic diversity Range of variations exhibited by human languages (IFAD Glossary).

Local food Local food refers to food that is produced near its point of consumption.

Marginalisation The process of pushing particular groups of people – usually minorities such as Indigenous Peoples or rural women – to the edge of society by not allowing them to have an active

Oral tradition A variety of spoken forms, including proverbs, riddles, tales, nursery rhymes, legends, myths, epic songs and poems, charms, prayers, chants, songs, dramatic performances and more, used to pass on knowledge, cultural and social values, and collective memory. They play a crucial part in keeping cultures alive (IFAD Glossary).

Ownership The rights to land that are, in everyday language, associated with the ability to use, control, transfer or otherwise enjoy a land parcel as long as those activities are allowed by law. In statutory tenure, it is often associated with freehold. However, land law does not tend to define explicitly what is meant by "ownership" (FAOTERM).

Pastoralism A wide family of livestock-based, livelihood/food production systems, which are specialised in improving the animals' diet and welfare through different forms of mobility (from short movements to nomadism), thus managing their grazing itineraries at a variety of scales in time and space (FAO, forthcoming).

Protected areas A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (IUCN Definition 2008).

Reciprocity Within this report, the concept acknowledges a moral and practical obligation for humans and biota to care for and sustain one another and arises from human gratitude and reverence for the contributions and sacrifices made by another biota to sustain humankind.

Restoration The active intervention and management of degraded biotic communities, landforms and landscapes in order to restore biological character, ecological and physical processes and their cultural and visual qualities (FAOTERM).

Rituals Understood as a network of practices, knowledge and behaviours, rituals associated with food form a key role in maintaining Indigenous world views, passing on practices and values and strengthening the sense of community and collective responsibility to conserve socio-ecological systems (Anacio, 2017).

Self-determination The ability or power to make decisions for oneself, especially to decide how to be governed. The UNDRIP (article 3) recognises the right of Indigenous Peoples to self-determination. By virtue of that right, they freely determine their political status and freely pursue their economic, social and cultural development.

Self-sufficiency A group is considered self-sufficient by its ability to produce all the materials it consumes and to consume what it produces. Self-sufficiency refers to a closed loop from production to consumption to production. It is a model, sometimes an ideal that is never achieved. Economic self-sufficiency is in total contrast to complete market economy, in which everything produced is traded and everything consumed is secured through trade (Callan and Coleman, eds., 2018).

Spirituality A fundamental belief in the sacredness of nature, Earth and the universe.

Stewardship (of the environment) The actions taken by individuals, groups or networks of actors, with various motivations and levels of capacity, to protect, care for or responsibly use the environment in pursuit of environmental and/or social outcomes in diverse social–ecological contexts (Bennett et al., 2007).

Subsistence Subsistence is the process whereby people supply themselves with the necessities of life, such as food and shelter. Subsistence relates primarily to self-provisioning by small productive units, often families. These groups are referred to as autarkic for being able to supply all their own needs with no dependence on or interaction with others to obtain necessities (Callan and Coleman, eds., 2018).

Territory Lands and waters traditionally occupied or used by Indigenous and local communities.

Traditional custodian The group, clan or community of people, or an individual who is recognised by a group, clan or community of people, in whom the custody or protection of the expressions of culture are entrusted in accordance with the customary law and practices of that group, clan or community (IFAD, 2015).

Traditional lands and territories Lands and waters traditionally occupied or used by Indigenous and local communities.

Traditional resources Tangible or intangible assets of biological, spiritual, aesthetic, cultural and economic value used traditionally by Indigenous Peoples and local communities.

Traditional medicine The medicinal preparations, often based on centuries-old traditions, that contain derivatives from plants or animals that have proven or reputed medicinal properties (CITES Glossary).

United Nations Declaration of Rights on Indigenous Peoples (UNDRIP) Adopted by the General Assembly in September 2007, the UNDRIP contains provisions on land, natural resources and subsistence activities relevant for the realisation of Indigenous Peoples' right to food and food sovereignty. It also includes the protection of traditional knowledge, biodiversity and genetic resources, and sets limits on the activities of third parties on the territories of Indigenous communities without their consent.

Use rights ("usufruct") Right to use the land for growing crops, passage, grazing animals and the utilisation of natural and forest products. A holder of a use right may not have the right to sell the property, etc. (FAO TERM).

Value systems Set of values according to which people, societies and organisations regulate their behaviour. Value systems can be identified in both individuals and social groups (IPBES Glossary).

Vulnerability The ability to be easily physically, emotionally or mentally hurt, influenced or attacked. Vulnerable groups define those who have insufficient access to the quantity and quality of food that would ensure a healthy life and/or are at risk of losing such access altogether (World Food Programme [WFP]).

Wellbeing A context- – and situation- – dependent state, comprising basic material for a good life, freedom and choice, health, good social relations and security (UN, 2008).

Western science (also called modern science) A broad term to refer to knowledge typically generated in universities, research institutions and private firms following paradigms and methods typically associated with the "scientific method" consolidated in Post-Renaissance Europe on the basis of wider and more ancient roots. It is typically transmitted through scientific journals and scholarly books. Some of its central tenets are observer independence, replicable findings, systematic scepticism and transparent research methodologies with standard units and categories.

Wild food (or "uncultivated food") Wild plants, animals and insects that are not cultivated or reared in captivity. They are part of the minor crops and underutilised species, and include roots and tubers, vegetables and leafy vegetables, fruits, insects, amphibians, reptiles, birds, game and mammals gathered for food (Bioversity International, 2017).

Worldviews Worldviews defined by the connections among networks of concepts and systems of knowledge, values, norms and beliefs. Individual person's worldviews are moulded by the community to which the person belongs. Practices are embedded in worldviews and are intrinsically part of them (e.g., through rituals, institutional regimes, and social organisation, but also in environmental policies, in development choices, etc.).

References[1]

Anacio DB (2017) Threats and challenges to ensuring the requirement of biodiversity and ecosystem services for the indigenous begnas ritual system of Sagada, Northern Philippines. In: Karki M, Hill R, Xue D, Alangui W, Ichikawa K, Bridgewater P (eds) Knowing our lands and resources: indigenous and local knowledge and practices related to biodiversity and ecosystem services in Asia. UNESCO, pp 6–14

Armitage D, Berkes F, Dale A, Kocho-Schellenberg E, Patton E (2011) Co-management and the co-production of knowledge: Learn-ing to adapt in Canada's Arctic. Glob Environ Chang 21(3): 995–1004. https://doi.org/10.1016/j.gloenvcha.2011.04.006

Bennett EL, Blencowe E, Brandon K, Brown D, Burn RW, Cowlishaw G, Davies G et al (2007) Hunting for consensus: Reconciling bushmeat harvest, conservation, and development policy in West and Central Africa. Conserv Biol 21:884–887

[1] This brief summarises the full White/Wiphala paper, which may be referred and contains the full reference list.

Bioversity International (2017) Mainstreaming agrobiodiversity in sustainable food systems: Scientific foundations for an agrobiodiversity index. Rome, Italy. (Also available at https://hdl.handle.net/10568/89049)
Callan H, Coleman S (eds) (2018) The International Encyclopedia of Anthropology, vol 12. Wiley, New York
Díaz S, Settele J, Brondízio ES, Ngo HT, Agard J, Arneth A, Balvanera P et al (2019) Pervasive human-driven decline of life on Earth points to the need to transformative change. Science 366(6471). [online], [Cited 12 May 2021]. https://doi.org/10.1126/science.aax3100
FAO (2010) FAO Policy on Indigenous and Tribal Peoples. Rome, FAO 44 pp. (also available at http://www.fao.org/3/I4476E/i4476e.pdf)
FAO (2021a) The White/Wiphala Paper on Indigenous Peoples' food systems. Rome. https://doi.org/10.4060/cb4932en
FAO (2021b) The share of food systems in total greenhouse gas emissions. Global, regional and country trends, 1990–2019. FAOSTAT Analytical Brief Series No. 31. Rome. https://www.fao.org/food-agriculture-statistics/data-release/data-release-detail/en/c/1454718/
Ford JD, King N, Galappaththi EK, Pearce T, McDowell G, Harper SL (2020) The resilience of Indigenous Peoples to environmental Change. One Earth 2(6):532–543
Garnett ST, Burgess ND, Fa JE, Fernández-Llamazares Á, Molnár Z, Robinson CJ, Watson JEM et al (2018) A spatial overview of the global importance of Indigenous lands for conservation. Nat Sustain 1:369–374
Hunter D, Burlingame B, Remans R (lead authors) (2015) Biodiversity and nutrition. In Connecting Global Priorities: Biodiversity and Human Health, a State of Knowledge Review (Romanelli et al. eds). Convention on Biological Diversity/World Health Organization
Hunter D, Borelli T, Gee E (2020) Biodiversity, Food and Nutrition: A New Agenda for Sustainable Food Systems. Routledge
International Fund for Agricultural Development (IFAD) (2015) Indigenous Peoples Glossary, 2nd edn, Rome
ILO (2019) Implementing the ILO indigenous and tribal peoples convention No. 169: towards an inclusive, sustainable and just future, Geneva
ICC-Alaska (2015) Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic From an Inuit Perspective. Technical Report, Anchorage
Lee RB, Heywood Daly R, Daly R (1999) The Cambridge Encyclopedia of Hunters and Gatherers. University Press, Cambridge
Maxted N, Hunter D, Ortiz R (2020) Plant Genetic Conservation. Cambridge University Press
Mijatović D, Van Oudenhoven F, Eyzaguirre P, Hodgkin T (2013) The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. Int J Agric Sustain 11(2):95–107
Sobrevilla. (2008) The role of Indigenous Peoples in Biodiversity Conservation. The Natural but Often Forgotten Partners, Washington, DC
United Nations Department of Public Information (UNDPI) (2018) Indigenous languages [online]. New York [Cited 31 August 2020]. www.un.org/development/desa/indigenouspeoples/wp-content/uploads/sites/19/2018/04/Indigenous-Languages.pdf
Van Uffelen A, Tanganelli E, Gerke A, Bottigliero F, Drieux E, Fernández-de-Larrinoa Y, Milbank C, Sheibani S, Strømsø I, Way M, Bernoux M (2021) Indigenous youth as agents of change – actions of Indigenous youth in local food systems during times of adversity. FAO, Rome
Zavaleta-Cortijo C, Ford JD, Arotoma-Rojas I, Lwasa S, Lancha-Rucoba G, García PJ, Miranda JJ, Namanya DB, New M, Wright CJ, Berrang-Ford L (2020) Climate change and COVID-19: reinforcing Indigenous food systems. Lancet Planet Health 4(9):e381–e382

Marginal Areas and Indigenous People Priorities for Research and Action

Sayed Azam-Ali, Hayatullah Ahmadzai, Dhrupad Choudhury, Ee Von Goh, Ebrahim Jahanshiri, Tafadzwanashe Mabhaudhi, Alessandro Meschinelli, Albert Thembinkosi Modi, Nhamo Nhamo, and Abidemi Olutayo

1 Context

Business-as-Usual Is Not Working Marginal environments and the indigenous people who cultivate them have one thing in common – they are forgotten. Their soils and climates, crops and livestock, beliefs and knowledge systems rarely attract academic interest, policy studies or investment. Marginal environments refer to less-favorable agricultural areas (LFAAs) characterized by constrained agricultural potential and resource degradation attributable to biophysical and politico-socio-economic factors (Pender and Hazell 2000). Their low production potential is driven by rugged terrains, extreme weather conditions, poor soil and water quality, lack of socio-economic connectivity and limited exposure to agricultural intensification opportunities. In such regions, drought and erratic rainfall, salinization, and other factors present significant constraints for intensive agriculture. Marginal environments encompass all LFAAs and any favorable agricultural areas (e.g., areas not constrained by biophysical factors) with limited access to rural infrastructure and agricultural markets where cost-effective production is unfeasible (without additional support) under given conditions, cultivation techniques, and policy or

S. Azam-Ali (✉) · E. V. Goh · E. Jahanshiri
Crops For the Future, Cambridge, UK
e-mail: sayed@cropsforthefutureuk.org

H. Ahmadzai · N. Nhamo · A. Olutayo
International Center for Biosaline Agriculture, Dubai, United Arab Emirates

D. Choudhury
International Centre for Integrated Mountain Development, Kathmandu, Nepal

T. Mabhaudhi · A. T. Modi
University of KwaZulu-Natal, Pietermaritzburg, South Africa

A. Meschinelli
Global Forum for Agricultural Research and Innovation, Rome, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_14

macro-economic settings. The agricultural expertise of indigenous communities is often overlooked by decision-makers, who, instead, advocate interventions based on mainstream crops and external technologies. While such approaches have had demonstrable impacts on food security and poverty alleviation elsewhere, they often fail in indigenous communities where a vast range of crops are cultivated in diverse production systems and in marginal environments. As a result, agricultural yields in marginal areas continue to decline and the gap between the actual and potential yield of mainstream food crops widens (Mustafa et al. 2021; Chimonyo et al. 2020; Leakey 2020). Hunger, malnutrition, and poverty in indigenous communities continue to increase, as one in five people on the planet is malnourished (UN Environment Programme 2020).

We Need Diverse Food Systems An alternative to top-down technological packages is to approach the existential challenges that indigenous people face from their own perspectives and resources. However, the agrobiodiversity and associated knowledge systems that these communities have protected for millennia are under threat. Nearly 10% of all domesticated breeds of animals for food and agriculture are already extinct and another one million plant and animal species now face extinction (Brondizio et al. 2019). Many of these species are climate-resilient and nutritious crops. For example, millet and gluten-free grains such as amaranth, teff and quinoa are rich in vitamins, minerals, essential fatty acids, phytochemicals, and antioxidants, and crops such as finger millet, cowpea and bambara groundnut are also adapted to extreme weather (drought and heat stress) and poor soil conditions (Mabhaudhi et al. 2019a; Tadele 2018). While the genetic diversity found in indigenous farming systems could become the foundation for future agricultural and food systems, of over 30,000 edible plants, fewer than 30 species grown as monocultures now provide most of the food consumed by 7.8 billion people (FAO 2018). These mainstream crops monopolize agricultural research, investment, support and formal markets.

Languages Are the Basis of Knowledge From over 7000 languages, only six are spoken by half the global population (Eberhard et al. 2020). Roughly 40% of languages are now classified as endangered and as few as 600 might still be spoken in 2100 (Krauss 1992). For indigenous people, this represents not just a catastrophic loss of languages, but of cultural and ethnic identity and agricultural knowledge that, without a written record, has been conveyed verbally for generations. Where a language is unwritten, or its speakers are illiterate, the indigenous knowledge of a community, along with potential solutions to modern challenges facing humanity, are lost.

Climate Change and Sustainable Development Climate change threatens those least able to withstand its impacts. In 2015, UN member parties agreed to limit mean global temperature increases to 2 °C above pre-industrial levels (TheWorldCounts 2021). Predicted global heating is between 3.1 and 3.7 °C (Salawitch et al. 2017). The consequences of such increases and the frequency of extreme events will disproportionately impact indigenous people – since many already live in hostile and marginal environments. However, indigenous people are inheritors of a unique social and cultural identity, have a distinct historical continuity and traditional knowledge of how people have interacted closely with their environments, and have developed and passed on such expertise across many generations (Berkes 2008; Kingsbury 1998). It has been estimated that indigenous people have an approximate population of 476 million across 90 countries, with about 5000 distinct cultures, accounting for most of the world's cultural diversity (UN 2009).

Of the seventeen UN Sustainable Development Goals (SDGs), SDG1 commits the world to *eradicate poverty in all its forms,* and SDG2 to *end hunger, achieve food security and improved nutrition and promote sustainable agriculture* (UN 2021). This entails moving from an economic definition of poverty (lack of income) and hunger (lack of food) to a multidimensional concept involving sustainable livelihoods, healthy diets, knowledge of food heritage and agricultural systems and the agency of communities to make their own decisions. A more articulate and inclusive notion of poverty and hunger eradication means achieving sustainable livelihoods, better nutrition and greater resilience of *all* communities, including indigenous people, to climate shocks.

2 Approach

The consolidation of mainstream agriculture, the decline of species and associated knowledge and the climate crisis all call for a different approach for indigenous people living in hostile environments. In such circumstances, it is they, not us, who are the experts. The challenge is how research can help these communities become agents of change and co-owners of innovations to help secure sustainable livelihoods and healthier lifestyles. Rather than being seen as passive recipients of external technologies, indigenous people need fair and equitable partnerships with research, education, extension, and private institutions that recognize human rights as the basis for sustainable food systems. This means that, wherever possible, the development of agricultural products, value chains, markets and food systems should remain under the jurisdiction of indigenous communities in terms of benefits, intellectual property, labor conditions, and negotiating power. This includes the contribution of underutilized or 'forgotten' crops and their knowledge systems to food security, balanced diets, income generation, agricultural diversification and better use of marginal lands.

3 Evidence

Knowledge Diversity Marginal environments are biogeographically distinct, and their communities are culturally diverse. For indigenous people to secure sustainable livelihoods and healthier lifestyles, we need research approaches that suit the particularities of regions and people and knowledge systems that provide the best options for different circumstances. This requires complementary skills to address systemic challenges to the whole food system, rather than just its components and networks from which viable options can be considered, evaluated and delivered by indigenous people in their own localities.

Knowledge Partners While there are many knowledge systems for mainstream agriculture, we are not aware of any integrated system that relates specifically to marginal environments and indigenous people. However, a number can be adapted to these circumstances by research institutions with expertise in different biogeographical regions. For example, Crops For the Future (CFF) has developed *CropBASE* as a global knowledge base for under-utilized crops (Mohd Nizar et al. 2021), their suitability (Jahanshiri et al. 2020), economic potential and nutritional values in different environments. Along with its partners in the Association of International Research and Development Centers for Agriculture (AIRCA), CFF has proposed a Global Action Plan for Agricultural Diversification (GAPAD) (Association of International Research and Development Centers for Agriculture 2016). The International Centre for Integrated Mountain Development (ICIMOD) facilitates the *Global Framework for Climate Service* (ICIMOD 2021). to collate, curate, and share data so as to support robust planning and policy decisions for climate resilience in mountain regions. The International Center for Biosaline Agriculture (ICBA) has developed integrated drought management, monitoring/early warning systems, vulnerability and impact assessment and mitigation for crop diversification with under-utilized, stress-tolerant crops for food, feed and biofuel (ICBA 2021). The UKN *Centre for Transformative Agricultural and Food Systems* is building resilient, sustainable and healthy food systems for climate-resilient agriculture to improve human wellbeing and livelihoods in semi-arid regions of sub-Saharan Africa (UKZN 2021).

Impact Pathways The Global Forum for Agricultural Research and Innovation (GFAR) is building collective actions to improve the livelihoods of poor farmers, including those in indigenous and other communities living in marginal areas, by enhancing the market value of forgotten foods and the crops from which they derive, intervening in supply chain bottlenecks and mobilizing small producers as co-innovators. By recognizing the rich local knowledge behind forgotten foods, GFAR members seek sustainable avenues for a community-centered, pro-poor transformation of food systems and the reorientation of research and innovation governance. For this, GFAR is co-ordinating a *Collective Action on Forgotten Foods* and a *Manifesto for Forgotten Foods* that explicitly calls for novel research and innovation systems (GFAR 2017).

4 Indigenous Food Systems and Knowledge: Challenges in Diverse Settings

Biogeographical and Cultural Diversity While each marginal region and indigenous community is unique, some themes and challenges link them. Common research and innovation approaches can be shared and applied across environments.

Here, we consider food systems in four biogeographical regions representing a significant proportion of the world's marginal land area, indigenous people and agricultural biodiversity. We then identify innovations, investment opportunities, priorities, and proposed actions to help transform indigenous peoples' food systems in marginal areas through agricultural diversification beyond mainstream crops and systems.

Arid (Drylands, Biosaline Soils and Coastal Regions) The importance of traditional food systems, especially in drylands, where indigenous people reside, cannot be over-emphasized. Indigenous people often hold a historical link between environmental heritage and food systems (Kuhnlein et al. 2013). Recent agricultural interventions have widely acknowledged the role of the indigenous knowledge of local people in the development of food systems in drylands. Effective and sustainable utilization of their cultural heritage regarding food systems can support environmental services, food preservation and food storage. Integration of various knowledge systems in co-innovation and co-production can transform traditional food systems, including food sovereignty, to avoid future hunger and malnutrition (Huambachano 2018; Pingault et al. 2020).

Despite the harsh environmental conditions in drylands, some indigenous food crops have exhibited outstanding performance and unmatched adaptation (Mabhaudhi et al. 2019a). Plant physiological adaptation to environmental stress has been a subject of intense research on dryland crops. Plant responses such as photosynthetic rate alteration, leaf area reduction, stomatal conductance regulation and waxy-substance production have been reported (Hasegawa 2013; Van Zelm et al. 2020). Drought evasion, albeit at the expense of biomass accumulation, has also been studied for many indigenous food crops. Similarly, rhizosphere microbiota (bacteria and fungi) cultivation has resulted in improved adaptation to water and nutrient stresses (Prasad et al. 2019). The application of microsymbionts and the rhizobiology associated with this innovation has explained, in part, the mechanisms of adaptation to stress by plant roots. Rhizobacterial nutrient solubilization, mobilization and salt mitigation using Azotobacter spp. has been found to increase synergy from inoculation (Srividhya et al. 2020). Mycorrhizal associations have also increased nutrient abstraction from the soils by 30%. Thus, co-inoculation with various species such as *Anthrobacter sp.*, *Bacillus sp.*, *Paenibacillus sp.*, *Pseudomonas sp.*, and *Rhizobia sp.* yielded between a 50% and 70% increase in nutrient uptake and use while enhancing photosynthesis and systems defense (Barriuso et al. 2008). Secretion of root exudates and stimulation of lateral root branching increased phosphorus uptake in the soil (Weih et al. 2018).

Both water- and nutrient-use efficiency are a function of the plant phenotype, management, and root architecture. Molecular marker-assisted breeding has made some inroads into the characterization of polygenic effects in relation to dryland environments. There is evidence that water-use efficiency (WUE) increases with water deficit, but not beyond 40% of irrigation requirement (Yu et al. 2020). The combination of high WUE and nutrient-use efficiency (NUE) in indigenous crops can improve yields. Recent developments in integrated drought monitoring and early warning systems have shaped mitigation options for smallholder farmers. With the adoption of controlled environment farming to produce vegetables, indigenous farmers will have the capacity and means to boost production and save about 90% water requirement (Eigenbrod and Gruda 2015). Research that introduces, evaluates, and adapts under-utilized crops for dietary diversification in marginal environments is underway. Several crops with proven tolerance to salt, salinity and/or water stress have been studied in drylands. So far, crop diversification has focused on cereals, legumes, fruit trees and fodder crops. There is evidence of improved crop yields, increased popularization of nutrient-dense crops and fodder suitable for drylands. Examples of dryland food crops include fruit trees (date palms), types of millet (finger-, pearl-, proso-, fonio-millet), pseudo cereals (amaranths, buckwheat, and quinoa), cereal grass (teff), pulses (chickpea, faba bean, pigeon pea lentil and groundnut), halophytes (Cumin, Salicornia, and Colocynths) and oilseeds (mustard, sesame, sunflower, safflower, and rapeseed). These crops have high nutritional values and are adaptable to harsh growing conditions. The genetic diversity among these crop species has been preserved and limited to the communities where they were being cultivated, e.g., teff in East Africa (areas around Ethiopia and Eritrea). Commercialization of these crops will contribute significantly to sustainable food and nutrition security.

Indigenous food systems face natural and anthropogenic extinction. While breeding techniques have advanced, only a handful of indigenous crops have received the required promotional support to facilitate widespread utilization.

Semi-Arid (Seasonally Dry, Rainfed, Impoverished Soils) Semi-arid regions are a subtype of environment with an aridity index (ratio of total annual precipitation to potential evapotranspiration) between 0.20 and 0.50 (Lal 2004). These regions are characterized by mean annual precipitation between 200 and 700 mm (Gallart et al. 2002), often with stormy character, clustered in alternating seasons. A complex range of topography, biodiversity and variability in rainfall and microclimatic conditions has meant frequent exposure to droughts and floods, with grievous implications for agricultural production, ecosystem services and social and cultural relations. The food system context across semi-arid sub-Saharan Africa (SSA) is one of significant environmental, political, socio-economic and cultural diversity. However, the region is regarded as being among the world's most food-insecure (Umetsu et al. 2014; Sutherland et al. 1999). Compounding threats, such as climate change, environmental degradation and increasing populations, have left many marginal communities vulnerable to food and nutritional insecurity (Mugari et al. 2020). This insecurity is further compounded by globalization and the homogenization of the food system, both of which have relegated many African indigenous crops, which are suited to these environments, to the status of neglected and under-utilized species (Chivenge et al. 2015).

Across SSA, food systems rely primarily on the staple food crop production of a few major crops and a few minor or endemic food crops (including under-utilized species) (Leff et al. 2004). Cereal staple crops such as maize, sorghum, wheat and pearl millet are grown and consumed extensively by rural farmers across the region

(Lal 2016; van Ittersum et al. 2016; Hadebe et al. 2017; Bvenura and Sivakumar 2017). However, rural farmers also rely on indigenous crops and associated knowledge systems to ensure their food security (Mabhaudhi et al. 2019b). They augment field crop harvests with different types of seasonal edible wild fruits, vegetables, and roots identified, harvested and processed using indigenous knowledge.

Rural farmers, usually women, are generally regarded as the custodians of under-utilized indigenous and traditional crops and the knowledge of their cultivation and use. It is generally recognized that, although indigenous food plants have, in the past, played an important role in the diet of African communities, the industrialization of food systems and formalization of markets has resulted in a decline in the use of African indigenous and traditional food crops. Also, in most cases, the promotion of Green Revolution technologies has inadvertently exacerbated inequalities and food insecurity. For example, in the 2000s, and after the massive roll-out of hybrid technologies, evidence from Rwanda (Dawson et al. 2016) and Ghana (Vercillo et al. 2020) showed significant growth in agriculture's contribution to the GDP. However, this was accompanied by greater inequalities and food insecurity for rural communities.

On the other hand, reports suggest that under-utilized crops offer a pathway to a more sustainable and equitable agricultural system for SSA, capable of addressing several SDGs related to socio-economic and socio-ecological wellbeing (Mabhaudhi et al. 2016). Researchers argue that one of the unintended outcomes of the global agro-industrial food system has been the replacement, and subsequent relegation, of under = utilized indigenous and traditional crops through the introduction of exotic and (now considered) "major" crops that were often higher-yielding, but also more input-intensive. This has led to the neglect of traditional crop species that had previously formed the basis of local indigenous food systems, which were resilient, sustainable and healthy.

Despite the lack of support, many smallholder farmers use indigenous crop species as nutritious foods that support cultural and ecosystem services. Many of these crops are favored in local markets for both household consumption and as medicines (Chandrasekara et al. 2016). Using traditional methods and knowledge, farmers select, harvest, store and trade indigenous crop varieties that possess desirable nutritional, medicinal and pharmaceutical properties (Dansi et al. 2012). Decades of research have shown that indigenous crops and associated knowledge-systems can improve food and nutritional security in marginal environments. However, it is important to identify traditional tools and strategies that can help address production constraints within marginal farming communities when integrated with modern and digital technologies.

Humid (Tropical, Rainforests) Tropical rainforests are home to many indigenous people and serve as a lifeline for many forest-dependent communities. While not all are indigenous, indicative estimates show that, globally, there are approximately 1.3 billion forest-dependent peoples (Chao 2012). Their food systems are complex chains of production, distribution, consumption, recirculation of food refuse, and the acquisition of trusted foods and ingredients from other populations built on a diversity of local or traditional practices for ecosystem management. These practices include multicropping, resource rotation, succession management, landscape patchiness management, and various methods of managing unpredictable ecological surprises (Whyte 2015; Berkes et al. 2000). Social mechanisms behind these practices include adaptations for the generation, accumulation, and transmission of knowledge; the use of local stewards and rules for social regulation; mechanisms for cultural internalization of traditional practices; and the development of appropriate world views and cultural values (Wiersum 1997; Kuhnlein and Receveur 1996). Resources are collectively managed, relying on group decisions, often by consensus and involving elders (Garí 2001). As the result of a constant struggle between modernization and survival, indigenous peoples have developed flexible strategies to maintain relatively stable and sustainable food systems that are biodiverse, resilient, and long-serving. While there is ample variation in the practices of each indigenous community living in the humid tropics, they share certain similarities in adaptive management. These include an emphasis on feedback learning, the treatment of uncertainty and unpredictability and resilience mechanisms that confer obvious advantages over conventional "modern" productive models (Toledo et al. 2003; Wilson and Woodrow 2009; Goldsmith 2012).

Tropical rainforests cover only a small part of the earth's surface (about 7%), yet house over half the species of plants and animals on the planet (Lima et al. 2020). High deforestation rates result in a significant reduction in the area and geography of mature tropical forests and a loss of diversity of tropical forest species (UN DESA 2009). As a consequence, many native societies of the rainforest have already been destroyed, and those cultures that still exist face a grim future due to poor policies and practices (Ohenjo et al. 2006). Indigenous peoples experience extreme disparities compared with greater-than-global averages in obesity, undernutrition and micronutrient malnutrition, as well as other health gaps that are grounded in poverty and marginalization (Port Lourenço et al. 2008; Companion 2013; Davis and Wali 1994).

Conflicts of land tenure and assimilationist policies have compelled and compounded the migration of indigenous peoples to urban areas (Hansungule and Jegede 2014; Xanthaki 2003; Lin 1994). This exodus contributes to their inability to realize sustainable diets based on local species and traditional knowledge (Kuhnlein 2003; Dounias et al. 2007; Dounias and Froment 2011; Berbesque et al. 2014; Powell et al. 2015; van Vliet et al. 2015; Ickowitz et al. 2016; Crittenden and Schnorr 2017; Kraft et al. 2018; Bethancourt et al. 2019; Reyes-García et al. 2019; Fernández 2020). Consequently, their vast knowledge and guardianship of 80% of global species diversity is also diminished and lost (FAO 2017). Not only are forest-dwelling cultures losing their forests, they are also losing their next generations to whom they would pass on the traditional indigenous knowledge and practices built over generations. There is a critical urgency to act before the current living generation of knowledge-holders and the species that they have inherited are lost forever. Recognizing this importance, there have been sporadic efforts to document this knowledge, resulting in highly variable data that lack workability and comparability (Agrawal 2002; Ngulube 2002; Quek and Friis-Hansen 2011; Naming et al. 2010;

Shapi et al. 2011). This piecemeal approach highlights the need for a global knowledge base of indigenous species and systems and the design of systematic approaches and methods of data collection and observation. As well as the continuing efforts to reverse the dispossession and marginalization of indigenous peoples, the recognition of their roles and knowledge should be increasingly advocated, not only for the benefit of their own communities, but as part of a collective global public good.

Without the contribution of indigenous peoples to international health and sustainability targets, many of the United Nations' SDGs cannot be achieved, most notably SDG1 (zero poverty anywhere) and SDG2 (food security and improved nutrition). The design of sustainable food systems is also necessary in order to ensure the delivery of healthy, safe, and nutritious foods in both sustainable and equitable ways in an era of changing climates. In each case, the knowledge of indigenous communities can provide essential contributions to sustainable diets and climate-resilient food systems (Kuhnlein et al. 2019).

Mountains The mountains and uplands of the world are home to diverse food systems, each with its accompanying repository of indigenous knowledge evolved through generations of empirical experience. In the Hindu Kush Himalaya, rangelands constitute around 60% of the land use, and Yak herding, Angora goat and sheep rearing form the basis of food systems in large parts of the Tibetan Plateau and the higher altitudes (Miller and Craig 1996; Miller 1999). On the southern slopes, transhuman pastoral communities carry out seasonal migrations, their animals grazing in the high-altitude *Bugyals* (pastures) during summer and descending to lower altitudes during the cold winter months (Mitra et al. 2013). The food system of these communities is linked to mixed farming systems across their migratory routes, and food grains are predominantly obtained from farmers in exchange for milk products. Mixed farming systems with cereal-based agriculture and livestock rearing, intricately linked to forests, constitute the food system in the mid-altitudes of western Himalaya. These systems are built around upland cereals – buckwheat, millet, amaranthus - and legumes, complemented with milk and milk products. In the Eastern Himalaya and much of the uplands of Southeast Asia, shifting cultivation, with a rich diversity of cereals, legumes, tubers and leafy vegetables, together with small ruminants, piggery and poultry, constitutes the food system of diverse communities inhabiting the region (Ramakrishnan 1992; Rerkasem and Rerkasem 1995; Cramb et al. 2009; Mertz et al. 2009). Regenerating fallows and young forests also form important constituents of the food system of shifting cultivators (Delang 2006; Cairns 2007; Rodericks 2020). Small pockets of settled agriculture, predominantly consisting of wet terraces and complemented with animal husbandry, and intricate links with forests are also found in pockets of Eastern Himalaya, with the *Aji*-system of the Apatanis in Arunachal Pradesh, the *Zabo* system of the Chakesangs of Nagaland and the *Buun* system of the Khasis of Meghalaya being prominent agricultural systems in a landscape otherwise dominated by shifting cultivation (Kumar and Ramakrishnan 1990; Agarwal and Narain 1995; Sundriyal and Dollo 2013; Mulyoutami et al. 2009). Further south, in the uplands of Southeast

Asia, Forest Gardens complement shifting cultivation and wet paddy systems constituting an important part of food systems of upland communities in Indonesia (Mulyoutami et al. 2009).

Knowledge systems and traditional practices associated with food systems of indigenous communities are rich. They reflect a deep understanding of crop, soil and water dynamics and the functioning of the surrounding environment. Animal husbandry and rangeland management of pastoralists centered around rotational grazing suggest an understanding of the carrying capacity of rangelands and high-altitude meadows. The intricate link between agriculture, animal husbandry and forests found in western Himalayan mixed farming systems similarly reflect an understanding of the link among forest litter, animal dung, nutrient management and crop productivity. Indigenous knowledge of shifting cultivators suggests a robust risk management strategy and underlies the conservation and management of a wide diversity of crops, together with a range of landraces. Food systems of these communities also extend to fallow management and indicate an indigenous understanding of the food and nutritional value of wild edibles and animal products supported by regenerating fallows and forests. The indigenous knowledge of shifting cultivators also includes weed management and traditional knowledge of soil management practices, including an understanding of crops best suited to each soil condition. This indigenous knowledge base offers opportunities for developing solutions to several of the challenges arising out of land degradation and climate-induced stress emerging in present-day upland agriculture. Indigenous food systems and the knowledge associated with such systems are under threat today. With the transition to commercially important monocropping driven by markets and a policy promoting commercialization and homogenization, indigenous food systems are rapidly being replaced by cash crop plantations and commercial agriculture (Fox et al. 2009; van Vliet et al. 2012). The rapid erosion of agro-germplasm has serious consequences for ensuring food and nutritional security of the future, as many of the crops found in food systems of the mountains are not only recognized future smart crops, but also important as 'building blocks' for developing stress-tolerant, nutrient-dense crops of the future crucial for ensuring food and nutritional security and attaining Zero Hunger (Kadambot et al. 2021).

4.1 Innovations and Investment Opportunities

Current agricultural policies promote staple crops for mainstream agriculture in favorable areas. This has been at the expense of indigenous and under-utilized crops, many of which are well adapted to hostile environments and yield nutritious products. Many favored agricultural lands have reached their saturation potential, are often overexploited due to demographic pressure, and are increasingly impacted by climate change. If we are to nourish more people on a hotter planet, marginal regions will have to play a more significant role in food systems. However, the current promotion of healthier diets and sustainable food systems has excluded indigenous people, their crops and expertise. Evidence shows that where investment has been targeted at such communities and their food systems, they can enhance productivity, improve nutrition and reduce carbon emissions. The challenge is to link formal and local knowledge to identify which crops best suit specific environments, deliver desirable products and support sustainable and equitable livelihoods. This requires investment and policy support for innovations and technologies that can mainstream diverse value chains, their crops, products and knowledge systems.

4.2 Game-Changer Technologies and Innovations

The need is urgent. To achieve sustainable livelihoods, indigenous people in marginal areas need game-changer technologies in which they are the agents of innovation. This requires approaches that ensure the conservation, quantity, quality and value of products from forgotten crops to external markets. Innovations and technologies need synergies between researchers and indigenous communities as partners, not clients. The innovation process must allow for participatory and demand-driven approaches that stimulate and build upon farmer innovations and suit local circumstances. For this, indigenous communities need access to better knowledge systems, improved genetic material, integrated management practices and novel technologies across the whole value chain that provide routes to markets. Again, this requires long-term research support and an enabling policy environment at each stage of the value chain, rather than sporadic efforts at specific points along it.

Better Knowledge Systems Agricultural research is often confined to silos and excludes local knowledge. Indigenous communities need knowledge systems that integrate their own expertise and belief systems with evidence from scientific studies and predictive models. This requires novel approaches to data collection, collation and curation and digital technologies that can make knowledge available to end-users.

Improved Seed Systems Breeding approaches need to utilize the inherent genetic variability in local crops to develop widely adapted cultivars for diverse biophysical and socio-economic conditions. This requires new cultivars with improved yield potential without compromising nutrient density and climate resilience, breeding programmes that utilize technologies and approaches from major and model species and community seed-saving and selection approaches that conserve and enhance agricultural biodiversity.

Integrated Management To be cost-effective, productive and sustainable, crop management in marginal areas must both enhance productivity and reverse resource degradation. This requires technologies that increase access to water and nutrients and cultivars that are more efficient in water and nutrient use than major crops. Innovations for marginal areas will also need to be context-specific and include survival mechanisms that enhance climate resilience. For this, innovations must utilize an understanding of ecological processes and soil health, rather than dependence on external inputs for crop production.

Technologies to Markets Indigenous food systems are predisposed to production and market risks due to harsh biophysical and socio-economic shocks. New technologies are needed to improve harvesting, post-harvest storage, milling and drying so as to support economically viable value chains, and digital systems are needed to trace crops and verify their products from field to consumers. Risk-mitigating innovations that promote resilience will protect communities from climate shocks and enhance sustainability.

5 Priorities and Proposed Actions

Mainstreaming Diverse Value Chains Addressing climate change, food security and malnutrition are global priorities. However, without mainstreaming the crops, foods and knowledge of indigenous people in marginal areas, the SDGs cannot be achieved. If we are to move beyond a narrow focus on specific SDGs, mainstreaming efforts must focus on improving the livelihoods of poor farmers, especially women, by enhancing the value of their under-utilized crops and forgotten foods to local and global markets. This requires technological and policy interventions to overcome bottlenecks along the production and consumption chain that also address global mandates for environmental sustainability and biodiversity conservation. It also requires the transformation of research systems to mobilize small producers as co-innovators and sources of ingenuity.

Evidence-Based Policies Development of policies must address challenges and knowledge gaps in technological innovations, social inclusion and environmental and economic equity for indigenous communities. Most importantly, for marginalized communities to actively become part of mainstream economies, policy instruments must ensure equal access to digital innovations, capacity development, crop insurance and friendly financing and investment. Priorities should be informed by global knowledge systems that use digital technologies to link global scientific evidence with local indigenous knowledge of the cultural and traditional value of traditional crops beyond yield-for-profit alone. A key requirement is policy reforms that are explicit in their support for indigenous people, are based on a global evidence base and share best practices between biogeographical regions and indigenous communities.

Advocacy for Agency We need to raise awareness of the potential of under-utilized crops and forgotten foods. This requires recognition of the rich local knowledge of indigenous people as custodians of agrobiodiversity and greater self-awareness of communities to unlock their creativity as agents of change. By increasing their self-esteem, self-pride and self-confidence, indigenous communities can become active drivers of new technologies for which formal research and innovation systems are currently the decision-makers. Advocacy supported by evidence, policy and the agency of indigenous communities opens avenues for farmer-centered, pro-poor transformation of food systems and the reorientation of research and innovation to mainstream value chains and value-added products from under-utilized crops.

Collective Actions Integrated strategies must evolve around a framework that is all-inclusive, but context-specific. An integrated and holistic policy approach is necessary to advocate for collective actions with indigenous communities that engage research institutions, policymakers, farmers, consumers and other stakeholders to unlock the untapped potential of marginal agriculture. The GFAR Collective Action on Forgotten Foods (GFAR 2017), which explicitly includes a *Manifesto for Forgotten Foods*, is a major opportunity for indigenous communities in marginal areas to be part of a global effort to mainstream diverse value chains.

Coordinated Investment Time is of the essence. If indigenous communities in marginal regions are to become agents of change, they need coordinated investment, accessible finance, co-innovations, traditional knowledge, governance, evidence, and empowerment. Policies encouraging public and private investments and research and development for indigenous communities and marginal areas are imperative to improve the sustainability and resilience of their food systems. Public-Private-Partnerships offer an important opportunity to leverage resources, access new technologies and innovations and facilitate risk-sharing. However, a conducive policy environment and global commitment of resources are essential prerequisites if we are to deliver diverse solutions for forgotten people in forgotten regions.

References

Agarwal A, Narain S (1995) Dying wisdom. 4th citizens report on the state of environment. Centre for Science and Environment, New Delhi

Agrawal A (2002) Indigenous knowledge and the politics of classification. Int Soc Sci J 54(173): 287–297

Association of International Research and Development Centers for Agriculture (2016) GAPAD – Global Action Plan for Agricultural Diversification [Internet]. Association of International Research and Development Centers for Agriculture [Cited 2021 Jan 26]. http://www.airca.org/index.php/airca-resources/gapad

Barriuso J, Solano BR, Lucas JA, Lobo AP, García-Villaraco A, Mañero FJG (2008) Ecology, genetic diversity and screening strategies of plant growth promoting rhizobacteria (PGPR). J Plant Nutr 4:1–17

Berbesque JC, Marlowe FW, Shaw P, Thompson P (2014) Hunter–gatherers have less famine than agriculturalists. Biol Lett 10(1):20130853

Berkes F (2008) Sacred ecology, 2nd edn. Routledge, London

Berkes F, Colding J, Folke C (2000) Rediscovery of traditional ecological knowledge as adaptive management. Ecol Appl 10(5):1251–1262

Bethancourt HJ, Leonard WR, Tanner S, Schultz AF, Rosinger AY (2019) Longitudinal changes in measures of body fat and diet among adult Tsimane' forager-horticulturalists of Bolivia, 2002-2010. Obesity 27(8):1347–1359

Brondizio ES, Settele J, Díaz S, Ngo HT (2019) Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES secretariat, Bonn. https://ipbes.net/global-assessment

Bvenura C, Sivakumar D (2017) The role of wild fruits and vegetables in delivering a balanced and healthy diet. Food Res Int 99:15–30. https://doi.org/10.1016/j.foodres.2017.06.046

Cairns MF (ed) (2007) Voices from the forest: integrating indigenous knowledge into sustainable upland farming. Resources for the Future, Washington, DC

Chandrasekara A, Kumar JT, Josheph Kumar T (2016) Roots and tuber crops as functional foods: a review on phytochemical constituents and their potential health benefits. Int J Food Sci 2016:1–15. https://doi.org/10.1155/2016/3631647

Chao S (2012) Forest peoples: numbers across the world. Forest Peoples Programme, Moreton-in-Marsh, p 27

Chimonyo VGP, Wimalasiri EM, Kunz R, Modi AT, Mabhaudhi T (2020) Optimizing traditional cropping systems under climate change: a case of maize landraces and bambara groundnut. Front Sustain Food Syst 4:562568. https://doi.org/10.3389/fsufs.2020.562568

Chivenge PP, Mabhaudhi T, Modi AT, Mafongoya P (2015) The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. Int J Environ Res Public Health 12:5685–5711. https://doi.org/10.3390/ijerph120605685

Companion M (2013) Obesogenic cultural drift and nutritional transition: identifying barriers to healthier food consumption in urban Native American populations. J Appl Soc Sci 7(1):80–94

Cramb RA, Pierce Colfer CJ, Wolfram D, Laungaramsri P, Trang Q, Muloutami E, Peluso NL, Wadley RL (2009) Swidden transformations and rural livelihoods in Southeast Asia. Hum Ecol 37:323–346. https://doi.org/10.1007/s10745-009-9241-6

Crittenden AN, Schnorr SL (2017) Current views on hunter-gatherer nutrition and the evolution of the human diet. Am J Phys Anthropol 162:84–109

Dansi A, Vodouhè R, Azokpota P, Yedomonhan H, Assogba P et al (2012) Diversity of the neglected and underutilized crop species of importance in Benin. Sci World J 2012:1–19. https://doi.org/10.1100/2012/932947

Davis SH, Wali A (1994) Indigenous land tenure and tropical forest management in Latin America. Ambio 23(8):485–490

Dawson N, Martin A, Sikor T (2016) Green revolution in sub-Saharan Africa: implications of imposed innovation for the wellbeing of rural smallholders. World Dev 78:204–218. https://doi.org/10.1016/j.worlddev.2015.10.008

Delang CO (2006) Indigenous systems of forest classification: understanding landuse patterns and the role of NTFPs in shifting cultivators subsistence economies. Environ Manag 37(4):470–486

Dounias E, Froment A (2011) From foraging to farming among present-day forest hunter-gatherers: consequences on diet and health. Int For Rev 13(3):294–304

Dounias E, Selzner A, Koizumi M, Levang P (2007) From sago to rice, from forest to town: the consequences of sedentarization for the nutritional ecology of Punan former hunter-gatherers of Borneo. Food Nutr Bull 28(2_suppl2):S294–S302

Eberhard DM, Simons GF, Fennig CD (eds) (2020) Ethnologue: languages of the world, 23rd edn. Dallas, SIL International

Eigenbrod C, Gruda N (2015) Urban vegetable for food security in cities. A review. Agron Sustain Dev 35(2):483–498

FAO (2017) 6 ways indigenous peoples are helping the world achieve #ZeroHunger [Internet], 9 August. http://www.fao.org/indigenous-peoples/news-article/en/c/1029002/

FAO (2018) Once neglected, these traditional crops are our new rising stars [Internet]. Food and Agriculture Organization of the United Nations, Rome [Cited 2021 Jan 21]. http://www.fao.org/fao-stories/article/en/c/1154584/

Fernández CI (2020) Nutrition transition and health outcomes among indigenous populations of Chile. Curr Dev Nutr 4(5):nzaa070

Fox J, Fujita Y, Ngidang D, Peluso N, Potter L, Sakuntaladevi N, Sturgeon J, Thomas D (2009) Policies, political-economy and swidden in Southeast Asia. Hum Ecol 37:305–322. https://doi.org/10.1007/s10745-009-9240-7

Gallart F, Solé A, Puigdefábregas J, Lázaro R (2002) Badland systems in the Mediterranean. In: Bull JL, Kirkby MJ (eds) Dryland rivers: hydrology and geomorphology of semi-arid channels. Wiley, Chichester, pp 299–326

Garí J (2001) Biodiversity and indigenous agroecology in Amazonia: the indigenous people of Pastaza. Etnoecologica 5(7):21–37

GFAR (2017) Harnessing forgotten foods for improved livelihoods [Internet]. http://www.gfar.net/sites/default/files/files/Forgotten%20foods%20concept_Sept2017%281%29.pdf29; https://www.gfar.net/content/kfa1-empowering-farmers-center-innovation

Goldsmith FB (ed) (2012) Tropical rain forest: a wider perspective, vol 10. Springer

Hadebe ST, Modi AT, Mabhaudhi T (2017) Drought tolerance and water use of cereal crops: a focus on sorghum as a food security crop in sub-Saharan Africa. J Agron Crop Sci 203:551–562. https://doi.org/10.1111/jac.12191

Hansungule M, Jegede AO (2014) The impact of climate change on indigenous peoples' land tenure and use: the case for a regional policy in Africa. Int J Minor Group Rights 21(2):256–291

Hasegawa PM (2013) Sodium (Na+) homeostasis and salt tolerance of plants. Environ Exp Bot 92: 19–31

Huambachano M (2018) Enacting food sovereignty in Aotearoa New Zealand and Peru: revitalizing indigenous knowledge, food practices and ecological philosophies. Agroecol Sustain Food Syst 42(9):1003–1028

ICBA (2021). https://www.biosaline.org/research-themes/climate-change-modeling-and-adaptation

ICIMOD (2021). https://www.icimod.org/initiative/climate-services/

Ickowitz A, Rowland D, Powell B, Salim MA, Sunderland T (2016) Forests, trees, and micronutrient-rich food consumption in Indonesia. PLoS One 11(5):e0154139

Jahanshiri E, Mohd Nizar NM, Tengku Mohd Suhairi TAS, Gregory PJ, Mohamed AS, Wimalasiri EM, Azam-Ali SN (2020) A land evaluation framework for agricultural diversification. Sustainability 12(8):3110

Kadambot HMS, Li X, Gruber K (2021) Rediscovering Asia's forgotten crops to fight chronic and hidden hunger. Nat Plant 7:116–122

Kingsbury B (1998) Indigenous peoples in international law: a constructivist approach to the Asian controversy. Am J Int Law 92:414–457

Kraft TS, Stieglitz J, Trumble BC, Martin M, Kaplan H, Gurven M (2018) Nutrition transition in 2 lowland Bolivian subsistence populations. Am J Clin Nutr 108(6):1183–1195

Krauss M (1992) The world's languages in crisis. Language 68(1):4–10. https://doi.org/10.1075/slcs.142.01sim

Kuhnlein HV (2003) Micronutrient nutrition and traditional food systems of indigenous peoples. Food Nutr Agric 32:33–39

Kuhnlein HV, Receveur O (1996) Dietary change and traditional food systems of indigenous peoples. Annu Rev Nutr 16(1):417–442

Kuhnlein HV, Erasmus B, Spigelski D, Burlingame B (2013) Indigenous people' food systems and wellbeing: interventions and policies for healthy communities. Food and Agriculture Organization of the United Nations (FAO), Rome

Kuhnlein H, Eme P, de Larrinoa YF (2019) Chapter 7: indigenous food systems: contributions to sustainable food systems and sustainable diets. In: Burlingame S, Dernini Q (eds) Sustainable diets: linking nutrition and food systems. CABI, pp 64–78. https://doi.org/10.1079/9781786392848.0064

Kumar A, Ramakrishnan PSR (1990) Energy flow through an Apatani Village Ecosystem of Arunachal Pradesh in Northeast India. Hum Ecol 18(3):315–336

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science (80–85) 304(5677):1623–1627. https://doi.org/10.1126/science.1097396

Lal R (2016) Feeding 11 billion on 0.5 billion hectare of area under cereal crops. Food Energy Secur 5(4):239–251. https://doi.org/10.1002/fes3.99

Leakey RR (2020) A re-boot of tropical agriculture benefits food production, rural economies, health, social justice and the environment. Nat Food 1(5):260–265. https://doi.org/10.1038/s43016-020-0076-z

Leff B, Ramankutty N, Foley JA (2004) Geographic distribution of major crops across the world. Global Biogeochem Cycles 18(1):1–27. https://doi.org/10.1029/2003GB002108

Lima M, do Vale JCE, de Medeiros Costa G, dos Santos RC, Correia Filho WLF, Gois G, de Oliveira-Junior JF, Teodoro PE, Rossi FS, da Silva Junior CA (2020) The forests in the indigenous lands in Brazil in peril. Land Use Policy 90:104258

Lin KG (1994) Resettlement and nutritional implications: the case of Orang Asli in regroupment schemes. Pertanika J Soc Sci Humanit 2(2):123–132

Mabhaudhi T, O'Reilly P, Walker S, Mwale S (2016) Opportunities for underutilised crops in Southern Africa's post–2015 development agenda. Sustainability 8:302. https://doi.org/10.3390/su8040302

Mabhaudhi T, Chimonyo VGP, Hlahla S, Massawe F, Mayes S, Nhamo L, Modi AT (2019a) Prospects of orphan crops in climate change. Planta 250:695–708. https://doi.org/10.1007/s00425-019-03129-y

Mabhaudhi T, Chibarabada TP, Chimonyo VGP, Murugani VG, Pereira LM, Sobratee N, Govender L, Slotow R, Modi AT (2019b) Mainstreaming indigenous crops into food systems: a South African perspective. Sustainability 11:172. https://doi.org/10.3390/su11010172

Mertz O, Padoch C, Fox J, Cramb RA, Leisz SJ, Thanh N, Duc Vien T (2009) Swidden change in Southeast Asia: understanding causes and consequences. Hum Ecol 37:259–264. https://doi.org/10.1007/s10745-009-9245-2

Miller DJ (1999) Nomads of the Tibetan Plateau Rangelands in Western China part two: pastoral production practices. Rangelands 21(1):16–19

Miller DJ, Craig SR (eds) (1996) Rangelands and pastoral development in the Hindu Kush-Himalayas. ICIMOD, Kathmandu

Mitra M, Kumar A, Adhikari BS, Rawat GS (2013) A note on transhumant pastoralism in Niti valley, Western Himalaya, India. Pastoralism 3(1):2–7

Mohd Nizar NM, Jahanshiri E, Tharmandram AS, Salama A, Mohd Sinin SS, Abdullah NJ, Zolkepli H, Wimalasiri EM, Mohd Suhairi TAST, Hussin H, Gregory PJ, Azam-Ali SN (2021) Underutilised crops database for supporting agricultural diversification. Comput Electron Agric 180:105920. https://doi.org/10.1016/j.compag.2020.105920

Mugari E, Masundire H, Bolaane M (2020) Adapting to climate change in semi-arid rural areas: a case of the Limpopo Basin Part of Botswana. Sustainability 12(20):8292. https://doi.org/10.3390/su12208292

Mulyoutami E, Rismawan R, Joshi L (2009) Local knowledge and management of simpukng (forest gardens) among the Dayak people in East Kalimantan, Indonesia. For Ecol Manag 257:2054–2061

Mustafa M, Mabhaudhi T, Massawe F (2021) Building a resilient and sustainable food system in a changing world – a case for climate-smart and nutrient dense crops. Glob Food Sec 28:100477. https://doi.org/10.1016/j.gfs.2020.100477

Naming M, Yu RA, Tu CL (2010) Traditional knowledge conservation and transmission of agrobiodiversity: sharing of experiences by the Penan community in Mulu Sarawak. In: Mirfat AHS, Salma I, Mohd Rani MY, Mohd NH, Mohd Shukri MA, Erny Sabrina MN, Noor Sarinah MN, Siti Noor Aishikin AH, Nor AI (eds) Second national conference on agrobiodiversity conservation and sustainable utilization, agrobidiversity for sustainable economic development. Malaysian Agricultural Research and Development Institute (MARDI), p 54

Ngulube P (2002) Managing and preserving indigenous knowledge in the knowledge management era: challenges and opportunities for information professionals. Inf Dev 18(2):95–102

Ohenjo N, Willis R, Jackson D, Nettleton C, Good K, Mugarura B (2006) Health of indigenous people in Africa. Lancet 367(9526):1937–1946
Pender J, Hazell P (2000) “Promoting sustainable development in less-Favored areas: overview”. Brief 1. In: Pender J, Hazell P (eds) Promoting sustainable development in less-favored areas. 2020 vision initiative, policy brief series, focus 4. International Food Policy Research Institute, Washington, DC
Pingault N, Caron P, Kolmans A, Lemke S, Kalafatic C, Zikeli S, Waters-Bayer A, Callenius C, Qin YJ (2020) Moving beyond the opposition of diverse knowledge systems for food security and nutrition. J Integr Agric 19(1):291–293
Port Lourenço AE, Ventura Santos R, Orellana JD, Coimbra CE Jr (2008) Nutrition transition in Amazonia: obesity and socioeconomic change in the Suruí Indians from Brazil. Am J Hum Biol 20(5):564–571
Powell B, Sandbrook C et al (2015) The historical, environmental and socio-economic context of forests and tree-based systems for food security and nutrition. In: Vira B, Wildburger C, Mansourian S (eds) Forests, trees and landscapes for food security and nutrition. A global assessment report, IUFRO world series, vol 33. IUFRO, pp 51–86
Prasad M, Srinivasan R, Chaudhary M, Choudhary M, Jat LK et al (2019) Seven – plant growth promoting rhizobacteria (PGPR) for sustainable agriculture: perspectives and challenges. In: Singh AK, Kumar A, Singh PK (eds) PGPR amelioration in sustainable agriculture. Woodhead Publishing, pp 129–157
Quek P, Friis-Hansen E (2011) Collecting plant genetic resources and documenting associated indigenous knowledge in the field: a participatory approach. Collecting Plant Genetic Diversity: Technical guidelines – 2011 update
Ramakrishnan PS (1992) Shifting agriculture and sustainable development: an interdisciplinary study from Northeast India. UNESCO-MAB series. Parthenon Publishers, Paris/Carnforth/ Lancs, pp 424 (Republished Oxford University Press, New Delhi 1993)
Rerkasem K, Rerkasem B (1995) Montane Mainland South-East Asia: agroecosystems in transition. Glob Environ Chang 5:313–322. https://doi.org/10.1016/0959-3780(95)00065-V
Reyes-García V, Powell B, Díaz-Reviriego I, Fernández-Llamazares Á, Gallois S, Gueze M (2019) Dietary transitions among three contemporary hunter-gatherers across the tropics. Food Secur 11(1):109–122
Rodericks A (2020) Living landscapes: embracing agro-biodiversity in Northern Laos National Agriculture and Forest Research Institute (NAFRI). Ministry of Agriculture and Forestry, Vientiane, Laos PDR
Salawitch RJ, Bennett BF, Canty TP, Hope AP, Tribett WR (2017) Paris climate agreement: beacon of hope. Springer, Cham, p 186
Shapi M, Cheikhyoussef A, Mumbengegwi DR, Matengu K, Van Kent A, Sifani J (2011) Evolution of data collection methods for indigenous knowledge systems at the Multidisciplinary Research Centre of the University of Namibia. Knowl Manag Dev J 7(3):308–316
Srividhya S, Kumari N, Surendranath R, Jeyakumar P (2020) Role of rhizobacteria in alleviating salt stress. In: Sharma V, Salwan R, Al-Ani LKT (eds) Molecular aspects of plant beneficial microbes in agriculture. Academic, pp 279–294
Sundriyal RC, Dollo M (2013) Integrated agriculture and allied natural resource management in northeast mountains – transformation and asset building. Agroecol Sustain Food Syst 37(6): 700–726
Sutherland A, Irungu J, Kang’ara J, Muthamia J, Ouma J (1999) Household food security in semi-arid Africa – the contribution of participatory adaptive research and development to rural livelihoods in Eastern Kenya. Food Policy 24(4):363–390. https://doi.org/10.1016/S0306-9192(99)00050-0
Tadele Z (2018) African orphan crops under abiotic stresses: challenges and opportunities. Science (Cairo) 2018:1–19

TheWorldCounts (2021) World average temperature (°C) [Internet]. TheWorldCounts, Copenhagen [Cited 2021 Jan 24]. https://www.theworldcounts.com/challenges/climate-change/global-warming/average-global-temperature/story

Toledo VM, Ortiz-Espejel B, Cortés L, Moguel P, de Jesús Ordoñez M (2003) The multiple use of tropical forests by indigenous peoples in Mexico: a case of adaptive management. Conserv Ecol 7(3)

UKZN (2021). https://researchspace.ukzn.ac.za/xmlui/

Umetsu C, Lekprichakul T, Sakurai T, Yamauchi T, Ishimoto Y et al (2014) Dynamics of social–ecological systems: the case of farmers' food security in the semi-arid tropics. In: Social-ecological systems in transition. Springer, pp 157–178

UN (2009) The state of the world's indigenous peoples. United Nations, New York. http://www.un.org/esa/socdev/unpfii/documents/SOWIP/en/SOWIP_web.pdf

UN (2021) The sustainable development agenda [Internet]. United Nations, New York [Cited 2021 Jan 29]. https://www.un.org/sustainabledevelopment/development-agenda/

UN DESA (2009) Indigenous peoples: culture [Internet]. United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/indigenouspeoples/mandated-areas1/culture.html

UN Environment Programme (2020) How to feed 10 billion people [Internet]. United Nations Environment Programme, Nairobi [Cited 2021 Jan 25]. https://www.unenvironment.org/news-and-stories/story/how-feed-10-billion-people

van Ittersum MK, van Bussel LGJ, Wolf J, Grassini P, van Wart J et al (2016) Can sub-Saharan Africa feed itself? Proc Natl Acad Sci 113(52):14964–14969. https://doi.org/10.1073/pnas.1610359113

van Vliet N, Mertz O, Heinimann A, Langanke T, Pascual U, Schmook B, Adams C, Schmidt-Vogt D, Messerli P, Leisz S, Castella JC, Jorgensen L, Birch-Thomsen T, Hett C, Bech-Bruun T, Ickowitz A, Kim Chi V, Yasuyuki K, Fox J, Padoch C, Dressler W, Zeigler AD (2012) Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. Glob Environ Chang 22:418–429

van Vliet N, Quiceno-Mesa MP, Cruz-Antia D, Tellez L, Martins C, Haiden E, Oliveira MR, Adams C, Morsello C, Valencia L, Bonilla T (2015) From fish and bushmeat to chicken nuggets: the nutrition transition in a continuum from rural to urban settings in the Tri frontier Amazon region. Ethnobiol Conserv 46:1

Van Zelm E, Zhang Y, Testerink C (2020) Salt tolerance mechanisms of plants. Annu Rev Plant Biol 71:403–433

Vercillo S, Weis T, Luginaah I (2020) A bitter pill: smallholder responses to the new green revolution prescriptions in northern Ghana. Int J Sustain Dev World Ecol 27(6):565–575. https://doi.org/10.1080/13504509.2020.1733702

Weih M, Hamnér K, Pourazari F (2018) Analyzing plant nutrient uptake and utilization efficiencies: comparison between crops and approaches. Plant Soil 430(1):7–21

Whyte K (2015) Indigenous food systems, environmental justice, and settler-industrial states. In: Rawlinson M, Ward C (eds) Global food, global justice: essays on eating under globalization. Cambridge Scholars Publishing, pp 143–156

Wiersum KF (1997) Indigenous exploitation and management of tropical forest resources: an evolutionary continuum in forest-people interactions. Agric Ecosyst Environ 63(1):1–16

Wilson G, Woodrow M (2009) Kuka kanyini, Australian Indigenous adaptive management. In: Adaptive environmental management. Springer, Dordrecht, pp 117–141

Xanthaki A (2003) Land rights of indigenous peoples in South-East Asia. Melb J Int'l L 4:467

Yu L, Zhao X, Gao X, Siddique KHM (2020) Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: a global meta-analysis. Agric Water Manag 228:105906

Priorities for Inclusive Urban Food System Transformations in the Global South

Paule Moustier, Michelle Holdsworth, Dao The Anh, Pape Abdoulaye Seck, Henk Renting, Patrick Caron, and Nicolas Bricas

1 Objective and Focus of the Chapter

This chapter is concerned with identifying: (i) challenges to food systems in Africa, Asia, and Latin America caused by urban development, (ii) how existing food systems respond to these challenges, and (iii) what can be recommended to improve their responsiveness. The chapter is based on the authors 'published research complemented by published literature.

We define 'urban food systems' as food systems linked to cities by material and human flows. *"A food system gathers all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities related to the production, processing, distribution, preparation and consumption of food, and the outputs of*

P. Moustier (✉)
Cirad, MoISA, Cirad, IAMM, INRAE, l'Institut Agro, IRD, University of Montpellier, Montpellier, France
e-mail: paule.moustier@cirad.fr

M. Holdsworth
IRD: French National Research Institute for Sustainable Development, MoISA, Montpellier, France

D. T. Anh
Vietnam Academy of Agricultural Science (VAAS), Hanoi, Vietnam

P. A. Seck
Senegal Ambassador of FAO in Italy and Former Ministry of Agriculture, Rome, Italy

H. Renting
Aeres University of Applied Science, Wageningen, the Netherlands

P. Caron
Cirad, University of Montpellier, Montpellier, France

N. Bricas
Cirad, MoISA, Director of UNESCO Chair in World Food Systems, Montpellier, France

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_15

these activities, including socio-economic and environmental outcomes" (HLPE 2014:29). This definition is close to the definition of food chains, with three major differences. First, it includes food acquisition, diets and consumer behaviour. Second, it considers a diversity of food products, which is crucial for nutrition security, as well as for the sustainability of production systems. Third, it emphasises the key role of food environments, i.e., *"the physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing and consuming food"* (HLPE 2017:28). Often, contradictory objectives are attributed to food systems, gathered under the general objective of achieving sustainability (Béné et al. 2019). According to FAO (2018:1), a sustainable food system (SFS) delivers food security and nutrition for all in such a way that the economic, social and environmental bases for generating food security and nutrition for future generations are not compromised. Among SFSs, inclusive food systems are defined by Fan and Swinnen (2020:9) as *"reaching, benefiting, and empowering all people, especially socially and economically disadvantaged individuals and groups in society."*

2 Challenges Posed by Urban Development

2.1 Urban Growth

The world is becoming increasingly urbanised. Half of the world's population now lives in cities, 40% in Africa, 49% in South-East Asia, and 81% in Latin America. By 2050, these figures are expected to increase by a further 25%. Cities differ considerably in size, and a high proportion of urban growth is taking place in secondary cities, especially in sub-Saharan Africa where, in 2015, half the population lived in cities of less than 500,000 inhabitants (OECD/SWAC 2020). Compared to the rural population, urban populations have more diverse cultural, economic, and social profiles. A middle class is emerging, defined as an individual's income ranging from 12 to 50 US$ per capita/day in Africa, accounting for 13% of the population (Neveu-Tafforeau 2017). In sub-Saharan Africa, income growth, which benefits urban areas, started in 2000, but it has faltered since 2013 (Tschirley et al. 2020 based on World Bank data). In Latin America, 40-50% of the population of most countries live in a small number of large cities with more than one million inhabitants. Urbanisation is positively correlated with income per capita, but Latin America is the continent with the highest income inequality, which also persists in urban areas (BBVA Research 2017; OECD 2019). As a region, Asia has modest levels of urbanisation, but is home to half of the world's urban community, and is the continent with the fastest urban growth (Leeson 2018).

2.2 *Challenges for Urban Food Systems*

Urbanisation poses several policy challenges for urban food systems. These are related to food and nutritional security, employment, and environmental protection.

2.2.1 Urban Food and Nutritional Security

In contrast to rural areas, most people who live in cities do not produce food and must rely on local markets. Food purchased in markets represents more than 80% of food consumption in cities in sub-Saharan Africa, compared with 50% in rural areas (Tschirley et al. 2020). There are many signs that urban food security is inadequately addressed, especially in Africa. *"Urban food insecurity in low-income countries, estimated by the Food Insecurity Experience Scale of the Food and Agriculture Organization of the United Nations, is higher (50%) than levels in rural areas (43%). In urban slums, other studies estimate food insecurity at up to 90%"* (Tefft et al. 2017:11–12).

Urban food consumption is characterised by a triple burden of malnutrition, with the persistence of undernutrition, micronutrient deficiencies – especially related to iron deficiency anaemia in women of reproductive age and young children - and the increasing prevalence of overweight/obesity (GNR 2020). With rising incomes, urban residents are eating more animal-source foods and processed foods that may be low in micronutrients, while high in calories and fat (Popkin et al. 2012; Yaya et al. 2018; Holdsworth et al. 2020; Rousham et al. 2020). These poor quality diets affect children of all ages from infancy to adolescence, and food systems do not currently account sufficiently for the nutritional needs of children and adolescents (UNICEF/GAIN 2018). Nutritional problems are amplified by excessively monotonous diets and limited consumption of fruit, vegetables, and pulses, as well as lack of physical activity (Popkin et al. 2012). Likewise, the consumption of imported food by urban dwellers is increasing – although the proportion is still limited: only 5% in Africa, mostly imported cereals, according to Bricas et al. (2016) and Tschirley et al. (2014); and consumers commonly combine local and imported products in meals, resulting in a hybridisation of cooking (Soula et al. 2020). In Latin American cities, food security improved for many years, partly as result of "zero hunger" strategies first developed in Brazil in the late-1990s and later in other countries in the region. However, in recent years, food insecurity has started to rise again as the result of increased social inequality and due to the Covid-19 pandemic. At the same time, Latin America is facing escalating obesity rates, which affect 24% of the regional – mostly urban – population, almost double the global level of 13.2%, which is explained by unhealthy diets and poverty (FAO, RUAF 2019).

In parallel, food safety has become a major public health issue. Food safety crises are regularly reported in the media, especially in South-East Asia, where consumers' fears are linked to chemical products in fruit and vegetables and antibiotic residues in meat (Figuié et al. 2004; Ortega and Tschirley 2017). This is due to new industrial and domestic sources of pollution close to agricultural production areas, and the increase in the use of chemical inputs by farmers (De Bon et al. 2010; Reynolds et al. 2015). The lengthening of food supply chains and the lack of knowledge about hygiene also creates risks of contamination in the processing, marketing, handling and consumption stages (Jaffee et al. 2018). Consumer concerns about food safety have potential nutritional consequences, as they may reduce the consumption of fruit and vegetables because of concerns about pesticides, or push consumers towards packaged (often highly processed) foods because they are perceived as safer.

2.2.2 Food Convenience

Another growing consumer pattern is related to the convenience of where they buy and what they buy. As women are increasingly employed outside their homes and lifestyles become more sedentary, demand is growing for packed, pre-prepared food that can be purchased near offices or shops where it is easy to park (for the middle classes) (Reardon et al. 2019). In sub-Saharan Africa, processed food accounts for between 60% (in West Africa) and 70% (in eastern and southern Africa) of total food consumption, compared to, respectively, 50% and 30% in rural areas. Food consumption outside the home is on the increase. The proportion varies across African cities, ranging from 6% in Freetown and Conakry to 25% in cities of Nigeria and Tanzania, and 30% in Cotonou, Lomé and Abidjan (Tschirley et al. 2020). Street food is especially convenient for urban workers and low-income households who may not have the resources and facilities to purchase raw ingredients and prepare dishes at home, especially in slums (Soula et al. 2020; Pradeilles et al. 2021). In Latin America, between 2000 and 2013, the consumption of ultra-processed products increased by more than 25%, and fast food consumption by almost 40% (PAHO 2015).

2.2.3 Urban Employment

Cities in the Global South are characterised by the absence of stable employment, and poverty is increasingly becoming an urban phenomenon (Ravaillon 2016). The difference in living standards among the urban population is widening, thereby increasing social inequalities. The informal sector still provides most employment (especially for women), accounting for up to 90% in low-income countries (LICs) and 67% in emerging countries (Bonnet et al. 2019). Sub-Saharan Africa is facing premature deindustrialisation, with only 11% of employment in the manufacturing sector, mostly in the food industry (Giordano et al. 2019 based on Rodrik 2016 and ILO 2018). In Latin America, 60% of mostly urban people are employed in the informal sector.

2.2.4 Quality of the Urban Environment

Last, but not least, the urban environment is responsible for major air, water and soil pollution (Amegah and Agyei-Mensah 2017; Adimalla 2020), severe risks of flooding (Douglas 2017; Pervin et al. 2020), and problematic waste disposal, as the balance between what enters and leaves the city is largely negative (Guerrero et al. 2013). This jeopardises the production of safe food in cities. At the same time, if handled safely, agriculture can recycle part of the waste produced (De Bon et al. 2010).

Cities can be viewed as concentrations of people and biomass that produce particular forms of economic and environmental stress (Chaboud et al. 2013). Yet, cities also concentrate knowledge, as people from different backgrounds mix, including rural and international migrants, and public and private investments provide a favourable substrate for innovation (Cobbinah et al. 2015).

The challenges faced by urban development and new consumer expectations lead to questions about the capacity of existing urban food systems to adapt. This is detailed in the following section.

3 The Characteristics of Urban Food Systems in the Global South

3.1 Spatial and Relational Organisation

The organisation of urban food systems in Africa, Asia, and Latin America is summarised in Fig. 1. We review the characteristics of the chains that supply food to urban consumers, their relations with urban food environments, and urban consumer profiles. The nature of urban food environments, especially food retailing landscapes, as well as consumer living standards, in addition to the perishability and origin of food, results in major differences among food supply chains.

Food chains and food systems in LICs are currently classified differently depending on their operation and organisation, which is related to the evaluation of their outcomes, impacts and performance. This type of classification relates to the market orientation, the scale of activities, informal versus formal (i.e., whether the business is registered or not), added value in the chain through the adoption of technologies and orientation towards consumer expectations, in particular regarding visual, organoleptic, and sanitary quality. The High Level Panel of Experts (HLPE 2017) report distinguishes traditional food systems, which are dominant in rural areas and involve open-air markets and small shops with limited concern for food quality or diversity, and modern food systems, which emerge in urban areas and are driven by the development of supermarkets and increased income, as well as an intermediary type termed mixed food systems. As the HLPE typology mostly considers differences between rural and urban settings, and as urban food supply

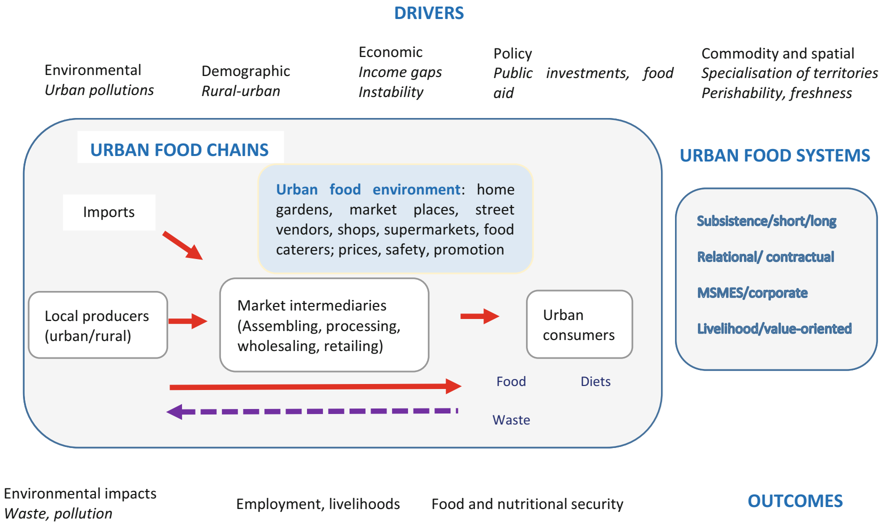


Fig. 1 The characteristics of urban food systems in the Global South. (Source: Adapted from HLPE (2017) and David-Benz et al. forthcoming)

chains are diverse, the rest of the chapter highlights the determinants of variable organisation and performance of urban food systems and leads us to propose six types.

Even though subsistence agriculture is of minor importance in terms of total urban food consumption, in cities in the Global South, it can play an important role in the livelihoods and social inclusion of some vulnerable inhabitants, as proven in Tamale and Ouagadougou (Bellwood-Howard et al. 2018), Cape Town (Olivier and Heinecken 2017), Hanoi (Pulliat 2015), Quito and Rosario (Renting and Dubbeling 2013). Urban gardens also have important pedagogical functions, e.g., through schooling programmes or community gardens (Hou 2017). The multi-functionality of urban agriculture means that it is a ‘cheap’ producer of public goods.

We now turn to market-oriented urban food systems. Urban consumers are mainly supplied by small-scale market vendors and neighbourhood shops, even though supermarkets and convenience stores are increasing their market share. Supermarket distribution is still limited for food, especially in Africa and South-East Asia: less than 10% of purchases in *Côte* d’Ivoire (Neveu-Tafforeau 2017), Kenya and Uganda (Wanyama et al. 2019), and less than 20% in Vietnam (University of Adelaide 2014) – the percentages being even lower for fresh food, all of which may be explained by low consumer purchasing power, as well as by consumer preference for traditional retail formats. So-called traditional urban food systems predominate in the urban context of LICs. There is overlap between what is termed traditional or informal markets/sectors/systems, both terms referring to the small scale of production, the absence of registration and public support. Traditional systems are often described as ‘poor-friendly,’ as suppliers are mostly concerned with subsistence incomes (Vorley 2013). Moreover, they are an important part of the social fabric of low-income urban communities, as seen in studies in Ghana and Kenya (Pradeilles et al. 2021). Food processing, food distribution, and food catering are major sources of urban employment, especially for the vulnerable poor (particularly women) who lack qualifications and social and economic capital (Allen et al. 2018). The urban food catering sector is varied, ranging from school canteens to street caterers and restaurants targeting different types of customers. Most processing takes place in MSMEs at an artisanal scale (Tschirley et al. 2020) in various locations within and outside cities. While street vendors are documented as major providers of food and livelihoods for poor urban residents, especially women, in Africa and Asia, they usually lack public support (Turner and Schoenberger 2011; Ogunkola et al. 2021).

Traditional food systems are sometimes judged to be inefficient in responding to new consumer expectations, especially concerning quality and convenience (Reardon et al. 2019). Low investments in infrastructure may limit the regular supply and availability of some nutrient-dense foods like fruit and vegetables (Maestre et al. 2017). Regarding the effect of traditional food systems on waste reduction, some studies report evidence for inefficiency related to poor logistics, while others argue that less stringent quality criteria help reduce waste.

In addition to scales and technology, another major factor that influences the organisation of food chains is food perishability, as it influences the location of production and the length of food chains, especially when logistics are limited, which is even worse in times of crisis, like the current Covid-19 pandemic. The location of production and the possibility of producing locally depend on the climate and the soil, as well as on the history of specialisation in some territories. Mapping food supply chains is crucial for representing differences in the length of chains, in the number of intermediaries and in their origin. This is the basis of approaches such as foodsheds, city-region food systems and short versus long chains (Blay-Palmer et al. 2018; Schreiber et al. 2021). Short versus long chains refers to physical as well as relational factors, and the two are linked. Short chains (in terms of distance and relations) have fewer intermediaries than long ones. This may lead to lower final prices than longer chains, but this is not systematically the case, because long chains may enable economies of scale (De Cara et al. 2017). In line with predictions from spatial economics, short food chains predominate in the supply of perishable produce, e.g., leafy vegetables, milk, eggs and chicken. These commodities are nutrient-dense and commonly under-consumed relative to nutritional recommendations. The farmers themselves, or their relatives, are frequently involved in wholesale and/or retail distribution. On the other hand, staple food crops, including cereals, tubers, pulses, vegetables that can be stored, e.g., onions, and some animal products, are supplied by long chains originating in local rural areas or by imports (Moustier 2017a, b; Karg et al. 2019; Lemeilleur et al. 2019). They often involve a chain of rural collectors, rural wholesalers, urban wholesalers, and urban retailers who supply all types of urban consumers. Transactions take place in wholesale and retail markets located so as to minimise traders' and consumers' transport costs (Blekking et al. 2017; Lemeilleur et al. 2019). With the development of transport, credit, and mobile phones, these chains may be shortened, and the roles of rural collectors and wholesalers may be reduced. This transformation is termed the 'quiet revolution' in agrifood value chains in low- and middle-income countries by Reardon (2015).

Another important aspect of chain organisation concerns business-to-business relationships. Food chains in LICs are characterised by long-term acquaintanceship and reciprocity, together with competition among hundreds of vendors, resulting in a certain degree of price homogeneity, even though oligopolies of wholesalers are observed because of limited access to credit and storage facilities (Fafchamps 2004).

Modern distribution systems, driven by supermarkets, are characterised by labour-saving and capital-intensive technologies in terms of logistics, refrigeration, self-service, packaging, and cash registers, in addition to the recourse to contractual arrangements with dedicated wholesalers (Hagen 2002). They are judged to be efficient in terms of logistics and quality (Reardon et al. 2019), but with potential negative effects on nutrition, because they supply a wide range of highly processed foods rich in fats and sugar (Demmler et al. 2018; Giordano et al. 2019; Wertheim-Heck and Raneri 2019). Regarding affordability for the poor, modern systems are usually presented as less poor-friendly because of higher prices and transport constraints. Modern systems also create less employment per unit of product (Moustier et al. 2009; Wertheim-Heck and Raneri 2019). Regarding differences in prices between supermarkets and traditional vendors, when controlling for quality differences, results are country-specific. When supermarkets gain a substantial market share, they can reduce their logistic costs and provide food at lower prices, especially food that can be stored (Reardon et al. 2010; Nuthalapati et al. 2020). Prior to that stage, food is usually cheaper and more accessible in open markets and small shops than in supermarkets (Moustier et al. 2009; Wanyama et al. 2019). Moreover, supermarkets favour the use of plastics for wrapping fresh food, which is a major environmental concern (Letcher 2020).

3.2 Innovations in Urban Food Systems

Considering the ability of urban food systems to adapt to new consumer demand for quality and convenience, we need to look beyond the traditional approach that qualifies modern or supermarket-driven chains as innovative and traditional chains as obsolete and lacking dynamics. A number of MSMEs are indeed increasingly upgrading their technologies and improving product quality in response to new consumer expectations. At the same time, they create new chain organisation patterns with increased chain interactions and different forms of vertical integration, with the general support of national and international public programmes (Moustier and Renting 2015; De Brauw et al. 2019; Tefft et al. 2017). This is the case with farmer organisations that sell food in shops or at farmers' markets in Laos, India, Ecuador, Colombia, Brazil, and Kenya, or by subscription in Dakar and in some South African cities (Freidberg and Goldstein 2011; Joshi et al. 2012; Renting and Dubbeling 2013). Entrepreneurial producers, e.g., *le Terroir* in Abidjan, can sell dairy products and cold cuts to wealthy urban consumers thanks to processing and cold storage (Neveu-Tafforeau 2017). Caterers, private companies, restaurants, and school canteens are developing strategies to ensure food safety and promote local products by signing contracts with local producer groups. This is also the case for public programmes targeting the urban poor, e.g., the food purchase programme in Brazil (Berchin et al. 2019). Food caterers and processing SMEs also innovate to supply processed local food to urban dwellers (Ferré et al. 2018; Reardon et al. 2021a). Yet, these initiatives are still precarious because of the cost of access to sales points for farmers, low levels of state support, lack of product diversity, and lack of guaranteed food safety.

Supermarket chains are expanding rapidly in countries where incomes are rising, as in South Africa, Côte d'Ivoire, and China. Supermarkets carry both local and international brands and are developing strategies for quality control and guaranteed origin, including using dedicated wholesalers and contracts, but still face difficulties concerning quality control and traceability. Supermarket chains are usually supported by city and national governments on the grounds of modernity and hygiene, but face increasing competition from traditional markets and from companies that use digital technology for logistics and delivery to consumers (Neveu-Tafforeau 2017 with reference to Côte d'Ivoire and Si et al. 2019 with reference to China). Overall, supermarkets vary in their supply strategies, including whether they favour linkages with local food chains, in their pricing and in the payment conditions offered to local farmers, as well as in the training and logistics they may provide to farmers (Minten et al. 2017).

Digital technology can be used by MSMEs, as well as by supermarkets or by new large-scale capital-intensive companies, which sometimes partner with SMEs for their supply, logistics, or final delivery (Reardon et al. 2021a; Tefft et al. 2017; Si et al. 2019). E-commerce has been spurred by sanitary crises, including SARS and Covid-19, and is developing particularly rapidly in Asian countries, including China, India and Vietnam (Reardon et al. 2021b; Vietnam news 2021; Dao 2020).

3.3 Six Types of Urban Food System

To summarise, we advocate going beyond the simplistic classification of traditional versus mixed and modern food systems. This classification may stigmatise the small-scale relational food systems that are competitive in terms of food availability, accessibility, and affordability. Moreover, it suggests a linear trend of change from one system to another, while the reality frequently turns out to be combinations and synergies between different patterns. Hence, based on our review of the literature, we propose the following typology – while acknowledging that overlaps between and combinations of types are possible. The main characteristics of each type are summarised in Table 1.

Table 1 Characteristics and outcomes of the six types of urban food system

Type of UFS (urban food system)	Description	Outcomes
Subsistence	Urban agriculture, including home gardens	Variable additional contribution to the food and nutrition security of the poor Waste recycling Possible food safety problems through use of polluted soil, water or waste
Short relational (perishables)	Chain of farmers and retailers in markets or streets Oral commitments All income categories of consumers	Provisioning of nutrient-dense fresh food at low cost Employment of low qualified population Limited quality management
Long relational (non-perishables)	Chain of farmers, collectors, wholesalers, market and street retailers Oral commitments All income categories of consumers	Possible high margins due to wholesalers' oligopolies Employment of low qualified population Limited quality management
Value-oriented SME-driven	Chain of farmers-entrepreneurs or collectives, processors, retailers; quality control and labelling Middle and high-income consumers	Employment and value added for low qualified population Rise in quality Rise in price
Supermarket-driven	Like above + common dedicated wholesalers + contracts Middle and high-income consumers	Rise in quality Rise in price Variable impacts on inclusion of the poor Increased availability of unhealthy food
Digital	Cross-cutting use of digital technologies in the types listed above, plus some specialised e-commerce companies delivering food, sometimes partnering with SMEs Middle and high-income consumers	Overcome risks linked with sanitary crises Higher traceability and trust, supporting for certification schemes Increased convenience Rise in price Exclusion of consumers with poor internet access

4 Adaptation to Demand and Crises in Urban Food Systems

The capacity of food systems in low- and middle-income countries to supply urban populations in sufficient quality and quantity is often questioned. The development of agribusiness at all stages of food chains is sometimes seen as one way to overcome these shortcomings. Large-scale private investments in mechanised production, processing, storage, and retailing are put to the fore. Yet, innovations are not neutral in terms of social inclusion. It is sometimes even claimed that the present problems of food security, including unhealthy food, are caused by innovations and agribusinesses (Glover and Poole 2019). Labour-saving and scale-biased innovations have a negative impact on employment for the poor and they are less suitable in regions where labour is in excess supply than is the case with capital-saving or neutral innovations (unless massive credit programmes targeting the poor are launched). Moreover, they ignore the diversity and creativity that exist at the level of food systems driven by MSMEs, including producer organisations, as explained in Sect. 3.2.

The Covid-19 crisis has caused major disturbances, the most important being the decrease in sources of income among vulnerable urban dwellers, with an impact on women and children, due to restrictions on movement and the disturbances in logistics systems (Shekar et al. 2021). In some countries, the increased vulnerability of the urban poor has been addressed through food aid programmes and increased social safety nets targeting women (Shekar et al. 2021). At the same time, the local food provisioning sector has proven to be quite resilient, with no major breaks in the food supply chains. Public policies restricting the sale of food in open markets have been varied, with mixed consequences for access to employment and to food by the poor. For instance, the municipalities of Abidjan and Dakar found ways to maintain retail sales of food in open markets through regulations concerning hygiene and social distancing, enabling some contactless proximity, which was not the case in Burkina Faso, where markets were shut down at the beginning of the crisis (Dury et al. 2021; IPES Food 2020; Moustier 2020; Devereux et al. 2020).

Considering their inclusiveness and resilience, we recommend supporting urban food transformations based on MSMEs. These are discussed in more detail in the following section.

5 Solutions for Enhancing Inclusive Urban Food System Transformations

In the previous section, we reported insights from the literature on the advantages and shortcomings of current urban food systems. Yet, these insights are quite patchy in terms of time, space, and commodity coverage. That is why our first recommendation concerns the need for better data. Second, we provide recommendations related to urban food planning, mostly concerning the protection of land for agriculture, marketplaces, and shops, as well as regulations pertaining to supermarkets and food safety. These should enable urban consumers to benefit from a variety of food retailing formats. We also recommend communication actions to promote nutrient-dense foods, e.g., fruit, vegetables, nuts and legumes, which may be available to consumers locally, but are not always purchased, because consumers may have little knowledge of their health benefits or of how to include them in their meals and dietary practices. Rural-urban transportation, which is the mandate of national governments, should be a priority to improve both food availability and quality and to reduce food losses. National programmes should also improve access to credit and

Table 2 Recommendations according to targeted types of urban food systems

	5.2.1. Land protection	5.2.2. Upgrading of open market places	5.2.3. Mobile vendors' markets	5.4.1. Rural-urban transportation	5.4.2. Services to MSMEs
Subsistence	X				
Short relational	X	X	x		
Long relational		X	x	x	
Value-oriented SMEs				x	x
Supermarket-driven				x	x
Digital					x

training on food processing and storage for food MSMEs. Improvements in food quality can be obtained through food processing and storage technologies, which are not always available to MSMEs because they have no access to credit and training programmes. Finally, securing coordination among food system actors is required to enhance the quality and availability of diverse food items. Details of these recommendations are given below. Some recommendations concur with the recent work of the Centre for Food Policy (London University) aimed at identifying policies and actions that can orient food systems towards healthier diets for all (Hawkes et al. 2020).

While some recommendations (Sects. 5.1 and 5.3) relate to all types of urban food system, some are more particularly relevant for some of the urban food system types identified here (see Table 2).

The recommended interventions are intended to upgrade the operation of MSMEs, as well as changing consumers' environments to enable healthier food, while keeping costs and prices affordable for the urban poor. This is why the proposed interventions are sober in terms of capital and energy; moreover, economies of scale are reached through coordination of SMEs, rather than by providing support to agribusinesses.

5.1 *Obtaining Accurate Data on Food Consumption, Foodsheds, and Food Chains*[1]

Policymakers need to support inter-disciplinary teams of researchers, including geographers, economists, specialists in consumption and statisticians, to collect accurate and updated data on food consumption, foodsheds and food chains.

[1] The lack of data was underlined at the Milan Urban Food Policy Pact meeting in Ouagadougou, February 15-19, 2021.

Available data on food consumption underestimate two kinds of patterns: food consumed away from the home, and seasonal food, including fruit and vegetables. Adequate and valid methods of measurement are needed to address this deficiency (Rousham et al. 2020). Identifying the specific role of different production areas and market intermediaries in urban food supply requires original sources of data. Comparing what is produced over a year in a city, what is produced in rural areas and what is imported has many limitations, including difficulties in capturing information on perishable seasonal products; additionally, such comparisons do not take the destination of products into consideration. Accurately appraising the role of different production areas and intermediaries in urban food supply requires surveys of wholesale and retail markets, and of the origin and quantities of products traded. Surveys should be conducted at different times of the year to account for seasonal variations, and with specific relational expertise. A foodshed approach (Schreiber et al. 2021) combined with value chain analysis is recommended to identify the production areas of targeted nutrient-dense food and to assess how the organisation of the value chain (geography and intermediation) determines the quality, accessibility and competitiveness of the supply of targeted food products.

5.2 *Urban Food Planning for Poor-Friendly Production and Marketing Spaces*

5.2.1 Protection of Land for Multifunctional Urban Agriculture

If market forces are left unrestricted, urban agriculture is doomed to disappear, given the forces of pressure on land and water. This is detrimental to urban food security and livelihoods and may create environmental problems. We consequently recommend protecting land for agriculture in areas where it is documented to play a major role in both food supplies and livelihoods, and where pollution is not an issue. Access to land can be secured through regulations (protecting agricultural parks or zoning measures) and formal contracts. How urban planning is enforced needs to be closely monitored, as it has frequently been observed that legal protection of land is regularly trespassed owing to the attraction of private investors' urban development schemes (De Bon et al. 2010; Valette and Philifert 2014; Dao 2019).

5.2.2 Upgrading Food Marketplaces

Urban marketplaces are frequently characterised by congestion, difficulty moving around, and lack of hygiene. Some past projects aimed to replace urban marketplaces with wholesale markets located outside the city boundaries, but these markets were underused due to limited transport facilities, as well as the high cost of market stalls

(Moustier 2017a, b). We thus recommend upgrading existing markets. The priority should be covering them and concreting the ground. Other basic infrastructures and services should be provided, including access to clean water. The planning of new markets should include in-depth consultation of a panel of market users, especially wholesalers and retailers (Hubbard and Onumah 2001). Food markets can also be combined with a "food hub" function, thereby creating new market linkages with food producers in the region, as developed in Colombia (Dubbeling et al. 2017). Market regulations concerning hygiene should be designed with the involvement of representatives of market users. Farmers' markets should be encouraged by providing adequate space and market services (Baker and de Zeeuw 2015).

5.2.3 Accommodating Space for Mobile Vendors

Given the importance of street vending in the livelihoods of vulnerable urban populations (especially women), we recommend their business should be acknowledged and support provided that aims at "semi-formality" (Cross 2000). Semi-formality refers to a self-regulating system with some light third-party regulatory enforcement, thus protecting the flexibility of street vending, which is uniquely adapted to the conditions of the urban poor. Regulatory enforcement requires consulting a panel of street vendors to protect some urban spaces so as to allow vendors to conduct their temporary business while ensuring their commitment to respecting rules of hygiene and traffic safety. Some examples of successful integration of street vending in urban planning can be found in Loc and Moustier in Vietnam (2016), in Srivastana in India (2012), in Dai et al. in China, (2019), and in Tangworamonycon in Thailand (2014).

5.3 Consumer-Oriented Promotion of Nutrient-Dense Food

Culinary recipes and techniques that enhance the nutritional quality of the food, as well as the packaging and labelling of local nutrient-dense food items, including fruit, vegetables, pulses, and nuts, should be promoted. These food items are recommended to enable urban consumers, including women and children, to diversify their diets in line with nutritional and planetary limits and the promotion of local biodiversity (EAT-Lancet Commission 2019). Different ways to increase public awareness about healthy food and promote traditional food cultures are discussed in Hawkes et al. (2020).

5.4 *National Provisioning of Infrastructures and Services for MSMEs*

5.4.1 Improving Rural-Urban Transport

Roads between cities and rural areas, which play a major role in supplying food to cities, need to be expanded and maintained, along with alternative transport routes by rail or water (Popoola et al. 2021).

5.4.2 Disseminating Small-Scale Food Processing Technologies

Technological innovations are available to improve the safety and nutritional qualities of food, but not at a sufficient scale for MSMEs (Ferré et al. 2018; Pallet and Sainte-Beuve 2016). Examples of small-scale food storage and processing technologies that reduce food losses, based on a thorough assessment of losses along food chains, are given by Tefft et al. (2017).

5.4.3 Service Provisioning for MSMEs

Innovation in the artisanal sector needs to be supported by providing credit to increase working capital, so as to enable investment in semi-industrial processing. Training on how to improve the quality of food also needs to be made available to MSMEs. This falls under the mandate of the public sector. As public resources are scarce, partnering with the retail sector may be an appropriate solution, if it enables sufficiently wide coverage of both farmers' and consumer's economic profiles. The public sector also needs to invest human resources in food quality control, with random checks of food safety and labelling frauds, as well as graduated sanctions for non-compliance, at various points along the chain, including wholesale and retail markets (Hawkes et al. 2020; Dao 2020).

5.5 *Fostering Multi-stakeholder Coordination and Governance*

Secured forms of coordination between food suppliers and vendors range from agreements on quality or quantity requirements to contractual joint commitments. Innovative producer organisations that include processing and distribution, e.g., "Entreprises de Services et Organisations de Producteurs" (ESOPs), should be encouraged, as this increases the scale of operation and investments in quality while creating added value for farmers (Maertens and Velde 2017). The concept of 'intermediate food systems' (*systèmes alimentaires du milieu*) developed by

Chazoule et al. (2018) and tested in some African situations (Sirdey 2020) can be used to model the hybridisation of traditional and modern systems that combine cooperation mechanisms with economies of scale.

Cities can become important actors in the development of SFSs, particularly through their governance of urban agriculture, school canteens, and waste management (Bricas 2019; Fages and Bricas 2017). Through the Milan food policy pact (https://www.milanurbanfoodpolicypact.org/), city officials are invited to commit to 31 actions aimed at sustainable food provisioning and consumption. In many cities, permanent urban food policy councils have been set up, with interesting outcomes, e.g., school catering programmes (Sonnino et al. 2019). Governing urban food systems in an inclusive way involves setting up multi-stakeholder city-region food platforms. These include public stakeholders working in different sectors (agriculture, trade, environment, health, social care) and at the national and city scales, together with a panel of value chain actors and service support organisations. The stakeholders meet regularly to exchange and discuss information, aiming to reach a consensus on desirable outcomes and on a set of policy recommendations (Blay-Palmer et al. 2018; see also https://ruaf.org/ for many examples of urban food policy platforms, sometimes on the basis of urban agriculture programmes, like in Quito). Food system assessment and dialogues are good starting points (Huynh et al. 2021; David-Benz et al. forthcoming).

In all these platforms, access and use of market information is strategic. Systems favouring interactions among farmers, traders and public agencies, conducive to new marketing decisions for farmers, new supply options for traders, and priorities for extension workers and input suppliers, e.g., for the support of off-season production as a substitute for imports, are termed alliances by the World Bank (2016), as quoted by Tefft et al. (2017), or market information and consultation systems (MICS). Modelling tools and serious games can be combined in such information and consultation systems to present options for local production that better address consumer needs (Verger et al. 2018; Mangnus et al. 2019).

6 Conclusion

In the context of continuous urban development and widening income disparities, urban food systems in countries of the Global South are becoming more market-oriented and innovative, with new investments in logistics and quality. Small-scale, labour-intensive food supply chains with relational governance and decentralised food distribution that provide food at a low price close to consumers' homes have proven resilient. They are poor-friendly and adapted to the time and work demands of women, in particular compared to agro-industrial schemes. Relative to the vast recent literature on food systems, this chapter highlights some peculiarities of the urban context and food systems of low- and middle-income countries. These include the importance of food caterers and mobile and open market vendors, as well as urban agriculture, in the provisioning of the urban poor; the high pressure on urban agricultural land and water; the innovative nature and consumer orientation of many food MSMEs; and the growing concerns and involvement of urban authorities in urban food security. Opportunities exist to respond to consumer demand and needs in terms of nutritional balance and food safety, while creating employment for less educated urban populations, especially for women. To exploit these opportunities, we have recommended a set of actions representing public support to endogenous patterns, adapted to the six types of urban food system that we brought to the fore, as a variety of food systems is needed to target different objectives and local contexts (Seck 2021).

Acknowledgements Thanks to Ninon Sirdey, two anonymous reviewers from the UNFSS scientific group for their comments on an earlier version, and to Jemimah Njuki, International Food Policy Research Institute, Africa Regional office c/o ILRI Nairobi.

References

Adimalla N (2020) Heavy metals pollution assessment and its associated human health risk evaluation of urban soils from Indian cities: a review. Environ Geochem Health 42(1):173–190

Allen T, Heinrigs P, Heo I (2018) Agriculture, food and jobs in West Africa. West African Papers, N°14. OECD Publishing, Paris

Amegah AK, Agyei-Mensah S (2017) Urban air pollution in sub-Saharan Africa: time for action. Environ Pollut 220:738–743

Baker L, de Zeeuw H (2015) Urban food policies and programmes. In: de Zeeuw H, Drechsel P (eds) Cities and agriculture: developing resilient urban food systems. Routledge, London, pp 26–55

BBVA Research (2017) Urbanization in Latin America. https://www.bbvaresearch.com/wp-content/uploads/2017/07/Urbanization-in-Latin-America-BBVA-Research.pdf. Accessed 01 Dec 2021

Béné C, Oosterveer P, Lamotte L, Brouwer ID, de Haan S, Prager SD, Talsma EF, Khoury CK (2019) When food systems meet sustainability. Current narratives and implications for actions. World Dev 113:116–130

Blay-Palmer A, Santini G, Dubbeling M, Renting H, Taguchi M, Giordano T (2018) Validating the City region Food system approach: enacting inclusive, transformational city region Food Systems. Sustainability 10(5):1680

Blekking J, Tuholske C, Evans T (2017) Adaptive governance and market heterogeneity: an institutional analysis of an urban Food system in sub-Saharan Africa. Sustainability 9:2191

Bellwood-Howard I, Shakya M, Korbeogo G, Schlesinger J (2018) The role of backyard farms in two west African urban landscapes. Landsc Urban Plan 170:34–47

Berchin II, Nunes NA, de Amorim WS, Zimmer GAA, da Silva FR, Fornasari VH, de Andrade JBSO (2019) The contributions of public policies for strengthening family farming and increasing food security: the case of Brazil. Land Use Policy 82:573–584

Bonnet F, Vanek J, Chen M (2019) Women and men in the informal economy: a statistical brief. International Labour Office, Geneva. https://www.wiego.org/sites/default/files/publications/files/Women%20and%20Men%20in%20the%20Informal%20Economy%203rd%20Edition%202018.pdf. Accessed 1 Dec 21

Bricas N, Tchamba C, Mouton F (eds) (2016) L'Afrique à la conquête de son marché intérieur. Editions AFD, Paris

Bricas N (2019) Urbanization issues affecting Food system sustainability. In: Brand C, Bricas N, Conare D, Daviron B, Debru J, Michel L, Soulard CT (eds) Designing urban Food policies. Concepts and approaches. Springer, pp 1–25

Chaboud G, Bricas N, Daviron B (2013) Sustainable urban food systems: state of the art and future directions. Communication to the fifth Aesop urban food planning conference. https://hal.inrae.fr/hal-02745437/document#page=39

Chazoule C, Lafosse G, Brulard N, Crosnier M, Van Dat C, Desole M, Devise O (2018) Produire et échanger dans le cadre de systèmes alimentaires du milieu. Pour 2:143–150

Cobbinah PB, Erdiaw-Kwasie MO, Amoateng P (2015) Africa's urbanisation: implications for sustainable development. Cities 47:62–72

Cross J (2000) Street vendors, and postmodernity: conflict and compromise in the global economy. Int J Sociol Soc Policy 20(1/2):29–51

De Bon H, Parrot L, Moustier P (2010) Sustainable urban agriculture in developing countries. A review. Agron Sustain Dev 30(1):21–32

Dai N, Zhong T, Scott S (2019) From overt opposition to covert cooperation: governance of street food vending in Nanjing, China. Urban Forum 30(4):499–518

Dao TA (ed) (2020) Developing a sustainable safe food value chain in Vietnam. Vietnamese version. Agricultural-Construction Publishing Houses, Hanoi

Dao TA (ed) (2019) Development of sustainable peri-urban agriculture in Vietnam. Vietnamese version. Agricultural Publishing House

David-Benz H, Sirdey N, Deshons A, Orbell C, Herlant P (forthcoming) Assessing national and subnational food systems. A methodological framework. CIRAD/FAO/EU. Draft version available at: https://knowledge4policy.ec.europa.eu/sites/default/files/food_system_analysis_rapid_methodology-english_18_may_2020.pdf. Accessed on 1 Dec 21

De Cara S, Fournier A, Gaigné C (2017) Local Food, urbanization, and transport-related greenhouse gas emissions. J Reg Sci 57(1):75–108

Demmler KM, Ecker O, Qaim M (2018) Supermarket shopping and nutritional outcomes: a panel data analysis for urban Kenya. World Dev 102:292–303

De Brauw A, Brouwer ID, Snoek H, Vignola R, Melesse MB, Lochetti G, Ruben R (2019) Food system innovations for healthier diets in low and middle-income countries, Working paper 1816. International Food Policy Research Institute, Washington

Devereux S, Béné C, Hoddinott J (2020) Conceptualising COVID-19's impacts on household food security. Food Security 12(4):769–772

Douglas I (2017) Flooding in African cities, scales of causes, teleconnections, risks, vulnerability and impacts. Int J Disaster Risk Reduction 26:34–42

Dubbeling M, Santini G, Renting H, Taguchi M, Lançon L, Zuluaga J, De Paoli L, Rodriguez A, Andino V (2017) Assessing and planning Sustainable City region Food systems: insights from two Latin American cities. Sustainability 9:1455. https://doi.org/10.3390/su9081455

Dury S, Alpha A, Zakhia N, Giordano T (2021) Les systèmes alimentaires aux défis de la crise de la Covid-19 en Afrique: enseignements et incertitudes. Cahiers Agric 30(12)

Fafchamps M (2004) Market institutions in sub-saharan Africa. Theory and evidence. The MIT Press, Cambridge

EAT-Lancet Commission (2019) Food in the Anthropocene: the EAT-Lancet commission on healthy diets from sustainable food systems. The Lancet Commissions. https://www.thelancet.com/commissions/EAT. Accessed on 1 Dec 21

Fages R, Bricas N (2017) Food for cities. What roles for local governments in the global South**?** Paris, AFD, [Full Text]

FAO (2018) Sustainable food systems: concept and framework. http://www.fao.org/policy-support/tools-and-publications/resources-details/fr/c/1160811/. Accessed on 1 Dec 21

FAO, RUAF (2019) Evaluación y planificación del Sistema Agroalimentario Ciudad-Región. Medellin, Roma. http://www.fao.org/3/ca5747es/ca5747es.pdf. Accessed on 1 Dec 21

Ferré T, Medah I, Cruz JF, Dabat MH, Le Gal PY, Chtioui M, Devaux-Spatarakis A (2018) Innover dans le secteur de la transformation agroalimentaire en Afrique de l'Ouest. Cahiers Agric 27(1): 15011

Figuié M, Bricas N, Than VPN, Truyen ND (2004) Hanoi consumers' point of view regarding food safety risks: an approach in terms of social representation. Vietnam Soc Sci 3(101):63–72

Freidberg S, Goldstein L (2011) Alternative food in the global south: reflections on a direct marketing initiative in Kenya. J Rural Stud 27(1):24–34

Giordano T, Losch B, Sourisseau JM, Girard P (2019) Risks of mass unemployment and worsening of working conditions. In: Dury S. et al (Eds), op.cit., 75–78

Glover D, Poole N (2019) Principles of innovation to build nutrition-sensitive food systems in South Asia. Food Policy 82:63–73

Guerrero LA, Maas G, Hogland W (2013) Solid waste management challenges for cities in developing countries. Waste Manag 33(1):220–232

Hagen JM (2002) Causes and consequences of food retailing innovation in developing countries: supermarkets in Vietnam, Working Paper, Cornell University, Department of Applied Economics and Management. https://ageconsearch.umn.edu/record/127310/

Hawkes C, Walton S, Haddad L, Fanzo J (2020) 42 policies and actions to orient food systems towards healthier diets for all. Centre for Food Policy, City, University of London, London

HLPE (2014) Food losses and waste in the context of sustainable food systems. HLPE report nr 8. http://www.fao.org/policy-support/tools-and-publications/resources-details/fr/c/854257/

HLPE (2017) Nutrition and food systems HLPE report nr 12. http://www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-12_FR.pdf

Holdsworth M, Pradeilles R, Tandoh A, Green M, Wanjohi M, Zotor F, Laar A (2020) Unhealthy eating practices of city-dwelling Africans in deprived neighbourhoods: evidence for policy action from Ghana and Kenya. Glob Food Sec 26:100452

Hou J (2017) Urban community gardens as multimodal social spaces. In: Tan P, Jim C (eds) Greening cities. Advances in 21st century human settlements. Springer, Singapore

Hubbard M, Onumah G (2001) Improving urban food supply and distribution in developing countries: the role of city authorities. Habitat Int 25(3):431–446

Huynh TTT, Pham TMH, Duong TT, Hernandez R, Trinh TH, Nguyen MT, Even B, Lundy M, Swaans K, Raneri J, Hoang TK, Hendriks A, Abbink H, Nguyen TK, Ha HT, de Haan S (2021) Food systems profile. Along a rural-urban transect in North Vietnam. https://cgspace.cgiar.org/handle/10568/113417

International Labour Organization (ILO) (2018) World employment and social outlook: trends 2018. ILO, Geneva

IPES Food (2020) COVID-19 and the crisis in food systems: Symptoms, causes, and potential solutions. http://www.ipes-food.org/_img/upload/files/COVID-19_CommuniqueEN%283%29.pdf. Accessed on 1 Dec 21

Jaffee S, Henson S, Unnevehr L, Grace D, Cassou E (2018) The safe food imperative: accelerating progress in low-and middle-income countries. World Bank Publications, Washington

Joshi A, Kaneko J, Usami Y (2012) Farmers' participation in weekly organic bazaars in Aurangabad, India. J Rural Prob 45(175):231–236

Karg H, Akoto-Danso EK, Drechsel P, Abubakari AH, Buerkert A (2019) Food-and feed-based nutrient flows in two West African cities. Nutr Cycl Agroecosyst 115(2):173–188

Fan S, Swinnen J (2020) Reshaping food systems. The imperative of inclusiveness. In: International Food policy research institute, global Food policy report: building inclusive Food systems. International Food Policy Research Institute, Washington, DC, pp 6–12. https://doi.org/10.2499/9780896293670

GNR (2020) Global Nutrition Report: Action on equity to end malnutrition. 2020. Bristol, UK: Development Initiatives. https://globalnutritionreport.org/. Accessed on 1 Dec 21

Leeson GW (2018) The growth, ageing and urbanisation of our world. J Popul Ageing 11:107–115

Letcher TM (2020) Introduction to plastic waste and recycling. In: Plastic waste and recycling. Academic, London, pp 3–12

Lemeilleur, S., d'Angelo l.,Rousseau, M., Brisson E., Boyer A., Lançon F., Moustier P. 2019. Les systèmes de distribution alimentaire dans les pays d'Afrique méditerranéenne et Sub-saharienne. Repenser le rôle des marchés dans l'infrastructure commerciale. Notes techniques de l'AFD. *Notes*, (51). http://admin.riafco.org/Images/Ressources/Pulication/64/51-notes-techniques.pdf. Accessed on 1 Dec 21

Loc NTT, Moustier P (2016) Toward a restricted tolerance of street vending of food in Hanoi districts: the role of stakeholder dialogue. World Food Policy 2:67–78

Maertens M, Velde KV (2017) Contract-farming in staple food chains: the case of rice in Benin. World Dev 95:73–87

Maestre M, Poole N, Henson S (2017) Assessing food value chain pathways, linkages and impacts for better nutrition of vulnerable groups. Food Policy 68:31–39

Mangnus AC, Vervoort JM, McGreevy S, Ota K, Rupprecht C, Oga M, Kobayashi M (2019) New pathways for governing food system transformations: a pluralistic practice-based futures approach using visioning, back-casting, and serious gaming. Ecol Soc 24(4)

Minten B, Reardon T, Chen KZ (2017) Agricultural value chains: how cities reshape food systems. Global food policy report, IFPRI book, pp 42–49

Moustier P (2020) Pour un accès inclusif aux aliments en temps de covid-19. https://www.agenceecofin.com/agro/1205-76552-pour-un-acces-inclusif-aux-aliments-en-temps-de-covid-19-paule-moustier. Accessed on 1 Dec 21

Moustier P (2017a) Short urban food chains in developing countries: signs of the past or of the future? Nat Sci Soc 25(1):7–20

Moustier P (2017b) What market planning policies should apply to urban food systems in developing countries? In: Debru J, Albert S, Bricas N, Conaré D (eds) Urban food policies: proceedings of the international meeting on experience in Africa, Latin America and Asia. Chaire Unesco alimentations du monde, Montpellier, pp 23–26. https://issuu.com/chaireunescoadm/docs/01-actespau_en_20juin/32

Moustier P, Renting H (2015) Urban agriculture and short chain food marketing in developing countries. In: De Zeeuw H, Drechsel P (eds) Cities and agriculture. Developing resilient urban food systems. Routledge, London, pp 121–138

Moustier P, Figuié M, Loc NTT (2009) Are supermarkets poor-friendly? Debates and evidence from Vietnam. In: Lindgreen A, Hingley M (eds) The crisis of food brands. Gower Publishing, London, pp 311–327

Neveu-Tafforeau MJ (2017) Grande distribution: quelles opportunités pour les filières agroalimentaires locales? Fondation Farm, Paris

Nuthalapati CS, Sutradhar R, Reardon T, Qaim M (2020) Supermarket procurement and farmgate prices in India. World Dev 134(105034):1–14

OECD/SWAC (2020) Africa's urbanisation dynamics 2020: Africapolis, Mapping a New Urban Geography. West African Studies, OECD Publishing, Paris. https://doi.org/10.1787/b6bccb81-en

OECD, Commission économique pour l'Amérique latine et les Caraibes, CAF Development Bank of Latin America and Union européenne (2019) Latin American economic outlook 2019: development in transition. OECD Publishing, Paris. https://doi.org/10.1787/g2g9ff18-en

Ogunkola IO, Imo UF, Obia HJ, Okolie EA, Lucero-Prisno DE III (2021) While flattening the curve and raising the line, Africa should not forget street vending practices. Health Promotion Perspect 11(1):32–35

Ortega DL, Tschirley DL (2017) Demand for food safety in emerging and developing countries: a research agenda for Asia and sub-Saharan Africa. J Agribusiness Dev Emerging Econ 7(1): 21–34

Olivier DW, Heinecken L (2017) Beyond food security: women's experiences of urban agriculture in Cape Town. Agric Hum Values 34(3):743–755

PAHO (Pan American Health Organization) (2015) Ultra-processed food and drink products in Latin America: trends, impact on obesity, policy implications, Washington, DC
Pallet D, Sainte-Beuve J (2016) Systèmes de transformation durables: quelles nouvelles stratégies pour les filières? In: Biénabé E, Rival A, Loeillet D (eds) Développement durable et filières tropicales. Editions Quae, Montpellier, pp 151–165
Pervin IA, Rahman SMM, Nepal M, Haque AKE, Karim H, Dhakal G (2020) Adapting to urban flooding: a case of two cities in South Asia. Water Policy 22(S1):162–188
Popoola AA, Adeyemi YD, Oni FE, Omojola O, Adeleye BM, Medayese S, Popoola OG (2021) Rural-urban Food movement: role of road transportation in Food chain analysis. In: Handbook of Research on Institution Development for Sustainable and Inclusive Economic Growth in Africa. IGI Global, pp 276–298
Popkin BM, Adair LS, Ng SW (2012) Global nutrition transition and the pandemic of obesity in developing countries. Nutr Rev 70(1):3–21
Pradeilles R, Irache A, Milkah N, Wanjohi HM, Laar A, Zotor F, Tandoh A, Senam KS, Graham F, Muthuri SK, Kimani-Murage EW, Coleman N, Green MA, Osei-Kwasi HA, Marco BM, Emily K, Rousham EK, Gershim AG, Akparibo R, Mensah K, Aryeetey R, Bricas N, Griffiths P (2021) Urban physical food environment drives dietary behaviours in Ghana and Kenya: a Photovoice study. Health Place 71:102647
Pulliat G (2015) Food securitization and urban agriculture in Hanoi (Vietnam). J Urban Res 7. https://journals.openedition.org/articulo/2845
Ravaillon M (2016) The economics of poverty. Paperback
Reardon T, Liverpool-Tasie LSO, Minten B (2021a) Quiet revolution by SMEs in the midstream of value chains in developing regions: wholesale markets, wholesalers, logistics, and processing. Food Security 13. https://doi.org/10.1007/s12571-021-01224-1
Reardon T, Belton B, Liverpool-Tasie LSO, Lu L, Nuthalapati CS, Tasie O, Zilberman D (2021b) E-commerce's fast-tracking diffusion and adaptation in developing countries. Appl Econ Perspect Policy 43:1243. https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/aepp.13160
Reardon T, Echeverria R, Berdegué J, Minten B, Liverpool-Tasie S, Tschirley D, Zilberman D (2019) Rapid transformation of food systems in developing regions: highlighting the role of agricultural research and innovations. Agric Syst 172:47–59
Reardon T (2015) The hidden middle: the quiet revolution in the midstream of agrifood value chains in developing countries. Oxf Rev Econ Policy 31(1):45–63
Reardon T, Henson S, Gulati A (2010) Links between supermarkets and food prices, diet diversity and food safety in developing countries. In: Hawkes C, Blouin C, Henson S, Drager N, Dubé L (eds) Trade, food, diet and health: perspectives and policy options. Wiley, pp 111–130
Renting H, Dubbeling M (2013) Synthesis report: innovative experiences with (peri-) urban agriculture and urban food provisioning - lessons to be learned from the global South. Supurbfood project report. Leusden, RUAF Foundation
Reynolds TW, Waddington SR, Anderson CL, Chew A, True Z, Cullen A (2015) Environmental impacts and constraints associated with the production of major food crops in sub-Saharan Africa and South Asia. Food Security 7(4):795–822
Rodrik D (2016) Premature desindustrialization. J Econ Growth 21(1):1–33
Rousham E, Pradeilles R, Akparibo R, Aryeetey R, Bash K, Booth A, Muthuri S, Osei-Kwasi HA, Marr C, Norris T, Holdsworth M (2020) Dietary behaviours in the context of nutrition transition: a systematic review and meta-analysis in two African countries. Public Health Nutr:1–17
Seck PA (2021) Some African expectations from the 2021 world summit on food systems. Embassy of Senegal at Italy
Schreiber K, Hickey GM, Metson GS, Robinson BE, MacDonald GK (2021) Quantifying the foodshed: a systematic review of urban food flow and local food self-sufficiency research. Environ Res Lett 16(2):023003
Shekar M, Condo J, Pate MA, Nishtar S (2021) Maternal and child undernutrition: progress hinges on supporting women and more implementation research. Lancet 397(10282):1329–1331

Sirdey N (2020) Pour une analyse des « systèmes alimentaires du milieu »: étude de la pertinence et de l'opérationnalisation de la notion en contexte africain. Document de travail Cirad

Si Z, Scott S, McCordic C (2019) Wet markets, supermarkets and alternative food sources: consumers' food access in Nanjing, China. Can J Dev Stud 40(1):78–96

Sonnino R, Tegoni CL, De Cunto A (2019) The challenge of systemic food change: insights from cities. Cities 85:110–116

Soula A, Yount-André C, Lepiller O, Bricas N (eds) (2020) Manger en ville: Regards socio-anthropologiques d'Afrique, d'Amérique latine et d'Asie. Editions Quae, Montpellier

Tangworamongkon C (2014) Street vending in Bangkok: legal and policy frameworks, livelihood challenges and collective responses. Woman in Informal Employment: Globalizing and Organizing. https://www.wiego.org/sites/default/files/resources/files/Street-Vending-Bangkok-Legal-and-Policy-Framework-Law-Case-Study.pdf

Tefft J, Jonasova M, Adjao R, Morgan A (2017) Food systems for an urbanizing world. World Bank and FAO

The EAT-Lancet Commission (2019) Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. The Lancet Commissions. https://www.thelancet.com/commissions/EAT

The World Bank (2016) Linking farmers to markets through productive alliances: an assessment of the World Bank experience in Latin America. World Bank, Washington DC

Tschirley D**,** Bricas N**,** Sauer C**,** Reardon T (2020) Opportunities in Africa's growing urban food markets. In: feeding Africa's cities: opportunities, challenges, and policies for linking African farmers with growing urban food markets. AGRA. Nairobi: AGRA, 25-56. Africa agriculture status report. https://agra.org/reports-and-financials/

Tschirley D, Haggblade S, Reardon T (2014) Africa's emerging food transformation, Eastern and Southern Africa. MSU. https://www.adelaide.edu.au/global-food/research/international-development/vietnam-consumer-survey

Turner S, Schoenberger L (2011) Street vendor livelihoods and everyday politics in Hanoi, Vietnam: the seeds of a diverse economy? Urban Stud 49(5):1027–1044

UNICEF/GAIN (2018) Food systems for children and adolescents. Summary report

University of Adelaide (2014) The Vietnam urban food consumption and expenditure studyFactsheet 4: where do consumers shop? Wet markets still dominate. https://www.adelaide.edu.au/global-food/ua/media/95/Urban_Consumer_Survey_Factsheet_04.pdf

Valette E, Philifert P (2014) L'agriculture urbaine: un impensé des politiques publiques marocaines? Géocarrefour 89:75–83

Verger EO, Perignon M, El Ati J, Darmon N, Dop MC, Drogué S, Amiot-Carlin MJ (2018) A "fork-to-farm" multi-scale approach to promote sustainable food systems for nutrition and health: a perspective for the Mediterranean region. Front Nutr 5:30

Vietnam news (2021) Agricultural products go online. https://vietnamnews.vn/economy/899756/agricultural-products-go-online.html

Vorley B (2013) Meeting small-scale farmers in their markets: understanding and improving the institutions and governance of informal agrifood trade. International Institute for Environment and Development (IIED)

Wanyama R, Gödecke T, Chege CG, Qaim. (2019) How important are supermarkets for the diets of the urban poor in Africa? Food Security 11(6):1339–1353

Wertheim-Heck SC, Raneri JE (2019) A cross-disciplinary mixed-method approach to understand how food retail environment transformations influence food choice and intake among the urban poor: experiences from Vietnam. Appetite 142:104370

Yaya S, Ekholuenetale M, Bishwajit G (2018) Differentials in prevalence and correlates of metabolic risk factors of non-communicable diseases among women in sub-Saharan Africa: evidence from 33 countries. BMC Public Health 18(1):1–13

Secondary Cities as Catalysts for Nutritious Diets in Low- and Middle-Income Countries

Kesso Gabrielle van Zutphen, Dominique Barjolle, Sophie van den Berg, Breda Gavin-Smith, Klaus Kraemer, Capucine Musard, Helen Prytherch, Johan Six, Simon Winter, and Kris Woltering

1 Introduction

The world is facing a global malnutrition crisis. One in nine people go to bed hungry, more than 2 billion people suffer from micronutrient deficiencies, while one-third of the global population is overweight or obese (Global Nutrition Report 2020). Unhealthy diets are the leading risk factor for deaths from non-communicable diseases (NCDs). Although laudable progress has been made in maternal, infant and young child nutrition, malnutrition persists at unacceptably high levels in every country in the world, and we are not on track to achieve the targets of Zero Hunger (Goal 2) of the Sustainable Development Goals (SDGs). To date, despite growing political attention, such as through the Scaling Up Nutrition (SUN) movement, no

K. G. van Zutphen (✉)
Sight and Life Foundation, Basel, Switzerland

Wageningen University & Research, Wageningen, the Netherlands
e-mail: kesso.vanzutphen@sightandlife.org

D. Barjolle · S. van den Berg · J. Six
Department of Environmental Systems Science, Group of Sustainable Agroecosystems, Zurich, Switzerland

B. Gavin-Smith · K. Woltering
Sight and Life Foundation, Basel, Switzerland

K. Kraemer
Sight and Life Foundation, Basel, Switzerland

Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA

C. Musard · H. Prytherch
Swiss Tropical and Public Health Institute, Basel, Switzerland

S. Winter
Syngenta Foundation for Sustainable Agriculture, Basel, Switzerland

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_16

country has managed to reverse the rapid rise in malnutrition in all its forms, and this was even before the disruption caused by the COVID-19 pandemic (Global Nutrition Report 2020). The coexistence of undernutrition, micronutrient deficiencies and overnutrition in countries, households and even within individuals, referred to as the triple burden of malnutrition, signals a major shift in the global burden of malnutrition, with great variations and inequalities at different levels i.e., age, gender, geographical location (urban-rural) and other sociodemographic factors.

As urbanization rates across the globe are rising and there is a continued push to decentralize decision-making power to levels that are closer to the people served, cities are gaining an increasingly important role in the global malnutrition crisis and offer entry points for food system transformation. Besides the role of cities in ensuring adequate diets and managing the rising burden of NCDs, cities could also play a key role in enhancing resilience to food security shocks. This chapter discusses the challenge of the growing triple burden of malnutrition in urban contexts and advocates for the role of secondary cities as game changers in transforming city region food systems. Secondary cities are introduced as emerging players in pioneering nutrition-centered food systems interventions, and in monitoring and evaluating their impacts for later improvements and out-scaling.

2 The Challenge: A Growing Triple Burden of Malnutrition in Urban Contexts

The triple burden of malnutrition has moved to the cities as the world's population becomes more urbanized. For the first time in history, more than half of the world's population lives in urban areas (United Nations, Department of Economic and Social Affairs, Population Division 2014). By 2050, two-thirds of the global population is expected to reside in urban areas, consuming 80% of the world's food and producing 85% of global economic output (United Nations, Department of Economic and Social Affairs, Population Division 2018). Infants and young children of parents with low socio-economic status are extremely vulnerable to poor nutrition, and the first 1000 days are considered critical for a strong foundation in life. It is estimated that one in three children affected by stunting currently resides in urban areas, with the most disadvantaged urban children having stunting rates, on average, only slightly lower than those of the most disadvantaged rural children (Ruel et al. 2017). Poor urban children are up to ten times more likely to be stunted than urban children of a high socio-economic status (Ruel et al. 2017). In parallel, child undernutrition rates are rivaling the levels found among the rural poor, while the prevalence of overweight children is often higher among urban areas (Ruel et al. 2017). Among adults, the accelerated increase of overweight over the past decade and a half was more concentrated in urban areas. Overall, the data point to a shift towards a greater overall burden of malnutrition in all its forms in urban, compared to rural, areas. By 2035, half of individuals in extreme poverty (i.e., daily income less than USD 1.25) will live in urban areas, thereby increasing the number of people who cannot afford a healthy diet (Ravallion 2002). An additional and growing concern relates to food safety issues associated with eating out, particularly regarding street foods. Economic development, population growth and increasing rates of urbanization are creating an urgency to specifically understand the role of food systems in sustainable food production, consumption, diets and nutrition in urban contexts (also referred to as city region food systems).

Poor diets among city inhabitants are the consequence of a combination of forces. These include changes in types of occupation, particularly for women, that increase the demand for convenience and for ready-to-eat meals and foods; food-environment factors such as the persistent marketing and availability of nutrient-poor and energy-dense foods; shifts in norms and attitudes regarding food that are correlated with urban living, such as pressures to move away from traditional diets and changes in food habits and demand for (ultra)processed foods (Ruel et al. 2017). The recognition and consumption of traditional diets are also hampered due to the increasing globalization of the food sector and dependence on imported foods, a development that might exclude opportunities to enhance local food production. Another key element relates to the affordability of healthy diets, in the light of 3 billion people not being able to afford a healthy diet due to food prices and income constraints (FAO et al. 2020). Although incomes are generally higher in urban contexts, cities struggle to provide affordable and healthy diets to the urban poor. Poor road conditions and long distances between rural agricultural areas and cities cause food losses and food safety concerns regarding the transport of food to markets. This is especially critical for perishable nutritious foods, including animal products, vegetables and fruit (FAO et al. 2020). In sub-Saharan Africa, 35% of fruit and vegetables are lost and wasted at the retail level (FAO et al. 2020). Post-harvest preservation and conservation techniques are still poorly developed, meaning that a lot of nutritious food does not make it to the urban table.

3 The Solution: Secondary Cities as Game Changers for Sustainable Food Systems

3.1 Secondary Cities' Unique Characteristics

Contrary to popular belief, urbanization is not causing existing cities to develop into so-called 'mega-cities,' but is rather creating a patchwork of smaller urban areas (Satterthwaite 2007; Swilling and Annecke 2012). In 2018, close to half of the world's urban residents lived in settlements or towns with less than 500,000 inhabitants (United Nations, Department of Economic and Social Affairs, Population Division 2018). These settlements are classified as secondary cities and are, in terms of population, the fastest growing urban areas. Besides secondary cities, urban areas also consist of primary cities. These are generally defined as "the leading city in its country or region, disproportionately larger than any others in the urban hierarchy." Secondary cities are known as the 'second tier' in this urban hierarchy. There is no universally agreed-upon definition of a 'secondary city' (Goodall 1987). The term is contextual and can relate to population size, an administrative area, or a system of cities/towns with a particular significance within a country or geographical region (Roberts 2014a). Importantly, secondary cities within countries and regions are not uniform and can be classified into three broad categories generally described as "(1) the extractive city, whose economy and sole reason for existence was informed by and is now reliant on an extractive resource (often a single resource); (2) the trunk or trade city, located on a transport route or at a transport intersection; and (3) a satellite city, whose existence is informed by and deeply reliant on another city or country" (Roberts 2014b).

Secondary cities are characterized by a relatively smaller spatial scale and a physical proximity to rural areas when compared to primary or mega-cities. In contexts where power is decentralized to lower administrative levels, this characteristic offers unique opportunities to transform the city region food system for improved human and planetary health. In fact, in low- and middle-income countries (LMICs) specifically, linking urban areas with agricultural hinterlands could increase food security resilience through, for instance, a reduced dependence on international trade and a reduced vulnerability to natural disasters and climate change, which may result in food shortages (Blay-Palmer et al. 2018; Dubbeling et al. 2017). Additionally, localized food production in city region food systems creates the possibility of shortening food supply chains and reconnecting consumption and production. This has been found to enhance local and rural development and promotes information-sharing between producers and consumers (Belletti and Marescotti 2020). Short supply chains could provide ecological, health and socio-economic benefits. They have been linked to reduced food loss and are generally associated with decreased carbon emissions (resulting from, e.g., reduced transportation) (Blay-Palmer et al. 2015). Moreover, they have been described as an effective strategy when aiming to develop urban agriculture for enhanced food security. However, short value chains could also face challenges related to possible inefficient small-scale production processes or logistics (small freights/empty trucks). Inefficient production processes, logistics and use of resources could negatively affect pricing and even compromise the generally low emission of greenhouse gasses associated with short value chains (Borsellino et al. 2020). The potential of short value chains to benefit human and planetary health should therefore always be subject to context-specific assessments.

In short, when compared to primary cities, the city region food systems in secondary cities are largely characterized by strong urban-rural linkages and the opportunity for localized food production and consumption. In high-income countries, secondary cities are increasingly seen as important drivers to sustainably advance economic and social developments. In 2015, Parkinson et al. recommended that the European Commission increase their investments in secondary cities when "(i) the gap with capitals is large and growing, (ii) the business infrastructure of second-tier cities is weak because of national underinvestment and (iii) there is clear evidence about the negative externalities of capital city growth" to realize the economic potential of these cities (Parkinson et al. 2015). While primary cities have received the highest attention, the growing importance of secondary cities for urbanizing populations makes them uniquely positioned to serve as critical entry points for city region food system transformations.

3.2 *Secondary Cities Face Challenges That Can Be Turned into Opportunities*

Secondary cities, however, also face persistent challenges and disadvantages. In Europe, they play a key economic and social role, but compared to primary cities, they lack economic, demographic and, especially, political importance (Cardoso and Meijers 2017). Disadvantages resulting from this lack of importance may, in turn, lead to several setbacks in terms of infrastructure, governance, autonomy, decision-making space and the power required to raise resources and galvanize meaningful action. The disadvantages faced by secondary cities in Europe are more pressing in less-developed economic regions. Although the available body of research on secondary cities in LMICs appears to be less extensive, it is important to acknowledge that the underlying processes that shape urbanization in Africa are very distinct from those in other regions, such as Europe. Urban expansion in Africa is largely characterized by unplanned and/or unregulated growth and the absence of strong urban planning institutions (Pieterse and Parnell 2014). Consequently, secondary cities in sub-Saharan Africa and other LMICs are faced with several key challenges, as witnessed in Europe, but in a generally more complex context (Haysom and Fuseini 2019). Indeed, secondary cities are rapidly growing and are challenged by the fact that this increasing urban population is starting to call municipal leadership to account when access to basic services is compromised. Furthermore, similarly to Europe, governance and accountability remains a key challenge, as budgets, skills and capacities are often limited when compared to primary cities and hinder the effective governing of pressing issues related to poverty, health and social safety. Finally, the rapid growth experienced by secondary cities may put basic infrastructures (road networks, housing, access to markets, health and education services) under pressure, which may cause social inequalities to increase, with women and young girls of low socio-economic status particularly at risk of being excluded and exploited. In fact, whereas the original structure of a city might have met the needs of the population, it might not be an adequate foundation for rapid and unregulated expansion. All of these hinder sustainable economic growth (Haysom and Fuseini 2019) and make it difficult to attract private sector investments, create jobs and retain capital (Roberts 2014a). Although opportunities to transform secondary city food systems are apparent, the combination of rapid population growth and lagging development may cause poverty, malnutrition and related issues to concentrate among vulnerable populations (women, youths and the poor) in these same cities.

Without significant investment, a real effort to become more integrated and improved governance to bring different sectors, local business and civil society to the table, these locations will become a force for deeper exclusion and inequalities. The generally limited governance capacities in secondary cities calls for an improved understanding as to how these cities are governed, attention to the question of the decentralization of power, and how this shapes poverty and the production, distribution and consumption of food. As suggested by Satterthwaite (2007), the rapid urban growth in itself is not the main issue in cities. In fact, the most pressing challenge is the inadequate governance and planning from national and local institutions that is vital to adapting to this urban growth (Satterthwaite 2007). Although some research on how city governance affects urban poverty is available, the relationship among governance, poverty and the related nutrition and health outcomes in smaller cities needs further investigation.

The coming two to three decades will be critical in defining urban development in Africa, Asia and Latin America. Time is of the essence when conceptualizing, planning, financing and implementing this development (Pieterse et al. 2018). The rapid growth and the above-mentioned characteristics of secondary cities position them to take the lead in innovative and urgently needed food system interventions to ensure human and planetary health. However, as these cities struggle with challenges, increased investment and research in LMICs are needed.

The initiatives described below are practical examples that, when applied to the secondary cities context, can be leveraged to transform urban food systems and combat malnutrition and poverty. The examples highlight secondary cities' unique opportunities, namely, their power to convene key stakeholders, to make decisions and to raise and channel resources. Another opportunity is their ability to strengthen the supply and demand of diverse, locally produced and nutritious foods with short chains benefiting both producers and consumers.

3.3 Secondary Cities Can Accelerate Food Systems Transformation – Three Case Studies from LMICs

3.3.1 Nutrient Profiling with OBAASIMA in Ghana

Nutrient profiling (NP) is a scientific method for assessing the nutritional quality of (processed) foods and beverages based on their energy content and nutrient composition. NP and, for instance, the translation to front-of-pack labeling is a useful approach to informing, educating and empowering consumers and shifting consumer demand towards more diverse and healthy foods while allowing the food supply chain to respond to this demand. Creating consumer demand for nutritious foods is especially relevant in urbanizing contexts in which populations are increasingly exposed to (ultra)processed foods. To date, different NP models have been applied in high-income countries. However, transferring these models to urbanizing LMIC contexts remains challenging, as the current models are not tailored to address the triple burden of malnutrition, nor fortified foods and the affordability of diets. Also, LMIC contexts experience challenges related to access to basic education and nutrition literacy. In Ghana, the OBAASIMA project aims to stimulate the sustainable supply and the demand for high-quality, safe and affordable micronutrient-rich foods designed for women of reproductive age.

The OBAASIMA project builds on a demand-driven approach to increase the consumption of high-quality fortified food. It uses a front-of-package seal for foods that adhere to the minimum fortification content and nutrition criteria (18 vitamins and minerals), in combination with a social marketing campaign that provides information on nutrition and nutritious foods to women. The growing demand for products with the OBAASIMA seal offers entrepreneurial opportunities and encourages local small and medium-sized enterprises (SMEs) involved in food processing and fortification to adhere to fortification and quality standards. Ultimately, the project aims to improve food and nutrition security in Ghana, where women of reproductive age are severely affected by micronutrient deficiencies.

To date, the project has supported the development and nutritional optimization of three different products in Ghana. Since the launch of the products in 2017, they have been subject to marketing campaigns targeted towards women of reproductive age. The products are also included in the World Food Programme's cash and voucher strategy to improve the nutrition status of vulnerable women. Preliminary evidence is pointing towards increased consumer awareness of OBAASIMA and increased capacity of SMEs to produce nutritious and safe products.

Initially, the OBAASIMA products were launched in two secondary cities in Ghana (Sunyani and Tamale). Currently, the distribution of the products is expanding to three additional cities in Ghana, including the capital city Accra. OBAASIMA recognizes the presence of persistent challenges in secondary cities, such as poverty and limited access to roads, that reduce the availability and accessibility of nutritious foods for vulnerable populations when compared to primary cities. Consequently, the positive impact of the OBAASIMA products is expected to be greater in these secondary cities. This example shows secondary cities' potential in pioneering and scaling such NP models in LMICs. Developing suitable NP models could play a vital role in increasing both the supply and demand for nutritious products, as well as enhancing nutrition literacy in secondary cities.

3.3.2 Participative Urban Agriculture with the AGRUPAR Project in Quito, Ecuador

Urban agriculture can offer improved access to nutritious foods (e.g., fruit, vegetables, dairy) and provides a source of income and employment. As found in a study by Zezza and Tasciotti, urban farming improved dietary diversity in ten out of fifteen analyzed countries (Zezza and Tasciotti 2010). In Quito, Ecuador, the Participative Urban Agriculture Program AGRUPAR targets the most vulnerable population of the city through the production of organic food and by promoting urban agriculture as a livelihood and a powerful strategy for improved food security and nutrition.

Throughout the project, both the production and consumption of locally grown food is promoted. The project stimulates subsistence farming and facilitates selling surplus products through organic produce markets (bioferias). The project also facilitates the provision of technical assistance, microcredit and capacity-building to the urban growers and uses applied research to stimulate the use of agroecology. The bioferias play an important role in the stimulation of the consumption of fresh and local foods. In fact, the local markets include an educational component and are located next to health centers to promote the use of free health assessments for citizens and provide information on healthy diets. Ultimately, the project aims to improve food security for the most vulnerable groups, and therefore actively involves female-headed households, the elderly, children, youths, migrants, and the disabled.

The AGRUPAR project received the badge of Special Mention 2016 from the Milan Urban Food Policy Pact under the Food Production category. The program demonstrates the strong potential of urban agriculture in terms of improving food producers' livelihoods, job creation, food and nutrition security and democratization of the food system in secondary cities. The project could serve as a model for other (secondary) cities. However, despite its demonstrated benefits, urban policies and regulations often do not favor urban agriculture. Challenges related to access to inputs and waste management could arise and should be carefully considered. As described earlier, the urban areas of secondary cities are generally well embedded in the surrounding rural areas and the urban-rural connections are strong. As shown in the AGRUPAR project, urban farming has the potential to support short supply chains by actively connecting the supply and demand sides of the food system. Although secondary cities generally experience challenges related to governance, their rapid growth and development could be leveraged and shaped towards an urban agriculture-friendly environment. When this is combined with the provision of technical assistance and capacity-building (as described in the AGRUPAR project), secondary cities become a strategic entry point to further explore possibilities for urban and peri-urban farming.

3.3.3 KUMWE HARVEST – A New Post-Harvest Model for Combating Aflatoxin Contamination in Rwanda

Africa Improved Foods (AIF) is a Kigali-based social enterprise. In collaboration with the Government of Rwanda, AIF's objective is to address malnutrition and stunting by manufacturing high-quality nutritious supplementary foods. These foods are targeted towards vulnerable populations, including children and pregnant women. One of the main challenges AIF has faced is the quality of the local maize supply (a main component of the supplementary foods), particularly with respect to aflatoxin contamination (Nishimwe et al. 2017; Grosshagauer et al. 2019). Kumwe Harvest, a local start-up, developed a logistics model to address the high quantities of rejected maize.

The model in question limits the vulnerability of maize to contamination by enabling AIF to purchase maize from cooperatives, farmer groups and individual farmers in cob form, as opposed to already shelled grains. Improved harvest and post-harvest practices reduce the predominant aflatoxin production on the crops. Aflatoxin contamination has severe implications for food safety, and when vulnerable commodities (such as maize) are dietary staples, exposure to aflatoxins becomes chronic and can lead to long-lasting detrimental health effects (cancer, weakened immune function, stunting). Mycotoxin control is therefore key to ensuring food security. Besides improving food safety, the Kumwe Harvest model has increased the farmers' incomes and saved them time and labor. Additionally, food losses among the maize value chain have been reduced and AIF has benefited from a more reliable supply of high-quality and locally sourced maize. This, in turn, results in the continued production of safe and nutritious supplementary foods that contribute to the nutrition and health outcomes of vulnerable populations.

The Kumwe Harvest model is an example of the beneficial effects of short supply chains on the supply of nutritious foods for consumers, farmers' income and livelihood and food losses. Adapting this model to secondary city contexts could help to overcome the challenges related to infrastructure and logistics and ensure the efficiency of local and short supply chains. Post-harvest logistics models could be applied to nutrient-dense and perishable supply chains (such as fruits, vegetables and dairy) in which significant losses and reductions in quality occur. Consequently, these models could increase the availability and quality of local and nutrient-dense foods in secondary cities.

Sharing experiences and best practices on interventions targeting different dimensions of food systems (such as supply, demand and food security) in secondary cities or comparable contexts is key when aiming to acquire new knowledge on what works (and what does not) in the transformation of city region food systems (De la Peña et al. 2018). When compared to primary or mega-cities, the characteristics of secondary cities appear to provide a favorable environment for implementing and scaling ideas that could convert city region food systems to benefit nutrition and health. However, impact assessments from such projects, interventions and ideas are required to assess if and how these projects could be implemented in secondary cities. Collecting high-quality data and mainstreaming promising models, as described above, offer opportunities for secondary cities to become global game changers in city region food system transformation and improve nutrition and health outcomes for their populations.

4 Conclusion and Call to Action

The world is facing a global malnutrition crisis, and the drivers of co-existing problems such as undernutrition, micronutrient deficiencies and overweight are diverse and complex. To tackle these challenges, multisectoral and context-specific municipal leadership that connects the different sectors is essential to facilitate progress towards global nutrition targets.

While current urban development efforts are mostly targeted towards capital cities, we consider secondary cities in LMICs as a vast untapped potential for altering urban food systems due to their unique embeddedness in rural-urban linkages and the identified challenges related to functioning governance structures and infrastructure. The huge potential for secondary cities is embedded in the opportunity to strengthen and couple the supply and demand of diverse, locally produced and nutritious foods with short chains that benefit both producers and consumers. The identification of secondary cities in LMICs as gamechangers for global food system transformation is in alignment with several initiatives aimed at strengthening food systems and nutrition in urban contexts. As the Milan Urban Pact, FAO Food-for-cities network, CITYFOOD Network, WHO Healthy Cities and other city networks testify, there is no better time than now to focus on secondary cities to ensure that they are fully integrated into the global food system and set the best foundations for their own transformation into more sustainable local food systems. Despite a seeming lack of attention towards secondary cities in Africa and other continents, their physical proximity to rural areas and their smaller spatial scale can no longer be ignored and must be leveraged.

Against the context of many of the challenges raised in this chapter, the Swiss Agency for Development and Cooperation has initiated and provides funding for a project starting in 2021, that aims to improve nutrition in secondary cities in three countries. The Nutrition in City Ecosystems (NICE) project works with selected secondary cities in Bangladesh (Dinajpur and Rangpur), Kenya (Bungoma and Busia) and Rwanda (Rubavu and Rusizi), and places a particular focus on women, youths and vulnerable groups in city regions. Key elements of NICE are to strengthen the supply of and demand for agroecologically produced, local and nutritious foods, foster multisectoral governance, and stimulate greater public and private sector engagement in resilient food systems and improved nutrition outcomes. NICE is co-financed and implemented by a Swiss consortium comprised of the Swiss Tropical and Public Health Institute, the Swiss Federal Institute of Technology of Zurich (Sustainable Agroecosystems & Food Processing Groups and World Food System Centre), Sight and Life, and the Syngenta Foundation for Sustainable Agriculture.

NICE aims to achieve its goals by focusing on four outcome areas: (1) participatory governance and systems, (2) the production and availability of agroecological and locally produced foods, (3) knowledge and demand generation for nutritious and agroecologically produced food and (4) policy and advocacy. Consultations with the six selected cities draw attention to several of the challenges outlined above, such as unemployment, social inequality, lack of decentralized governance and financial and human capital and overall difficulties in accessing finance and technology. Moreover, low levels of nutrition literacy and inefficient chains for local supply were identified as bottlenecks to reducing poverty and improving nutrition and health outcomes. The consultations indicated a high level of support from relevant stakeholders within the cities for working collaboratively towards solutions. The cities and consortium look forward to sharing evidence and experiences from the NICE project in the forthcoming years, as well as creating linkages with the International Mayor Summit for peer-learning among cities and making the case to include a secondary cities' food system angle in the summit.

Acknowledgements The authors acknowledge the leadership of the cities of Dinajpur and Rangpur in Bangladesh, Bungoma and Busia in Kenya, and Rubavu and Rusizi in Rwanda, and of the stakeholders in these six cities that have engaged in consultations with the forthcoming Swiss Agency for Development and Cooperation initiated Nutrition in City Ecosystems (NICE) project during its inception and helped to shape the discussion in this chapter. The comments provided by Karin Gross from the Swiss Agency for Development and Cooperation in an earlier version of this chapter are also acknowledged.

References

Belletti G, Marescotti A (2020) Short food supply chains for promoting local food on local markets. United Nations industrial development organization

Blay-Palmer A, Renting H, Dubbeling M (2015) Understanding the city region (CRFS) food system: planning for a more food secure and resilient city

Blay-Palmer A, Santini G, Dubbeling M et al (2018) Validating the City region food system approach: enacting inclusive, transformational city region food systems. Sustainability 10:1680

Borsellino V, Schimmenti E, El Bilali H (2020) Agri-food markets towards sustainable patterns. Sustainability 12:2193

Cardoso RV, Meijers EJ (2017) Secondary yet metropolitan? The challenges of metropolitan integration for second-tier cities. Plan Theory Pract 18:616–635

De la Peña I, Garrett J, Gelli A (2018) Nutrition-sensitive value chains from a smallholder perspective: A framework for project design. IFAD. Report No. 30

Dubbeling M, Santini G, Renting H et al (2017) Assessing and planning sustainable city region food systems: insights from two Latin American cities. Sustainability 9:1455

FAO, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. FAO, Rome

Global Nutrition Report (2020) 2020 global nutrition report: action on equity to end malnutrition. Development Initiatives, Bristol

Goodall B (1987) The penguin dictionary of human geography. Puffin Books, London

Grosshagauer S, Milani P, Kraemer K et al (2019) Inadequacy of nutrients and contaminants found in porridge-type complementary foods in Rwanda. Matern Child Nutr 16:Article e12856

Haysom G, Fuseini I (2019) Governing food Systems in Secondary Cities in Africa. University of Cape Town: African Centre for Cities, Cape Town

Nishimwe K, Wanjuki I, Karangwa C et al (2017) An initial characterization of aflatoxin B1 contamination of maize sold in the principal retail markets of Kigali. Rwanda Food Control 73:574–580

Parkinson M, Meegan R, Karecha J (2015) City size and economic performance: is bigger better, small more beautiful or middling Marvellous? Eur Plan Stud 23:1054–1068

Pieterse DE, Parnell S. Africa's urban revolution. Zed Books Ltd, London; 2014

Pieterse E, Parnell S, Haysom G (2018) African dreams: locating urban infrastructure in the 2030 sustainable developmental agenda. Area Dev Policy 3:149–169

Ravallion M (2002) On the urbanization of poverty. J Dev Econ 68:435–442

Roberts H (2014a) The systems of secondary cities: the neglected drivers of urbanising economies [Internet]. Washington, DC: World Bank Group [cited 2021 Mar 11]. Report No.: 89861. Available from: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/400881468181444474/The-systems-of-secondary-cities-the-neglected-drivers-of-urbanising-economies

Roberts B (2014b) Managing systems of secondary cities: policy responses in international development. Cities Alliance, Brussels

Ruel MT, Garrett JL, Yosef S (2017) Food security and nutrition: growing cities, new challenges. IFPRI Book Chap:24–33

Satterthwaite D (2007) The transition to a predominantly urban world and its underpinnings. IIED, London

Swilling M, Annecke E (2012) Just Transitions: Explorations of Sustainability in an Unfair World – United Nations University [Internet]. [cited 2021 Apr 23]. Available from: https://unu.edu/publications/books/just-transitions-explorations-of-sustainability-in-an-unfair-world.html#overview

United Nations, Department of Economic and Social Affairs, Population Division (2014) World urbanization prospects: the 2014 revision. Report No.: ST/ESA/SER.A/366

United Nations, Department of Economic and Social Affairs, Population Division (2018) World urbanization prospects: the 2018 revision. Report No.: ST/ESA/SER.A/420

Zezza A, Tasciotti L (2010) Urban agriculture, poverty, and food security: empirical evidence from a sample of developing countries. Food Policy 35:265–273

Part IV
Actions for Sustainable Food Production and Resource Management

Boost Nature-Positive Production

Elizabeth Hodson de Jaramillo, Urs Niggli, Kaoru Kitajima, Rattan Lal, and Claudia Sadoff

Definition
Nature-positive food systems are characterized by a regenerative, non-depleting and non-destructive use of natural resources. This is based on stewardship of the environment and biodiversity as the foundation of critical ecosystem services, including carbon sequestration and soil, water, and climate regulation. Nature-positive food systems refer to the protection, sustainable management and restoration of a productive system. Finally, nature-positive food systems cover the growing demand for food in a sufficient way and include sustainable and healthy nutrition.

E. Hodson de Jaramillo (✉)
School of Sciences of the Pontificia Universidad Javeriana, and member of Inter-American Network of Academies of Sciences (IANAS), Bogotá, Colombia
e-mail: ehodson8@outlook.com

U. Niggli
Research Institute of Organic Agriculture (FiBL), Frick, Switzerland

K. Kitajima
Kyoto University Graduate School of Agriculture, Kyoto, Japan

R. Lal
CFAES Rattan Lal Center for Carbon Management and Sequestration, Ohio State University, Columbus, OH, USA

C. Sadoff
Consultative Group on International Agricultural Research,
Washington, DC, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_17

1 Introduction

This chapter provides a high-level overview of evidence in favor of nature-positive food systems, discussing opportunities and challenges associated with sustainable, efficient agricultural production with a view towards concrete policy suggestions. The aim is to present these complex issues comprehensibly and impartially, so that proposed actions are science-based, solution-oriented, applicable, and restorative, balancing trade-offs and optimizing available synergies.

2 What Do We Want to Achieve?

The primary objective of the Food Systems Summit 2021 (FSS 2021) is to achieve multiple Sustainable Development Goals (SDGs) through internationally coordinated actions across the food system chain (production, distribution, and consumption). More concretely, the overall goal is to provide healthy and nutritious food to all people, while creating livelihood opportunities and reducing the negative environmental, climate, and health impacts associated with food systems. The Five Action Tracks of UNFSS 2021 will explore achievable means to: (1) ensure access to safe and nutritious food; (2) shift to sustainable consumption; (3) boost nature-positive production; (4) advance equitable livelihoods; and (5) build resilience to shocks and stress. Here, as a brief chapter on the Action Track 3 of the Food Systems Summit 2021, the focus is on food production systems, primarily on land. Food systems in water, whether at sea or in aquaculture, are equally important, since fish and seafood help to assure healthy diets. This aspect of food systems is dealt with in a planned separate evidence-based Brief for the Scientific Group for the Food Systems Summit.[1]

The current global food production system is the result of 100 years of successful scientific and technical innovation. Yields of agricultural crops have increased more than ever before in human history, with sharp increases in production efficiency per area and per labor unit. Resultantly, the twentieth century has seen an increase in the production of food greater than the growth of the global population. However, this development entails considerable trade-offs. It negatively impacts climate stability and ecosystem resilience. Scientific assessments by IPCC (2019) and IPBES (2019) have concluded that many aspects of current food production systems drive degradation of land productivity, water resources and soil health, as well as biodiversity loss at multiple spatial scales, ultimately compromising the sustainability of food production systems. The IPCC Special Report on Climate Change and Land (IPCC 2019) has comprehensively laid out the ways in which food systems, as they currently function, undermine our ability to feed the global population projected to be 10 billion by 2050. Another report, from IPBES (2019), shows that one million

[1] Researchers who are part of the Blue Food Assessment (BFA; https://www.bluefood.earth/).

species are threatened with extinction, which impacts human well-being associated with biodiversity, indicating that agriculture, as a key driver of deforestation and the depletion of ocean resources, is responsible for a significant part of this biodiversity crisis. Similarly, the latest Living Planet Report (WWF 2020) revealed that the most important direct driver of biodiversity loss in terrestrial systems in the last several decades has been land use change – primarily, the conversion of pristine native habitats (forests, grasslands and mangroves) into agricultural systems – while a massive percentage of the oceans have been subject to overfishing. Meanwhile, in freshwater ecosystems, biodiversity loss as a result of food production has increased by 50%. Agriculture accounts for some 70% of freshwater withdrawals worldwide and contributes to water pollution from agrochemicals, organic matter, drug residues, sediments and saline drainage into water bodies (Mateo-Sagasta et al. 2018).

The degradation and fragmentation of natural and semi-natural ecosystems is known to increase the risk of emergence and spread of zoonotic diseases such as Ebola, HIV, SARS and Covid-19. As the habitat loss of wild animals and an overall loss of biodiversity, in addition to contact possibilities of wild animals with large livestock populations, become greater, risks of zoonosis increase (Keesing and Ostfeld 2021). Humans depend on the stable and adaptive interaction among plants, microorganisms and life-support systems such as water and soil. Hence, we need a radical transformation of current food systems that tend to disrupt these beneficial interactions. Such transformation must encompass all relevant environmental and socio-economic elements affecting the environment, people, inputs, processes, infrastructures, institutions and all activities that relate to the production, processing, distribution, preparation, consumption, and waste-disposal of food (see Action Track 1, Bortoletti and Lomax 2019; HLPE 2014).

The need for a comprehensive approach in nature-positive food systems is also recognized through the development and promotion of various interconnected and complementary elements, such as the ten elements of agroecology (FAO 2018):

- Diversification and resource use efficiency, including local varieties to protect food security; increasing productivity and improving nutritional balance through the consumption of diverse kinds of cereals, pulses, fruits, vegetables and animal source proteins; intercropping and crop rotation practices for resource efficiency.
- Increased resource efficiency through innovative practices to produce more with fewer external resources and create synergies among the system components; recycling biomass, nutrients and water to reduce external resources; reducing costs and negative externalities.
- Fostering synergies and promoting multiple ecosystem services to increase resilience: e.g., biological nitrogen fixation in intercropping or rotations reduces the need for external fertilizer and contributes to soil health and climate change mitigation.
- Recycling of nutrients, biomass, and water: minimizing waste and pollution with lower economic and environmental costs.
- Improving resilience through crop-system diversification: maintaining a functional balance so that production systems can tolerate pests and diseases or reduce

the magnitudes of pest outbreaks. With diversification, producers reduce their vulnerability, because they will have several options in case any product fails.
- Promoting the acceptance and implementation of innovations through the promotion of participatory processes for sharing knowledge and co-creating solutions to local challenges.
- Protecting human and social values and improving rural livelihoods, where dignity, equity, inclusion, and justice are an integral part of sustainable food systems, trade, and employment. Since culture and food traditions play a central role in society and in shaping human behavior, they are closely tied to landscapes and food systems.
- Fostering responsible and effective governance at the local, national and global levels, maintaining the transformation processes for sustainable FS. These include incentives for ecosystem services.
- Supporting innovation for circular and solidarity economies within the planetary boundaries and reconnecting producers and consumers as the basis for inclusive and sustainable development. Here, local markets and local economic development are key, while circular economies can help to tackle the global food waste challenge, making food value chains more resource-efficient at every level.

The global community of policymakers, as well as actors along the entire food chain, supported by citizens, must jointly transform the current "net-nature-negative" into "nature-positive" situations at the global scale, by developing and applying effective and efficient incentives. This means fostering and enhancing positive practices already in existence, while reducing impacts from negative practices at the landscape level. Such practices are innovations in soil and water management, land use planning, biodiversity conservation, circular economy approaches, new science and technologies in molecular biology and plant breeding, alternative protein sources, and digital tools for the management of agriculture and land and natural resources. In promoting these practices, the boosting of nature-positive food systems will put the global society on a pathway to a more resilient future and sustainable well-being in line with the Building Back Better Initiative of the United Nations (Mannakkara et al. 2019). Food, feed and fiber production must support biodiversity, restore soils, protect freshwater supplies, increase water security, withdraw carbon from the atmosphere and store it in the terrestrial biosphere (i.e., soils, trees and wetlands), create employment, increase food security, and enhance climate resilience and social stability. In response to the Covid-19 pandemic, the necessity of changing the production systems so as to be more sustainable and circular is all the more urgent. Simultaneously, the current crisis provides a unique opportunity to challenge the perceived dilemma between economic growth and environmental stability.

3 What Do We Mean by Nature-Positive Food Systems?

Nature-positive food systems globally meet the fundamental human right to healthy food, while operating within boundaries that limit the natural resources available for sustainable exploitation (Steffen et al. 2015). Using the concept of a safe operating

Table 1 Scientific targets for six key Earth system processes and the control variables used to quantify the planetary boundaries

Earth system process	Control variable	Boundary (uncertainty range)
Climate change	Greenhouse gas (CH_4 and N_2O) emissions	5 Pg of carbon dioxide equivalent per year (4·7–5·4)
Nitrogen cycling	Nitrogen application	90 Tg of nitrogen per year (65–90[a]; 90–130[b])
Phosphorus cycling	Phosphorus application	8 Tg of phosphorus per year (6–12[a]; 8–16[b])
Freshwater use	Consumptive water use	2500 km^3 per year (1000–4000)
Biodiversity loss	Extinction rate	Ten extinctions per million species-years (1–80)
Land-system change [?]	Cropland use	13 million km^2 (11–15)

Source: Willett et al. (2019)
[a]Lower boundary range if improved production practices and redistribution are not adopted.
[b]Upper boundary range if improved production practices and redistribution are adopted and 50% of applied phosphorus is recycled.

space for food systems, the EAT-Lancet Commission has prepared an outline of human health and environmental sustainability for global food systems with clear scientific targets (Willett et al. 2019). They described six central environmental dimensions for planetary health, using the planetary boundaries concept for food production to ensure a stable Earth system (Table 1). These dimensions take into account the environmental limits within which food systems should jointly operate, ensuring that a broad set of universal human health and environmental sustainability goals are achieved (Willett et al. 2019) (Fig. 1).

Cohen-Shacham et al. (2016) have defined the term Nature-based Solutions (NbS), an overall concept that we use for nature-positive food systems accordingly. It is based on three pillars: "protect," "sustainably manage" and "restore" (agro) ecosystems.

3.1 *First Pillar: Protect Natural Systems and Protected Areas from New Conversions for Food Production, and Save and Set Aside Some Land and Water to Be Given Back to Nature*

Any further conversion of natural ecosystems and undisturbed habitats should be halted. Land use change, especially the loss of forests and trees in the landscape through farming and the expansion of intensive agriculture and large livestock populations, is a critical driver of risks related to exposure to emerging infectious diseases (Shaw et al. 2020) and destabilizes the safe operating space of humanity (Steffen et al. 2015). Exploiting natural land for agriculture can lead to drastically increased emissions of greenhouse gases (GHGs) and losses of biodiversity (Kiew

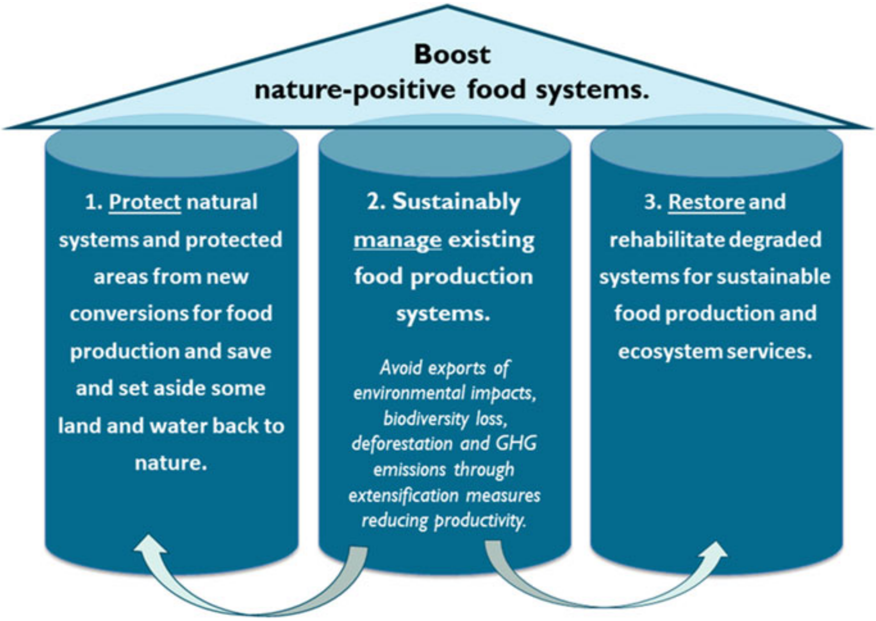


Fig. 1 The three pillars of nature-positive food systems

et al. 2020; Dargie et al. 2017). Important drivers are high-income countries, which import large amounts of food and feed from unsustainable farming systems in low-and middle-income countries. As this generates a significant incentive for such unsustainable activities, importing countries should also take responsibility for protecting lands elsewhere – in a globalized world, these also constitute part of their food system.

Likewise, agriculturally marginal lands that are areas of high biodiversity (e.g., steep lands, shallow soils, wetlands, peatland) must be protected. As poverty and lack of knowledge are significant drivers of habitat destruction, protection of such natural systems requires actions that radically change societies and economies. Many smallholder farmers are locked into low yields and highly degrading livestock practices (Garrett et al. 2017). These practices persist because of historical legacies, political instability, market failures, cultural lock-in and fire risks. However, very importantly, the preservation of natural ecosystems depends on how successfully humanity can manage existing production systems in a productive and sustainable way. The three pillars interact directly and indirectly, with actions in one place sometimes having intended and unintended consequences in remote places getting more food from less land (see pillar 2) enables restoring degraded farmland (see pillar 3), safeguarding natural ecosystems and returning some land back to nature (pillar 1). Setting aside land and water is made possible by more efficient production on existing agricultural land. Extensification measures that compromise yield on productive land export negative externalities through the importing of food.

3.2 Second Pillar: Sustainably Manage Existing Food Production Systems

Nature-positive food systems are characterized by a regenerative, non-depleting, and non-destructive use of natural resources (Lal 2020). This is based on biodiversity as the foundation of ecosystem services – particularly soil, water, and climate regulation – that farmers manipulate with external inputs and with human or mechanical forces. For terrestrial food production, healthy soil and clean water are the essential means by which we produce healthy food (Lal 2017). Equally essential are pollinators, on which 70% of crops depend (Reilly et al. 2020). These will be the most critical indicators of success in producing nature-positive outcomes. Here, as always, the need is to work towards food systems that deliver net-positive ecosystem benefits.

Nature-positive production hinges upon a circular bioeconomy, in which local and regional integration of production, consumption and the use of all residues are integrated and balanced. It aims for strong innovation, but balances different types of innovation – the social, environmental and technological – in an equal manner. Production systems are driven by the pure food needs of a growing population, which means that society needs to focus on sustainable dietary patterns (reduced food waste and reduced reliance on cereal-based meat and dairy products) and reduced production of energy crops on arable land. As a consequence, the efficiency narrative ("produce more from less") must be complemented by the sufficiency narrative ("consume moderately") to avoid rebound effects (Müller and Huppenbauer 2016). The nature-positive food system recognizes the fact that the health of soil, plants, animals, people, ecosystems, and, ultimately, the planet is one and undividable (Lal 2020). A transformation of agriculture towards nature-positive food systems depends, first of all, on actions at the **landscape** scale. Here, the ethical and political framing of issues, financial and infrastructural incentives, and general innovation strategies and the degree of participation of stakeholders and actors are designed and decided upon. The dietary behavior of the population at large, and the way that food is handled, is also an issue that shapes the landscape. The second level is the **management practice** and **production technology** of the entire value chain that must be linked to the objectives of improving and maintaining non-commodity ecosystems services in productive agriculture. In nature-positive production systems, the technologies used are consistent with the salient and contextual territorial, cultural and socio-economic conditions, and are compatible with natural processes. Currently, a significant share of food production fails to meet these criteria. Nonetheless, some farming systems and technologies already perform better in this respect than others. These approaches include agroecological practices, regenerative conservation agriculture, integrated nutrient and pest management, river basin management, sustainable groundwater management, agroforestry and agro-silvo-pastoral systems and sustainable pastoralism in the rangelands. The development and use of bio-inputs such as bio-fertilizers and bio-protectants is another environmentally-friendly approach, combined with integrated crop management, intercropping and cover cropping. Some strategies include precision agriculture and climate-smart agriculture. Several specific programs for farmers target individual improvements, such as introducing semi-natural habitats on the farm, applying no-till arable cropping, or strictly reducing the use of pesticides and nitrogen fertilizers.

Many examples of traditional food production systems involving landscape-level management exist. Many rural settlements in Asia and Africa have sustained their productive landscapes for centuries: for example, "satoyama" in Japan (Kobori and Primack 2003; JSSA 2010; Indrawan et al. 2014). Likewise, sustainable socio-ecological landscapes involving a variety of traditional approaches have been continuously fine-tuned by people in response to the climate and soil characteristics of their lands. These provide hints for low-cost and sustainable watershed management, which could be scaled up with modern technologies involving optimal and sustainable land use design.

3.3 Third Pillar: Restore and Rehabilitate Degraded Systems for Sustainable Food Production and Ecosystem Services

One-third of global land area is degraded (FAO 2015), comprising 47% of forests and 18% of cropland (Bai et al. 2008). There are approximately 2 billion hectares of degraded and degrading lands in the world. Resultantly, the potential for restoration or rehabilitation is huge, and, as such, it is key to avoiding new conversion of natural habitats and ecosystems. Here, specific technical measures must be taken, depending on the site, socio-economic and cultural conditions.

One option is targeted at rewilding natural ecosystems at the landscape level to restore soil health and enhance biodiversity and ecosystem services. Such activities often have additional benefits, as they could increase resilience. Another option involves rehabilitating agricultural productivity, and this is equally important. Both of these forms of land restoration can help sequester carbon (IPCC 2019). In this context, ideal results typically occur when scientific information and traditional, local knowledge cooperate in finding solutions. The potential offered by such partnerships in helping to avoid new conversion of natural habitats and ecosystems and in reverting some agriculturally marginal land back to nature is enormous (Lal 2021). Specific measures must be taken depending on the local bio-physical, socio-economic and cultural conditions (including pillar 1 measures). In addition, intensive cooperation and benefit-sharing with all actors and stakeholders involved in a region or site must be ensured. The development and use of adequate financial mechanisms and public policies must be based on their social, environmental and economic returns. And research must focus on new knowledge and technologies to restore land and soils, in collaboration with food producers and other actors in the landscape.

4 Challenges of Nature-Positive Food Systems

The transition to nature-positive food systems is slowed or made impossible by numerous agronomic, economic and social challenges, which are compounded by deficits in knowledge systems.

4.1 Agronomic Challenges

Yield Reductions Related to Nature-Positive Production
Replacing conventional systems or subsistence farming in marginalized conditions with diversified nature-positive production can increase the overall output of farms (Pretty et al. 2018). However, on average, and particularly in temperate zones with highly intensive agriculture, conversion to nature-positive systems typically results in a reduction of yields that must be compensated by cost savings, higher product prices, or other support measures, as to ensure the economic viability of the farms. This is particularly true in the case of organic farming (Knapp and van der Heijden 2018; Seufert et al. 2012), but much less distinctive for integrated production systems with restrictions on plant protection and nitrogen fertilization (Morris and Winter 1999). The trade-off between high yields and biodiversity-rich, non-commodity ecosystem services, such as soil nutrient cycling, soil carbon sequestration, pollination and indirect pest control, is the greatest challenge at present.

4.2 Economic Challenges

Higher Labor Demand
Nature-positive food systems have a high initial demand for labor and can be more labor-intensive in general. This can be a serious constraint when manual labor cannot be substituted by mechanized labor. In situations where mechanization is possible, the investment required can also be a hurdle. However, provided that work conditions are decent, this can also be an opportunity for job creation.

Higher Transaction Costs
As nature-positive food systems are more diverse, they tend to yield a greater number of crop or livestock products with a smaller volume of each product. This can limit market and processing opportunities and requires high levels of knowledge and risk taking/experimentation. Furthermore, farmers may have to carry the financial and knowledge burden of identifying and applying alternative inputs. A number of nature-positive practices depend on collective action across a landscape scale, involving multiple farms and a range of actors. This requires higher levels of coordination and increases transaction costs.

Failed Valorization of Sustainability Throughout the Value Chain
Healthy, safe and sustainably produced raw materials and food are desired by policymakers and citizens worldwide. However, these additional services are not rewarded in the value chain, neither at the farm level, nor at the level of processing, trade and consumption. Cheap food continues predominantly to be purchased because consumers have other priorities in their household budgets or because they cannot afford something better.

A major challenge is that the monocropping of calorie-dense food commodities offers large scale-economies and lower unit costs, as opposed to the more diversified production of a portfolio of food commodities needed for a healthy diet.

4.3 Political Challenges

Policy Incoherence.
Current agricultural and trade policies, including subsidy schemes, still favor the intensive, export-oriented production of a few crops, and there are still incentives for the use of fossil fuel and chemical inputs in place (Eyhorn et al. 2019). Furthermore, different governmental policies are contradictory and conflicting, especially agriculture, environmental, health, trade and science/education policies. Finally, the transition towards nature-positive farming is decelerated by past decisions made by farmers, such as investment in large machines, skills, and retail relationships (HLPE 2019, IPES-Food 2016). A return on those investments is more difficult when farmers shift their strategy towards nature-positive food systems. Therefore, the reorientation of governments towards more ecological and social sustainable goals is always delayed.

4.4 Deficits Along Agricultural Knowledge Systems

Weak Knowledge and Advisory Systems
Public and private investment in research on nature-positive food systems has been substantially lower in comparison to other innovative approaches, which results in significant and persistent knowledge gaps (HLPE 2019). A systems-oriented, transdisciplinary, and long-term field research approach is clearly lacking (Edwards and Roy 2017). Therefore, there is a disconnect in the knowledge and advisory systems required to support nature-positive food systems and build the capacity of actors.

There is also a shortage of inter- and transdisciplinary research on nature-positive food systems that takes into account the context specificity of the approaches. Nature-positive system thinking and solutions are not sufficiently well integrated into the curricula of universities and farming schools.

4.5 Call for Actions to Successfully Cope with Trade-Offs and Scaling Up Nature-Positive Food Systems

There are several structural lock-ins that keep the current unsustainable food production system in place. These create a set of feedback loops that reinforce this system and include investments and policies that create path dependency, such as the purchasing of expensive equipment or subsidies for chemical pesticides, export orientation, the expectation of cheap food, compartmentalized and sectoral short-term thinking, certain discourses about feeding the world and a sole focus on production volumes and measures of success (looking at single crops) (IPES-Food 2016). Other typical lock-ins that reinforce the current system are the concentration of power in the food chain and institutional, agricultural research and technological lock-ins (WWF 2016). Therefore, a systematic change towards nature-positive food systems requires a fundamental reorientation of many societal actors and a realignment of the cooperation among them. The inclusion of local actors, particularly of the most vulnerable voices, in decision-making will lead to more effective solutions. The nine actions can provide guidance to ensure an integrated, systemic approach.

Action 1: Increase Policy Coherence and Strengthen Adequate Governance Nature-positive food systems require a different type of government support that goes beyond incentives such as income-oriented subsidies or those for particular inputs or unspecific marketing actions. Further research is therefore needed to better understand which government policies can support nature-positive food systems and the multi-functionality of agriculture more generally. Importantly, more information is needed on the public and private costs of sectoral approaches that result in contradictory and conflicting policies.

The decisive level in fostering transition is the landscape. This is the level where actors and innovations come together and where food producers' strategies interact with other users of the landscape, with governance policies and with natural systems. Sustainability at the landscape level is essential for water and soil management. The health of upland watersheds, for example, can be critical to water regulation and recharge, and the stabilization of soils. For this reason, the landscape approach has been promoted by agencies such as the Organization for Economic Co-operation and Development and the European Union as the scale at which it is most meaningful to align policies and incentives towards nature-positive outcomes. Landscape-level regulations and incentives, as well as infrastructure planning and other intervention strategies, should be designed and decided at this level, preferably through inclusive, participatory processes and institutions. An important element in these interventions is therefore not just the creation and sharing of knowledge, technologies and practices that better link to the objectives of improving and maintaining non-commodity ecosystems services, but, importantly, the governance systems that are driving certain technologies, processes or behaviors.

Landscape-level governance is critical. Governance frameworks – including, for example, regulations, incentives and extension programs – influence farmers everywhere and play a crucial role in the adoption of good farming practices. In some countries, these governance systems are quite sophisticated cascading systems that are clearly targeted at promoting sustainability. Laws and regulations on environmental, human and animal health, animal welfare or land management are effectively implemented so that farmers who are found to be in violation can be fined or excluded from related government support and services. Farmers receiving income support have to respect additional environmental standards, such as maintaining soil quality or protecting groundwater, landscape and biodiversity (cross-compliance). A powerful incentive for the adoption of sustainable agricultural practices and, especially, nature-positive production are payments for ecosystem services (Piñeiro et al. 2020).

However, in other countries, governance institutions may not administratively align with landscape levels or may not be adequately empowered or well-resourced to implement similar efforts. In these cases, in parallel to broader governance strengthening, nature-positive practices can be more immediately advanced through mechanisms that include support for relevant applied research and extension activities, land conservation and restoration efforts, education and training, facilitation of access to credit and insurance, and legal and administrative reforms to secure land tenure and enhance farmers' willingness to invest in sustainability.

Unfortunately, the transition towards nature-positive farming can be decelerated by incentives for food producers to invest in large machines, skills, and retail relationships that are economically attractive only if applied in unsustainable farming systems (HLPE 2019, IPES-Food 2016). Similarly, large subsidies on agricultural water promote unsustainable water usage, while subsidies on pesticides and fertilizers can encourage overuse, resulting in degraded water quality. These lock-ins make it difficult for producers to shift their strategy towards more nature-positive food systems.

Additional to the efforts and advances of several agencies connected with UN and CGIARs, it is essential to coordinate and integrate several relevant initiatives that are ongoing globally, such as Water, Land and Ecosystems (https://wle.cgiar.org), EarthBioGenome (https://www.earthbiogenome.org), Future Food Systems, Australia (https://www.futurefoodsystems.com.au), Next Generation Food Systems (https:// www.ucdavis.edu/news), DivSeek International Network (https://divseekintl.org), CropBooster-P (https://www.cropbooster-p.eu), EMPHASIS –ESFRI- (https://emphasis.plant-phenotyping.eu), and Living Soils of the Americas initiative (https://iica.int), among others.

Action 2: Improve Sustainable Soil Management

Soil degradation, being exacerbated by climate change, along with land misuse and soil mismanagement, is worsening the malnutrition that is already affecting more than 2 billion people globally (Lal 2009). Restoration and sustainable management of soil are also critical to enhancing and maintaining ecosystem services, identifying and implementing nature-positive agriculture, producing more food from less land,

and advancing the UN SDGs (e.g., SDG#2, Zero Hunger, SDG #13, Climate Action, SDG #15, Life on Land) (Lal 2018). Developing resilient food production systems for local consumers is especially important during the Covid-19 pandemic, promoting food production through urban agriculture and home gardening (Lal 2020). Achieving the targets of land degradation neutrality, adopted by the United Nations Convention to Combat Desertification, will also improve the nutritional quality of the food. Translating into action the concept of "the health of soil, plants, animals, people and environment is one and indivisible" through restoration of degraded soils and adoption of nutrition-sensitive agriculture will also improve human health and well-being (Lal 2020). Soil health and its capacity to generate ecosystem services must be enhanced through sequestration of soil organic matter content by adopting a system-based conservation agriculture, enriching the soil by planting nitrogen-fixating plants or adding N fixating microorganisms, mycorrhizae, growing cover and inter-crops, diversifying crop sequences, and integrating crops with trees and livestock in agro-silvopastoral systems (Jensen et al. 2020; Smith et al. 2012). Adoption of nature-positive practices that enhance soil organic matter content can reduce dependence on chemicals, irrigation, tillage and other energy-intensive inputs, and would reduce losses of nutrients and water, enhance eco-efficiency and sustain productivity. Sequestration of soil organic carbon has been recommended by several international initiatives, such as 4p1000, adopted by COP21 in Paris in 2015, Adapting African Agriculture by COP22 in Marrakech in 2016 (Lal 2019), Platform on Climate Action in Agriculture by COP25 in Madrid/Santiago and the international initiative for the Conservation and Sustainable Use of Soil Biodiversity under the Convention on Biological Diversity.

Nature-positive production implies adaptation to climate change and the protection and enhancement of soil health and food security. This can be achieved through bioeconomy strategies with the approach of integrated cycles in whole value chains to increase efficiencies by recycling resources through diverse products and coproducts in animal, plant, and microbial systems. The goal is to promote resource efficiency while enhancing productivity, and increase resilience in crop systems able to cope with biotic and abiotic stresses.

Action 3: Boost Knowledge and Innovation for Nature-Positive Food Systems
The dramatic increase in food demand projected for 2050 requires a broad-based environmental, social and technological innovation strategy; one that is supported by farmers, scientists, food value chain actors and citizens. Innovations must not be hindered if they serve the goals of nature-positive food systems. **Ecological innovations** or optimizations are driven by biodiversity and ecosystem functions. Most fundamentally, soil fertility is vital to plant growth factors, such as mineralization of nutrient elements, water supply, aeration and loosening of the root zone and rooting depth. **Social innovations** include those in the socio-economic space, such as new ideas for the governance of landscape-level networks, innovation of institutions, novel approaches to building farmers organizations, creative use of finance to support these transitions, and co-operations in marketing and food distribution such as community-supported agriculture (CSA), as well as new modes of learning

and capacity-building. **Technological innovations** encompass digitalization, the smart use of data for prediction and prevention, various breeding techniques, production of bio-inputs or the separation, processing and recycling of organic waste.

Innovations across all of these categories can be mutually reinforcing, particularly when they are embedded in the systems approach of nature-positive food systems. Therefore, strict criteria for the choice of technological innovation must be applied consistently with this paradigm. Centrally, these include requirements for the protection of biodiversity, reduction of greenhouse gas emissions, improvement of biological and physical soil quality, human well-being, equitable access regardless of farm size and gender, and compatibility with traditional knowledge. In light of this, technological innovations must always be sensitively integrated with local cultural and affiliated knowledge contexts, under the aegis of an overarching systems approach.

Already, global agriculture is undergoing major transformations through this kind of technology convergence, such as new digital technologies and the use of artificial intelligence to optimize agricultural production processes. Drones and advanced analysis of image data can identify pests and diseases in real time and provide a powerful toolbox for all farmers, regardless of farm size. With improved access to biotic (pests and diseases) or physical (meteorological, SAT early warning systems) information and remote sensing, producers can use their mobile phones to strengthen their practices, making the best use of resources and inputs. Digitalization has been developed on and for broad-acre farms. The technology can work flexibly and on a small scale. It can intervene with pinpoint accuracy, and the devices become smaller, lighter and work in coordinated networks. The software makes it possible to carry out operations in small spatial and temporal structures in an efficient, labor-saving and energy-saving way. Depending on how the algorithms are programmed, networking and diversity emerge. Further developments also promise to make such technologies affordable for small and medium-sized farmers.

Parallel to digital technologies, novel bio-inputs provide a valuable supplement to NbS (Syed Ab Rahman et al. 2018; Liu et al. 2018; Kavino and Manoranjitham 2017). It is crucial to promote and strengthen studies on plant microbiome, which comprises all micro- and macro-organisms living in, on, or around the plant, including bacteria, archaea, fungi, and protists for food security (d'Hondt et al. 2021). We recommend that greater emphasis be given to the development of green technologies that deploy indigenous perennial species, tapping into the symbiotic relationships that naturally exist between microbes and plant species (Hohmann et al. 2020). In the African context, for example, it has already been established that the combined use of many different beneficial microorganisms (producing multi-strain or multi-bacterial inoculants) can greatly boost nature-positive production (Adedeji et al. 2020).

A similar role can be played by bio-stimulants from land and marine/ocean resources (e.g., Kelpak from seaweeds, molecules such as lumichrome, riboflavin, and nodulation factors from soil rhizobia and other mutualistic microbes), which replace chemical fertilizers in promoting crop plant growth and increasing yields. Plant protectants, such as botanicals (plant extracts), are currently under-exploited, but we can look to future scientific and technological developments to increase the portfolio of bioproducts developed from the local biodiversity, in keeping with a circular economy approach.

Maintaining and increasing biodiversity in agricultural settings is key to fostering and expanding nature-positive food systems, and can yield additional benefits for consumers. For example, local cultivars that are often more nutritious than common staples and better adapted to local climate and soil conditions (Leclère et al. 2020). Subjecting these to conventional and molecular breeding programs, including gene editing, capitalizes on their inherent advantages, improving productivity and/or tolerance to adverse biotic or abiotic conditions. In the context of climate change, these methods may be critical for maintaining beneficial agrobiodiversity in the face of new environmental pressures. This underlines the need for advanced knowledge in plant genetic diversity, microbial diversity and interactions, taking into account local climate variability, soils, nutrients, water and contextual environmental impacts.

To conclude, the key to successful innovation in support of nature-positive food systems lies in developing these technologies with the active participation of farmers, consumers, and citizens. This ensures that measures adopted locally are the most suited to their specific conditions and cultures. In the future, the target system, which we have defined as nature-positive, will guide the development of technologies and their use, and not vice versa. At the same time, interdisciplinary approaches are required to make the best use of advances in molecular, sensor, and modeling sciences, which can be used to understand and predict production patterns. The use of multiple phytobiomes will be needed along with integration of molecular, ecological, and evolutionary information to obtain significant models. The outcome of this transformation in research practices should be made accessible to food producers on the ground, building on knowledge and resources that are already locally available. In this way, international and collaborative research and local, contextual knowledge systems are harnessed together in support of the overarching aim to save costs and reduce environmental impact: producing more food and fewer negative externalities (WRI 2018).

Action 4: Adapt and Intensify the Knowledge-Sharing of Farmers, Farm Advisors and Farm Teachers

In regard to immediate actions, understanding of the complexity of nature-positive production can be considerably improved. The scientific knowledge is tremendous, but its integration with the knowledge of farmers, consumers and citizen remains vastly unsatisfactory. The promise of traditional knowledge practiced by indigenous peoples and local communities is still underestimated compared to modern scientific knowledge. This in part reflects the fact that the former remains critically under-documented. In order to stimulate interactions between traditional knowledge and science-driven innovation, greater cooperative work in the context of local farms, including the joint design of experiments, is an effective approach. To interest farmers in long-term solutions, the time lag between action and results, and the risk related to it, could be compensated with financial support during the first few years of transition. For farmers, co-learning activities that prominently include both them and the consumers they serve are important. Scientists and farm advisors should learn to use the power of peer-to-peer learning and collaborative action among and with farmers. These are attractive, fruitful, and satisfying alternatives to providing top-down advice. Here, a complete overhaul of agricultural extension services in terms of capacity issues, incentives and accountability to farmers will accelerate transition. Additionally, innovative approaches, like using vouchers for advisory services, should be promoted. These can be given directly to farmer group associations to source extension services from private providers. A combination of public funding and private delivery, based on the farmers' satisfaction with services provided and the promotion of nature-positive food systems, can be combined with entrepreneurial proficiency. Likewise, ICT use for information and advisory services, in partnership with private providers, should be scaled up.

In light of these proposals, a real revival of agricultural education at universities and farming schools is needed. The complex interdisciplinary concept of nature-positive food systems has to become gradable content in teaching, adaptive experimentation, and locally relevant information exchange. So reformed, the mutual permeability of educational institutions would promote understanding for the transformation of agriculture and its actors. Most of all, public investment in research on nature-positive production should be considerably increased. As nature-positive production requires making complex decisions and coping with uncertainties and trade-offs, as well as accepting higher risks of failure, inter- and transdisciplinary research is a prerequisite.

Action 5: Strengthen Information for Citizens on Sustainable Nutrition and Food Diets The development and scaling-up of nature-positive production is dependent on the transition to sustainable consumption and more plant-based diets. In many countries, market forces determine access to healthy, sustainable and nutritious food (Action Track 1). One aspect of sustainable nutrition means a higher degree of sufficiency or consumer moderation, characterized by a reduction in food wastage. Food wastage varies considerably across different contexts and is influenced by socio-economic and cultural factors. In addition, a significant part of the unavoidable food losses should be reused via a circular economy of feed and food. Furthermore, competition for the scarce resources of arable land and water among food, feed and energy production must be reduced. Global food mass flow models show that, by using arable land primarily for direct human nutrition while maintaining grassland-based dairy and meat production with ruminants, the goals of preserving biodiversity and environmental integrity and securing human energy and protein supply by 2050 could be achieved simultaneously (Schader et al. 2015, Müller et al. 2017). Such changes in human nutrition and eating habits influence and change land use, ultimately reversing the loss of biodiversity (Leclerc et al. 2020), decreasing GHG emissions (Bajželj et al. 2014; Tilmann and Clark 2014) and improving the ecological footprint (Westhoek et al. 2014).

How can arable land be primarily used for human nutrition? Energy production on arable land can be reduced by ending state subsidies for the cultivation of these crops and for the production of biogas. Here, more energy-efficient and economically-viable alternatives to fossil fuel already exist in the form of solar and wind energy (Blankenship et al. 2011). The collective change of individual consumption and eating patterns presents a more difficult challenge. In the first place, it requires better information, dissemination and integration of sustainable nutrition into the curriculum of schools. Therefore, it will be a multi-generational effort. Further activities can include the development of personalized shopping guidance and all kinds of nudging campaigns. Furthermore, levies and taxes on the transport of concentrated feeds or on the consumption of meat could lead to behavioral changes and make plant proteins more attractive. Meat substitutes based on plant components or on animal cells grown in the laboratory are already technically possible, but currently remain prohibitively expensive (Furuhashi et al. 2021). However, less drastic solutions are still open for exploration and adoption. For example, replacing plant protein in animal feed with insects grown on organic waste materials can also be much more climate-friendly than conventional methods (van Huis et al. 2013). More ambitiously, raw materials for processed foods that are still underused, such as algae, would be almost inexhaustible and ecologically less burdensome for human nutrition.

Action 6: Empower Rural Areas by Cross-Farm Co-Operations and through High Local Value Creation Any activities that strengthen rural societies, including through local and regional markets, participatory guarantee systems (PGSs), certification systems for remote markets such as voluntary sustainability standards (VSS), or organic farming can considerably improve farm incomes and livelihoods. There are many successful examples of how this kind of social innovation helps boost nature-positive production. To strengthen territorial development, the value addition to products must take place at the local and regional levels, and so related regional networks must be strengthened.

Nature-positive farming systems usually give rise to a larger number of farm activities and more products that need to be marketed. This is especially true for agroforestry systems, for example, where several layers of food crops and energy plants are grown (Ajayi et al. 2009). Currently, there is a lack of adequate market and processing facilities for smaller volumes, which sometimes also require high levels of knowledge and experimentation. Greater emphasis should therefore be placed on supporting local processing facilities, as well as investment in local training in technologically simpler food processing, quality assurance, and, ultimately, improvement in storage and transport routes.

Nature-positive production systems have a high initial demand for labor and can be more labor-intensive in general, especially for women. This can be a serious constraint when manual labor entails onerous and low-skill work that cannot easily be substituted by mechanized labor. However, at the same time, it offers opportunities for employment, and for the revitalization of rural areas, particularly when labor conditions are decent and financial incentives are re-shaped (Schuh et al. 2019).

Cooperative models of productive relations must therefore be supported so as to mitigate increases in workload.

Action 7: Improve Access to Land, Water and Biodiversity Especially for Women Inadequate and insecure access to and tenure rights for various elements of natural ecosystems (unfortunately, a reality in the global North, as well as the South) increase vulnerability and undermine nature-positive production. Insecure access provides little incentive for food producers to invest in long-term nature-positive production. Land fragmentation, soil degradation, climate change, and large scale water and land acquisition all block the possibilities for nature-positive production, thus increasing the likelihood of environmental degradation.

Women are actively involved in food systems in several fundamental functions, growing and managing crops, livestock, agribusinesses and food retailing, and preparing food for their families. Women and women's groups have been shown to be a critical partner in water and soil sustainable management (https://www.wri.org/blog/2018/10/women-are-secret-weapon-better-water-management). However, very often, they face restrictions that prevent them from participating on equitable and fair terms. The role of women in the transition towards sustainable food systems centrally includes increasing efficiency, changing diets, and improving integrated value chains. Inclusion means not only ensuring their participation and access to benefits, but, more importantly, guaranteeing their empowerment to make strategic life choices (Malapit et al. 2020). Thus, supporting sustainable and efficient food systems requires technologies, practices and policies that ensure women's participation and enhance their resilience.

5 Conclusions

The Calls to Action in this chapter provide an integrated, systemic approach to realigning our food systems for a sustainable, resilient, 'nature-positive' future.

While today's food systems are "net nature-negative," they can and must become "nature-positive." Food systems across the world are driving habitat and biodiversity loss, land and water degradation, and greenhouse gas emissions. These phenomena, in turn, undermine the productivity, sustainability and resilience of food systems. This vicious circle can be broken if we take several fundamental steps to realign our food, feed and fiber production to achieve nature-positive agricultural production at scale. We must strive to: (i) protect natural ecosystems from degradation and conversion, (ii) manage existing production systems more sustainably in support of ecosystem health, and landscape-level resilience, and (iii) restore degraded ecosystems.

This realignment builds on innovations at the landscape level, including soil and water management, land use planning, biodiversity conservation, principles of agroecology and circular economy approaches, new science and technologies in molecular biology and plant breeding, alternative protein sources, and digital tools for the management of agriculture and land and natural resources.

Importantly, shifting food systems from net nature-negative to nature-positive will require not only innovation in technologies and practices, but also changes in food system governance. This entails radical change in policies, investments, incentives, and subsidies that today fail to promote these practices. Nature-positive approaches will need to be integrated into agricultural extension programs, school and college curricula, and vocational educational programs. And they will need to build on broad, inclusive and empowered partnerships – with women, small-farmers, and the private sector, among others – to co-create, promote, and entrench nature-positive innovation.

References

Adedeji AA, Häggblom MM, Babalola OO (2020) Sustainable agriculture in Africa: plant growth-promoting rhizobacteria (PGPR) to the rescue. Sci Afr 9. https://www.sciencedirect.com/science/article/pii/S2468227620302301

Ajayi OC, Akinnifesi FK, Sileshi G, Kanjipite W (2009) Labour inputs and financial profitability of conventional and agroforestry-based soil fertility management practices in Zambia. Agrekon 48(3). https://www. econbiz.de/Record/labour-inputs-and-financial-profitability-of-conventional-and-agroforestry-based-soil-fer- tility-management-practices-in-zambia-ajayi-olu-clifford/10009446486

Bai ZG, Dent DL, Olsson L, Schaepman ME (2008) Proxy global assessment of land degradation. Soil Use Manag 24(3):223–234

Bajželj B, Richards K, Allwood J et al (2014) Importance of food-demand management for climate mitigation. Nature Clim Change 4:924–929. https://doi.org/10.1038/nclimate2353

Blankenship RE, Tiede DM, Barber J et al (2011) Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement. Science 332(6031):805–809

Bortoletti M, J Lomax (2019) Collaborative Framework for Food Systems Transformation. A multi-stakeholder pathway for sustainable food systems. UN environment, p 58. ISBN: 978–92–807-37-3753-0

Cohen-Shacham E, Walters G, Janzen C, Maginnis S (eds.) (2016) Nature-based solutions to address global societal challenges. IUCN, Gland, Switzerland

D'Hondt K, Kostic T, McDowell R et al (2021) Microbiome innovations for a sustainable future. Nat Microbiol 6:138–142. https://www.nature.com/articles/s41564-020-00857-w

Dargie G, Lewis S, Lawson I et al (2017) Age, extent and carbon storage of the Central Congo Basin peatland complex. Nature 542:86–90. https://doi.org/10.1038/nature21048

Edwards MA, Roy S (2017) Academic research in the 21st century: maintaining scientific integrity in a climate of perverse incentives and hypercompetition. Environ Eng Sci 34:51–61

Eyhorn F, Müller A, Reganold JP, Frison E, Herren HR, Luttikholt L, Mueller A, Sanders J, El-Hage Scialabba N, Seufert V, Smith P (2019) Sustainability in global agriculture driven by organic farming. Nat Sustain 2:253–255

FAO (2015) Status of World Soil Resources (SWSR). Food and agriculture organization of the United Nations and inter-government technical panel on soils, Rome, Italy Available at http://www.fao.org/3/a-i5199e.pdf

FAO (2018) The 10 elements of agroecology guiding the transition to sustainable food and agricultural systems. Available at http://www.fao.org/3/i9037en/I9037EN.pdf

Furuhashi M, Morimoto Y, Shima A et al (2021) Formation of contractile 3D bovine muscle tissue for construction of millimetre-thick cultured steak. npj Sci Food 5:6. https://doi.org/10.1038/s41538-021-00090-7
Garrett RD, Niles MT, Gil JDB, Gaudin A, Chaplin-Kramer R, Assmann A, Assmann TS, Ke B, de Faccio Car-valhom PC, Cortner O, Dynes R, Garbach K, Kebreab E, Mueller N, Peterson C, Reis JC, Snow V, Valentim J (2017) Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty. Agric Syst 155(2017): 136–146
HLPE (2014) Food losses and waste in the context of sustainable food systems. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome. http://www. fao.org/3/a-i3901e.pdf
HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome
Hohmann P, Schlaeppi K, Sessitsch A (2020) miCROPe 2019 – emerging research priorities towards microbe-assisted crop production. FEMS Microbiol Ecol 96. https://doi.org/10.1093/femsec/fiaa177
Indrawn M, Yabe M, Momura H, Harrison R (2014) Deconstructing satoyama – the socio-ecological landscape in Japan. Ecol Eng 64:77–84
IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. In: Díaz S, Settele J, Brondízio ES, Ngo HT, Guèze M, Agard J, Arneth A, Balvanera P, Brauman KA, Butchart SHM, Chan KMA, Garibaldi LA, Ichii K, Liu J, Subramanian SM, Midgley GF, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Chowdhury RR, Shin YJ, Visseren-Hamakers IJ, Willis KJ, Zayas CN (eds) IPBES secretariat, Bonn, p 56. https://doi.org/10.5281/zeno-do.3553579
IPCC (2019) Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [PR Shukla, J Skea, E Calvo Buendia, V Masson-Delmotte, H-O Pörtner, DC Roberts, P Zhai, R Slade, S Connors, R van Diemen, M Ferrat, E Haughey, S Luz, S Neogi, M Pathak, J Petzold, J Portugal Pereira, P Vyas, E Huntley, K Kissick, M Belkacemi, J Malley (eds)]
IPES-Food (2016) From Uniformity to Diversity. http://www.ipes-food.org/_img/upload/files/UniformityToDiver-sity_FULL.pdf
Jensen ES, Carlsson G, Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev 40:5. Springer Link Available at https://link.spring- er.com/article/10.1007/s13593-020-0607-x
JSSA (Japan Satoyama Satoumi Assessment) (2010) Satoyama – Satoumi ecosystems and human Well-being: socio-ecological landscapes of Japan – summary for decision makers. UNU, Tokyo
Kavino M, Manoranjitham SK (2017) In vitro bacterization of banana (Musa spp.) with native endophytic and rhizospheric bacterial isolates: novel ways to combat fusarium wilt. Eur J Plant Pathol 151:371–387. https://doi.org/10.1007/s10658-017-1379-2
Keesing F, Ostfeld RS (2021) Impacts of biodiversity and biodiversity loss on zoonotic diseases. Proc Natl Acad Sci 118(17):e2023540118
Kiew F, Hirata R, Hirano T, Xhuan WG, Aries EB, Kemudang K, Wenceslaus J, San LK, Melling L (2020) Carbon dioxide balance of an oil palm plantation established on tropical peat. Agric For Meteorol 295:108189
Knapp S, van der Heijden MGA (2018) A global meta-analysis of yield stability in organic and conservation agriculture. Nat Commun 9:3632. https://doi.org/10.1038/s41467-018-05956-1
Kobori H, Primack RB (2003) Participatory conservation approaches for satoyama. The traditional forest and agricultural landscape of Japan. Ambio 32:307–311

Lal R (2009) Soil degradation as a cause for human malnutrition. Food Security 1:45–57
Lal R (2017) Improving soil health and human protein nutrition by pulse-based cropping systems. Adv Agron 145:167–204
Lal R (2018) Saving global land resources by enhancing eco-efficiency of agro-ecosystems. J Soil Water Conserv 73(4):100A–106A
Lal R (2019) Promoting "4 per 1000" and "Adapting African Agriculture" by south-south cooperation: conservation agriculture and sustainable intensification. Soil Till Res 188:27–34. https://doi.org/10.1016/j.still.2017.12.015
Lal R (2020) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Secur 12:871–876. Available at https://link.springer.com/article/10.1007/s12571-020-01058-3
Lal R (2021) Feeding the world and returning half of the agricultural land back to nature. J Soil Water Consev 76:69A–72A
Leclère D, Obersteiner M, Barrett M et al (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585:551–556. https://doi.org/10.1038/s41586-020-2705
Liu K, McInroy JA, Hu CH, Kloepper JW (2018) Mixtures of plant-growth-promoting rhizobacteria enhance biological control of multiple plant diseases and plant-growth promotion in the presence of pathogens. Plant Dis 102:67–72. https://doi.org/10.1094/PDIS-04-17-0478-RE
Malapit HJ, Meinzen-Dick RS, Quisumbing AR, Zseleczky L (2020) Women: transforming food systems for empowerment and equity. In: 2020 Global Food Policy Report. Chapter 4, International Food Policy Research Institute (IFPRI), Washington, DC, pp 36–45. https://doi.org/10.2499/9780896293670_04
Mannakkara S, Wilkinson S, Potangaroa R (2019) Resilient post-disaster recovery through building Back better. Routledge
Mateo-Sagasta J, Marjani Zadeh S, Turral H (2018) More people, more food, worse water? A global review of water pollution from agriculture. FAO, Rome, p 225p
Morris C, Winter M (1999) Integrated farming systems: the third way for European agriculture? Land Use Policy 16(1999):193–205
Müller A, Huppenbauer M (2016) Sufficiency, Liberal societies and environmental policy in the face of planetary boundaries. Gaia Ecol Perspect Sci and Soc 25(2):105–109. https://doi.org/10.14512/gaia.25.2.10
Müller A, Schader C, Scialabba NEH, Bruggemann J, Isensee A, Erb KH, Smith P, Klocke P, Leiber F, Stolze M, Niggli U (2017) Strategies for feeding the world more sustainably with organic agriculture. Nat Commun 8:1290
Piñeiro V, Arias J, Dürr J, Elverdin P, Ibáñez AM, Kinengyere A, Opazo CM, Owoo N, Page JR, Prager SD, Torero M (2020) A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nature Sustainability 3:809–820
Pretty J et al. (2018) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1(8):441–446. ISSN 2398–9629
Reilly J, Artz D, Biddinger D, Bobiwash K, Boyle N, Brittain C, Brokaw J, Campbell J, Daniels J, Elle E, Ellis J, Fleischer S, Gibbs J, Gillespie R, Gundersen K, Gut L, Hoffman G, Joshi N, Lundin O, Winfree R (2020) Crop production in the USA is frequently limited by a lack of pollinators. Proc R Soc B Biol Sci 287(1931):20200729. https://doi.org/10.1098/rspb.2020.0922
Schader C, Müller A, Scialabba NE, Hecht J, Isensee A, Erb KH, Smith P, Makkar HPS, Klocke P, Leiber F, Schwegler P, Stolze M, Niggli U (2015) Impacts of feeding less food competing feedstuffs to livestock on global food system sustainability. J R Soc Interface 12(113):20150891
Schuh B et al. 2019 Research for AGRI Committee – The EU farming employment: current challenges and future prospects, European parliament, policy department for structural and cohesion policies, Brussels
Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485:229

Shaw R, C Anderson, C Fabricius, L Glew, B Loken, S Mahajan, N Olwero, J Opperman, P Pacheco, L Pendleton, D Thau, C Weber (2020) Beyond Boundaries: Insights into emerging zoonotic diseases, nature and human well-being. WWF Global Science. Internal Science Brief. Unpublished. WWF-Science-Brief-Beyond-Boundaries-Insights-into-Emerging-Zoonotic-Diseases.pdf

Smith J, Pearce B, Wolfe MS (2012) A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renew Agric Food Syst 27(4):323–332. https://doi.org/10.1017/S1742170511000597

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B, Sorlin S (2015) Planetary boundaries: guiding human development on a changing planet. Science 347(6223):1259855. https://doi.org/10.1126/science.1259855

Syed Ab Rahman SF, Singh E, Pieterse CMJ, Schenk PM (2018) Emerging microbial biocontrol strategies for plant pathogens. Plant Sci 267:102–111. https://doi.org/10.1016/j.plantsci.2017.11.012

Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515:518–522. https://doi.org/10.1038/nature13959

van Huis A, Van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, Vantomme P (2013) Edible insects: future prospects for food and feed security. FAO Forestry Paper 171. http://www.fao.org/3/i3253e/i3253e00.pdf

Westhoek H, Lesschen JP, Rood T, Wagner S, De Marco A, Murphy-Bokern D, Leip A, van Grinsven H, Sutton MA, Oenema O (2014) Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Glob Environ Chang 26:196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon L, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Sibanda L et al (2019) Food in the Anthropocene: the EAT-Lancet commission on healthy diets from sustainable food systems. Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

WRI (2018) World resources report. Creating a sustainable food future. A menu of solutions to feed nearly 10 billion people by 2050. Available at https://research.wri.org/sites/default/files/2019-07/creating-sustain-able-food-future_2_5.pdf

WWF (2016) Living Planet Report 2016. Risk and resilience in a new era. Available at Living Planet Report 2016| Pages | WWF (worldwildlife.org)

WWF (2020) Living Planet Report. Bending the curve of biodiversity loss. Living Planet Report 2020: Bending the curve of biodiversity loss – ICRI (icriforum.org)

Pathways to Advance Agroecology for a Successful Transformation to Sustainable Food Systems

Urs Niggli, Martijn Sonnevelt, and Susanne Kummer

1 Introduction

Transforming agriculture and food systems in line with Sustainable Development Goals (SDGs) is an imperative that can no longer be ignored or deferred (CNS-FAO 2019; Eyhorn et al. 2019). In facing up to this challenge, agroecological approaches stand to play an indispensable role by connecting environmental sustainability with social justice in production and consumption. It combines the global challenge of ending hunger with locally adapted solutions and strengthens both participation and the mobilization of local actors and their knowledge (HLPE 2019). Agroecology optimizes the system approach and integrates scientific progress responsibly. To allow for agroecology to exploit its potential, there is a need for transformation that supports the shift from a capital- to a more labor-dominated approach that strengthens the social relations of production and moves farming beyond the logic of scale-enlargement, technology-driven intensification and specialization (Van der Ploeg 2021).

This chapter is based on a well-documented multi-stakeholder process of the Swiss National FAO Committee (CNS-FAO) developed over several years to provide scientific support to the Swiss government and the public on agroecology (CNS-FAO 2016, 2019, 2021). The aim of the chapter is to highlight the potentials of agroecology in regard to the strengthened effort of the UNFSS 2021 to achieve the

U. Niggli (✉)
Institute of Agroecology, Aarau, Switzerland
e-mail: urs.niggli@agroecology.science

M. Sonnevelt
World Food System Center, ETH Zurich, Zurich, Switzerland

S. Kummer
Research Institute of Organic Agriculture (FIBL), Vienna, Austria
e-mail: susanne.kummer@fibl.org

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_18

SDGs, and highlight the necessary actions for mainstreaming agroecological management practices.

2 Global Challenges

We identify three major key challenges of global agriculture and food systems: the first challenge is that much of the world's population remains inadequately nourished, with more than 820 million people suffering from hunger. Many more consume low-quality diets, contributing to a substantial rise in the incidence of diet-related illness and obesity (Willett et al. 2019; IPCC 2019). A second challenge with global impact is the unsustainable way in which food production and consumption patterns substantially exploit the natural resources of soil, water and air (IPBES 2019). This has caused an immense biodiversity loss (Leclère et al. 2020; IPBES 2019). Third, greenhouse gas emissions are rising dramatically all around the world, with global agriculture causing 23% of anthropogenic greenhouse gas emissions, and therefore contributing substantially to global warming (IPCC 2019).

Not least due to the current Covid-19 pandemic, the fragility and vulnerability of food systems are clearer than ever. Food insecurity and acute hunger have increased, along with the number of people living in extreme poverty (HLPE 2020). Providing food for an estimated 10 billion people in 2050 is challenging. It will take a 56% increase in crop calories compared to the base year 2010 (FAO 2017), and that without even addressing such other issues as unsustainable consumption patterns, food loss and waste and the use of food crops for animal feedstuff and biofuels. The resulting substantial expansion of agricultural land, amounting to 593 million hectares (crop and grassland), must be contained wherever possible if we are to avoid releasing large amounts of CO_2 equivalents and putting biodiversity reserves at risk. Current agriculture should mitigate 11 gigatons of greenhouse gases to meet the Paris climate target of less than 2 °C of warming (World Resources Institute 2018). Future solutions must also take into account that, by 2050, it is forecasted that 68% of the world's population will live in cities (United Nations 2019), increasing the importance of urban food production.

3 Need for Transformation

A radical transformation of global food systems that addresses both the way we produce, process, trade and consume food and, with the same priority, the improvement of the livelihoods of farmers, farm workers and their families is necessary and cannot tolerate any delay. To provide enough food for the global population, several overriding strategies are being pursued, namely, a substantial increase in productivity, a sustainable intensification (Godfray and Garnett 2014) and an ecological intensification (Tittonell 2014). Agroecology implements the ecological intensification strategy in agricultural practice.

Agroecology offers a powerful means of accelerating the needed transformations. Agroecology, as we understand it, has a common framework grounded in the FAO's ten elements (FAO 2018b). The ten elements of agroecology are interlinked and interdependent. They encompass ecological characteristics of agroecological systems (diversity, synergies, efficiency, resilience and recycling), social characteristics (the co-creation and sharing of knowledge, human and social values, culture and food traditions), and the enabling of political and economic environments (responsible governance, circular and solidarity economy) (FAO 2018b). These elements come together in a model that relies centrally on the non-exhaustive and non-destructive use of biodiversity and ecosystem services, with off-farm inputs playing a diminished role in production (CNS-FAO 2019).

Hundreds of thousands of farmers manage their farms with agroecological practices in one way or another, either to improve their own productivity and livelihoods or gain privileged access to markets with certificates. These practices include regenerative conservation agriculture, organic agriculture, agroforestry, permaculture, agro-silvo-pastoral systems, and sustainable pastoralism in rangelands, among others. An even higher number of farmers adopt only one or more selected techniques of agroecology, such as using integrated nutrient and pest management, introducing semi-natural habitats on the farm, applying no-till arable cropping, or adopting sustainable river basin and groundwater management. Some farmers use bio-fertilizers and bio-protectants instead of agrochemicals, apply intercropping and cover crops to increase the land equivalent ratio (LER) and involving precision agriculture and climate-smart agriculture. Nonetheless, fully agroecological farms have remained a niche. The classic role of niches is that of a "protective space" or a shelter where future solutions and novel ideas can be tried out (Smith and Raven 2012). These novel ideas could change or even replace the current regime (Geels 2011) or paradigm (Beus and Dunlap 1991).

Although agroecological practices have been successfully implemented on many farms globally and practices such as resource-conserving agriculture continue to spread to more farms and more hectares (Pretty et al. 2006), they have not become mainstream until now. The most salient obstacles to mainstreaming agroecology include the fact that it is currently unknown to the public; the time lag between implementing agroecological practices and observing positive results; weak knowledge and advisory systems; transaction costs; policy incoherence; crucial deficits in landscape-level coordination, incentive systems in research, and compensation for yield reductions; and the need to strengthen the aspect of sufficiency in a sustainability context (IIED 2015; CNS-FAO 2021).

The HLPE report (2019) found that, to effectively and sustainably address food and nutrition security, it is not sufficient to focus on technological solutions and innovations or incremental interventions alone. Food system transformation requires (i) inclusive and participatory forms of innovation governance; (ii) information and knowledge co-production and sharing among communities and networks; and (iii) responsible innovation that steers innovation towards social issues (HLPE 2019).

Given its holistic approach, transformation to agroecological practices and systems happens at various scales and dimensions, from management decisions on farms to complex and erratic transformations resulting from the sum of decisions of various actors within a wider landscape (Anderson et al. 2021). Therefore, a multi-level perspective has to be taken so as to understand enabling and disabling factors and processes relevant for mainstreaming (Geels 2011). Anderson et al. (2021) introduced the term "domains of transformation," within which they described factors, dynamics, structures and processes that constrain or enable transformation in sustainability transitions.

Agroecological transformation can be understood as having five levels (Gliessman 2015): at level 1, farming systems become more efficient by reducing the use of fertilizers, pesticides or fuel. Level 2 involves replacing agrochemical inputs with more natural ones such as bio-fertilizers and bio-protectants. The way we understand agroecology, it also includes technologies that are safe for the environment and human health and that strengthen the systemic processes. Level 3 is about redesigning farming systems with diversified crop rotations, mixed crops, and intercropping, leading to better closed cycles of nutrients and organic material. Successful food system transformation also includes increased farmer-consumer collaborations (level 4), either with short distribution channels or internet-based remote applications, and, finally, a comprehensive transformation of policies, rules, institutions, markets and culture (level 5). The various stages proceed dynamically and in parallel, so that when framework conditions are conducive, a variety of production systems coexist and rural regions continuously change towards a higher degree of sustainability.

In our chapter, we address all five levels and propose actions that enable transformation and remove lock-ins. There is no contradiction between mainstreaming agroecology and strongly improving sustainability. Therefore, agroecology plays a crucial role for achieving the SDGs and works remarkably well in both theory and practice (COAG 2018; HLPE 2019).

4 Impact of an Agroecological Transformation

Agroecology has the potential to contribute to economic growth and decent work (Van der Ploeg et al. 2019), particularly for the rural poor. It contributes to local economic and resource circulation, considerably increases and stabilizes the yields of subsistence farmers (Pretty et al. 2006), and reduces costs and external dependencies. Strategies such as diversification, external input reduction and alternative marketing channels have, in some cases, been shown to improve farmers' income by 30% (FAO 2018a). For example, integrated pest management can generate remarkable improvements: in a study in low-income countries, pesticide use declined by 71% and yields grew by 42% (Pretty et al. 2006). A study on 946 farms in France concluded that total pesticide use could be reduced by 42% without negative effects on either productivity or profitability on 59% of the investigated farms (Lechenet et al. 2017). Conservation tillage can improve soil carbon while raising yields, and integrated plant nutrient systems can achieve the same benefits with reduced fertilizer application (Bruinsma 2003; Pretty et al. 2003, 2006; Uphoff 2007).

Furthermore, there are indications that the economic performance of alternative and agroecological farming systems can be comparable to, and is sometimes better than, conventional farming systems (D'Annolfo et al. 2017), and provide greater predictability for farmers (Chappell and LaValle 2011). Organic farms can achieve the same (Smolik et al. 1995; Rosset et al. 2011) or even higher (Nemes 2009) profitability as conventional farms. Also, agroforestry systems can have a higher return on labor compared to monocultures, (Armengot et al. 2016). Extensive evidence indicates that agroecology can, on a global scale, provide a level of food security comparable to that of conventional agriculture (Chappell and LaValle 2011). Under conditions of subsistence agriculture in Sub-Saharan Africa, agroecological methods significantly improved food security and nutritional diversity (Bezner Kerr et al. 2019). Organic agriculture increases access to food by increasing the quantity of foods produced per household and producing food surpluses that can be sold at local markets, for instance (UNCTAD/UNEP 2008). The yields of organic agriculture outperform traditional subsistence systems. In their study, Pretty et al. (2006) analyzed the impacts of 286 resource-conserving practices in 57 low-income countries and found that these projects led to an average yield increase of 79%. Differences in terms of yield productivity are highly site-specific, as Tittonell (2013) showed for organic agriculture: on marginal sites, organic farming produces equal or slightly higher yields than conventional farming. However, on high-yield sites, organic farming produces significantly lower yields.

Furthermore, agro-biodiversity (a key element of agroecology) is an important driver for making a diverse range of food products available. Although the pathway is complex and not always positively correlated, agricultural diversity plays an important role in improving dietary diversity, which has a strong association with improved nutrition status, particularly the micronutrient density of diets (Fanzo et al. 2013). A recent publication by Bezner Kerr et al. (2021) found evidence for positive outcomes linked to the use of agroecological practices on food security and nutrition (FSN) in households in low- and middle-income countries. While 78% of the studies reported positive outcomes, some studies found mixed outcomes, and a few studies reported negative impact on FSN, using indicators such as dietary diversity. The most common agroecological practices included crop diversification, agroforestry, mixed crop and livestock systems, and practices improving soil quality, with positive outcomes on FSN indicators such as dietary diversity and household food security.

Yield increases alone will not address our concomitant challenges of hunger, micronutrient deficiencies and obesity. This requires broad-ranging system changes that tackle poverty, inequality and barriers to access. The systemic approach based on ethical values, often considered a part of agroecological methods, offers an opportunity to address these issues in an integrated manner. For example, in Madhya Pradesh, India, a development institute provided integrated training in agroecological techniques, health and nutrition to more than 8500 women from 850 villages over 30 years. This improved livelihoods for the majority of the women and broke the cycle of poverty (FAO 2018a).

Agroecological systems use natural resources more sustainably and efficiently, and reduce the release of agrochemicals into air, water and soil (Pretty et al. 2003; Lechenet et al. 2017). Through the enhanced proximity between producers and consumers, agroecology helps raise awareness and reduce food waste, e.g., by redistribution to food bank charities or by repurposing urban organic waste as animal feed or fertilizer (Beausang et al. 2017). Agroecology puts an emphasis on maintaining soil fertility and ecosystem services, which can improve the long-term productivity of the land. As species richness is, on average, 34% higher in organic farming (Tuck et al. 2014), and organic farming systems have higher floral and faunal diversity than conventional farming systems (Mäder et al. 2002), biodiversity can be conserved and potentially restored within agroecosystems. As organic farming is one of the best-documented agroecological farming systems in scientific terms, these results are fundamentally important for a better understanding of all agroecological practices. Studies have shown that, through diverse and heterogeneous agroecological approaches, it is possible to preserve and increase wild and domesticated biodiversity by up to 30% (FAO 2018a). The connection between climate action and agroecology is two-way – agroecological systems have the potential to contribute to reducing greenhouse gas emissions and offer management practices to adapt to climate change (FAO 2018a). Agroecological farming may lead to reduced greenhouse gas emissions by reducing emissions from the production of synthetic fertilizer and carbon capture in the soil (Müller et al. 2017; Smith et al. 2008; Wood and Cowie 2004). However, these benefits have to be weighed against the lower land use efficiency or the increased requirements for labor of agroecological – especially organic – systems (Meemken and Qaim 2018; Clark and Tilman 2017). Regarding climate change adaptation, agroecology may improve the resilience of smallholders through the diversification of production and the increase in resource use efficiency by integrating social aspects (Altieri et al. 2015; Liebman and Schulte-Moore 2015). Furthermore, soil fertility, which is higher in agroecological systems, is a key prerequisite for protection against erosion and flood (Seufert and Ramankutty 2017).

5 The Role of Diversity for Food Productivity

One central characteristic of agroecology is diversity (FAO 2018b). In contrast, most public policies and incentives designed to increase agricultural production carry the risk of reducing the diversity of diets, food systems and landscape. A defining feature of the agroecological approach is diversity of landscape and habitats, of farm activities, of crops grown, of livestock kept and of above- and below-ground flora and fauna. Agrobiodiversity represents the creativity of life; its irreversible erosion means less capacity to innovate and adapt in the future, especially to climate change (Dury et al. 2019). Substantial improvements in the environmental sustainability of agriculture are achievable now, without sacrificing food production or farmer livelihoods (Davis et al. 2012). While short-term productivity is increasing, there is a clear loss of diversity when traditional varieties or races are replaced by improved varieties (Khourya et al. 2014). This homogenization and high dependency on a few crops at the global scale increases vulnerability to pests, as historically illustrated by many examples in maize, banana and wheat (Dury et al. 2019). Additionally, risks of resistance increase through the wide use of pesticides and antibiotics (Dury et al. 2019). The development of ecosystem services over time in more diverse cropping systems and rotations increasingly displaces the need for external synthetic inputs while still maintaining crop productivity or even increasing yields (Ferrero et al. 2017; Davis et al. 2012).

While socioeconomic factors such as farm commercialization, off-farm income, education or seasonality significantly affect diets of rural households, the linkages between a household's own agricultural production and dietary diversity are not always clear (Muthini et al. 2020; Sibhatu and Qaim 2018; Bellon et al. 2016). A positive relation between agricultural diversification and diversified diets is shown in different contexts for both subsistence and income-generating household strategies (Jones et al. 2014; Muthini et al. 2020; Sibhatu and Qaim 2018). In a comparative analysis including 23 studies, (Jones et al. 2014) demonstrated that agricultural biodiversity has a small but clear and consistent association with more diverse household- and individual-level diets. These various relations between diversity and food and nutrition security calls for a production strategy that combines local productivity and yield stability to make best use of between- and within-crop diversification to increase long-term food and nutritional security.

Agroecological approaches elevate the role of farmers and other food producers in associated knowledge and value chains. This is especially the case for the knowledge and experience of women, as women play a key role in all stages of food production in almost all regions around the world, encompassing their practical knowledge on biodiversity, including seeds, on food preservation and recipes. Women's control of farm level decision-making is an important determinant in understanding household-level diet diversity, expressed by a positive relation between agricultural biodiversity and household diet diversity for households headed by women (Jones et al. 2014). Agroecology can create better opportunities for women by integrating diverse work tasks and specific forms of knowledge, providing a more significant role for women in the household and farm economy. As agroecology, through low initial investment costs and knowledge-intensive technologies, becomes more accessible to women, it also fosters their economic opportunities and autonomy. In its political dimension, agroecology seeks to achieve and implement a just system (Seibert et al. 2019).

6 Domains of Transformation with Enabling and Restraining Factors

The domains of transformation that we want to address are (i) strengthening knowledge on agroecology, (ii) working with markets, (iii) enhancing cooperation, and (iv) ensuring policy coherence to create a conducive policy context for agroecology. These four domains address both agroecological practices (levels 1, 2 and 3 of Gliessman 2015) and the wider food system changes (levels 4 and 5).

6.1 Strengthening Knowledge (Research, Education and Innovation) on Agroecology

The knowledge and advisory systems required to support agroecology and build the capacity of actors are insufficient (Wezel et al. 2018). A systems-oriented, transdisciplinary, and long-term field research approach is lacking. Instead, current global knowledge and research systems promote fragmented short-term output (Aboukhalil 2014; Edwards and Roy 2017).

In 2011, total global public and private investment in AgR4D exceeded 70 billion US dollars (in purchasing power parity dollars) (Pardey et al. 2016). Current global R&D investments focus mainly on major staple crops. More nutrient-dense crops such as pulses, fruits and vegetables, as well as orphan crops, are often neglected (Pan 2016; HLPE 2019). The Consortium of International Agricultural Research Centres (CGIAR) Research Programs still focus largely on breeding and efficiency in production systems, rather than expanding its scope to a food system perspective (Biovision and IPES-Food 2020). A study analyzing 728 AgR4D projects with a total budget of 2.56 billion US dollars showed that local and regional value chains, traditional knowledge and cultural aspects of food systems are underrepresented in research programs, while only a handful of projects take a participatory approach to research (Biovision and IPES-Food 2020). The public investment in agroecological approaches is estimated to range between 1% and 1.5% of total agricultural and aid budgets (HLPE 2019). In order to transform the current food system, it is crucial for research projects to address and include key aspects of socioeconomic and political change, such as decent working conditions, gender equality (Biovision and IPES-Food 2020) and the important role of young and highly qualified people.

To tackle these challenges, the research focus should be shifted to agroecological principles, research activities should be better contextualized and funding mechanisms should be adequately altered, providing more funding for systemic, interdisciplinary and transdisciplinary research. This also usually requires longer funding periods.

Besides providing adequate funding for agroecological research, it is also crucial to break down institutional silos and enhance system thinking in research and training. Interdisciplinary courses at the graduate and undergraduate levels should include non-academic actors. Educational structures and programs are already showing signs of evolving towards systems analysis, with several universities recently opening food system centers or units that break down the traditional structures of research. Knowledge on agroecological innovations requires front-end research, but also needs to be combined with "know-how" and "do-how" (Salliou et al. 2019). Therefore, tools and platforms allowing for the transdisciplinary exchange and development of knowledge are key, particularly with young people and women.

It is hence key to provide training that includes practitioner-led learning and to build a culture of accountability in which research is undertaken with and for farmers as the ultimate beneficiaries. Currently, these agents of change for agroecology are rarely among the recipients of research funding. Farmers' intuition and tacit knowledge, practical know-how and scientific R&D can be harnessed together to yield solutions that are better suited to their particular context and are more quickly implemented.

Public support should be provided to further develop agroecological curricula at colleges and universities and facilitate exchange between experienced and interested stakeholders (from research, civil society, donor organizations and the private sector). Establishing a network of decentralized centers of excellence in agroecology would further reinforce system thinking and enhance exchanges between different knowledge holders (Biovision and IPES-Food 2020; HLPE 2019). New methodologies developed at universities and research centers, such as the co-creation of knowledge and citizen science using digital tools, enhance participation and transdisciplinarity.

Implementing agroecological practices successfully is knowledge-intensive and requires more experimentation and site-specific adaptation than standardized, industrial farming practices (HLPE 2019). This potentially makes agroecological practices attractive to young people, and requires the skills and expertise of a diversity of practitioners and specialists, including farmers, researchers and extensionists. In many parts of the world, private extension services financed by the sales of goods and services are predominant. When it comes to developing extension systems that align with agroecological approaches, publicly funded extension services are crucial. Tackling them requires re-configuring knowledge and extension systems in ways that place a much greater emphasis on participation and social learning, e.g., farmer-to-farmer learning and on-farm demonstrations. Expanding the use of low-cost information and communication technology (ICT), such as interactive radio and the use of apps, videos, and social media, is an effective means to reach large numbers of people, including youths. ICT has the added advantage of being highly customizable to suit specific contexts, while digital tools are also highly versatile. Widening access will also require innovative approaches in the delivery of information, so that the private sector, farmer groups, volunteers, social workers and youth entrepreneurs can become partners in extension and advisory systems (Fabregas et al. 2019).

6.2 Working with Markets

Agroecological systems are more diversified in terms of farm activities and tend to yield a greater number of crop or livestock products, but with a smaller volume of each product. This can limit market and processing opportunities and requires higher levels of knowledge and risk-taking. Furthermore, local marketing structures have, in many regions, been replaced by food retail chains, with food producers finding themselves in the weakest position along the value chain.

Only 23% of all agricultural products are traded on international markets, and most food in the world is produced, processed, distributed and consumed within local, national and/or regional food systems (CSM 2016). The Covid-19 pandemic has shown that sustainable local food systems are crucial for maintaining stable access to food when the global system fails. Supporting short supply chains and alternative retail infrastructures with stronger participation and control of more and various food system actors, such as farmers' markets, fairs, food policy councils, and local exchange and trading systems, may enhance farmers' livelihoods and increase access to local, sustainably-produced and diverse food (Hebinck et al. 2014). More support should be given to develop local and regional markets, processing hubs and transportation infrastructures that provide greater processing and handling capacities for fresh products from small and medium-sized farmers who adopt agroecological and other innovative approaches, and to improve their access to local food markets (Wezel 2020). Strengthening local food systems depends on enhancing local authorities' (e.g., municipalities) capacity to design favorable local policies. These, in turn, could work to enhance direct connection between producers and consumers, provide public facilities, support farmers´ associations in building strong local marketing networks, and entrench participatory guarantee systems (PGS) to certify organic and agroecological producers (HLPE 2019).

Farmers (particularly smallholders, women and young people), producer organizations, input providers and businesses transforming their operations based on agroecological principles need access to credit and alternative investment platforms with low capital costs. Not only farmers, but food systems actors in general, require access to secure and low-cost capital to absorb risks (e.g., momentary lower profitability) in the course of converting towards more sustainable business models. Investments in FinTech research that accelerate and facilitate access to transformational capital (e.g., mobile microfinance, peer-to-peer lending platforms and crowdfunding) must be given due priority.

Food prices and the price for food waste should be "right," internalizing external costs and enhancing positive externalities. This means that both the nutritional value of a food item and its production- and consumption-associated costs along the entire food value chain should be taken into account (FAO 2018c). However, an increase in food prices has a negative impact on the ability of those on low incomes to buy food of appropriate quality. Similarly, the Eat-Lancet Commission states that "food prices should fully reflect the true costs of food." However, options that support vulnerable population groups and protect them from the negative consequences of the potential increase of food prices need to be considered (Willett et al. 2019). Besides food prices, financial and fiscal incentives of unsustainable production systems also have a significant influence on current food systems. To allow for food system transformation, the creation of a shared understanding of all of the positive and negative externalities of the food system, as well as of the best approaches to defining reduction targets, is crucial (Perotti 2020).

6.3 Enhancing Collaboration

Agroecological practices often depend on collective action across a landscape scale, involving multiple farms and a range of actors. Furthermore, agricultural innovations respond better to local challenges when they are co-created through participatory processes and endorsed by local-specific knowledge. Collaboration and coordination across local, regional and national levels is key to supporting the active involvement and self-organization of food system actors such as producers, private sector investors, academia, civil society and governments. There is growing evidence from the literature highlighting the need for collective action and coordination at the local level to create favorable sociotechnical conditions for agroecological transition (Lucas et al. 2019). Agroecological innovations, to be successful and implemented at a larger scale, require mobilizing a growing range of stakeholders with multiple perspectives (Triboulet et al. 2019). However, agroecological farmers often value community cooperation more highly and see it as more important compared to colleagues working in non-agroecological farming systems. This is in line with agroecology principles, in which the links to members of the community for knowledge-sharing and problem-solving are key to strengthening sustainability and resilience (Leippert et al. 2020). Through interactions with other stakeholders and networks, farmers and other agents of change are supported in their efforts to strengthen existing initiatives and further develop collective awareness, identity, and agency around agroecological management issues (Chable et al. 2020). This requires higher levels of coordination and increases transaction costs.

Multi-stakeholder dialogues built on evidence-based arguments can help to bring together different perspectives, as long as they are developed in an inclusive manner (HLPE 2019). Agricultural research projects and partnerships too often remain focused on one-way knowledge transfer via institutes based in the Global North. It is therefore crucial not only to promote a shift towards agroecological research, but also to rebalance North-South power relations through equal research partnerships and direct access to research funding. Additionally, increased funding to build lasting bridges for South-South collaboration is needed. Supporting the emergence of long-term partnerships and coalitions with a focus on agroecology, local ownership, and the meaningful involvement of social movements and farmers' organizations is equally important. In parallel, the Public-Private Partnership model that is so central to current AgR4D needs to be continually scrutinized with regard to the delivery of benefits vis-à-vis the SDGs (Biovision and IPES-Food 2020).

Social movements associated with agroecology have often arisen in response to agrarian crises and have joined forces to initiate the transformation of agriculture and food systems. Agroecology has become the overarching political framework under which many social movements and peasant organizations around the world assert their collective rights and advocate for a diversity of locally adapted agriculture and food systems mainly practiced by small-scale food producers. These social movements highlight the need for a strong connection among agroecology, the right to food and food sovereignty. They position agroecology as a political struggle, requiring people to challenge and transform existing power structures (HLPE 2019).

6.4 *Ensuring Policy Coherence to Create a Conducive Policy Context for Agroecology*

To take agroecology to the next level, a solid governance structure, combined with a set of coherent policy measures, is essential (Eyhorn et al. 2019). Laws, regulations, publicity awareness campaigns and fiscal incentives are all part of a framework that should serve society. Many policy measures have negative impacts on the goals of different national strategies and policy objectives such as climate, biodiversity, soil protection, animal welfare, environmental protection, nutrition and health. Current agricultural and trade policies, including subsidy schemes, still favor intensive, export-oriented production of a few crops, as well as the intensive use of fossil fuel and agrochemical inputs, and must be revised to address the multi-functionality of agriculture (Eyhorn et al. 2019; HLPE 2019). The holistic nature of agroecology requires a well-coordinated coherent policy framework and a shift from a production-focused perspective to one that includes new indicators covering nutritional aspects, environmental impact and the long-term stability of the system. Such a holistic accounting of the performance of food production would allow for an evaluation of all of the positive and negative externalities (Perotti 2020).

International trade relations should include or allow for specific tools or mechanisms to foster the marketing of products derived from agroecological systems. Bi- and multilateral trade agreements should not include policies or ask for laws that might hinder agroecological production and even put its central elements, as defined by FAO, at risk.

Government-provided agriculture benefits – at varying degrees – support measures all over the world. In Europe, these are mainly direct payments, which are paid out to farms to support their income. “Public money for public goods” is a claim that environmental politicians and NGOs have been making for 30 years. Fortunately, there is a growing consensus that this would be an effective greening strategy and would bring major benefits to agroecology. Piñeiro et al. (2020) investigated which measures were most effective in promoting sustainability in agriculture. By far, the most effective measures are government-supported eco-schemes in all political, economic and social contexts, worldwide. Education, extension or market incentives (demand) come second. This relates to the fact that the market only settles private goods and services, but not public goods. The important function of state intervention (direct payments, investment subsidies, contributions to research, education and advisory services) is therefore to minimize the conflict of goals between private and public goods and functions. If the funds available for the various policy areas were channeled into agroecology, a huge transformative force would develop very quickly.

One major challenge is that, on average, conversion to agroecological systems typically results in a short-term reduction of yields (Tittonell 2014; WWF 2021) that needs to be compensated for through cost savings, higher product prices or policy support measures to ensure the economic viability of the farms. Additionally, the definition of sustainability in agriculture and food systems must be broadened beyond the efficiency narrative. Sufficiency means reducing resource consumption by adopting sustainable diets, reducing the demand for certain goods (e.g., feedstuff and biofuels produced on arable land), or increasing the demand of goods with relative advantages that cause fewer emissions and less resource depletion under certain situations and in certain locations, and by reducing food waste. Although the efficient use of natural and human-made resources remains important, efficiency alone is often offset by rebound effects (Polimeni et al. 2008) such as higher consumption or wastage. Global mass-flow models show that narratives based on sufficiency can successfully reduce the trade-offs between productivity and eco-stability (Schader et al. 2015; Müller et al. 2017).

Making use of existing public purchasing obligations can provide economic and political opportunities to implement policy and build new and innovative socioeconomic relationships that create sustainable food systems. Public procurement of sustainably-produced food, for example, can support low-income and other groups within schools, hospitals and other public institutions, setting off mutually reinforcing circuits. Interventions that focus on local procurement of sustainably-produced food for school feeding programs, or that target groups vulnerable to food insecurity, so as to realize food sovereignty at the local and state levels, can be effective in addressing FSN while supporting sustainable food systems (Barrios et al. 2020). These initiatives can also support safe, decent, meaningful employment for marginalized groups, including young people and low-income workers within the food system.

International guidance to comprehensively measure outcomes of agroecological farming systems are the Tool for Agroecology Performance Evaluation (TAPE), SAFA Guidelines of FAO (2017) or UN System of Environmental Economic Accounting (SEAA). Research projects in general, and technology development in particular, should be subjected to a holistic, multi-criteria assessment measured against the elements of agroecology: FAO's TAPE (FAO 2019), the Agroecology Criteria Tool (ACT), the growing body of work on 'true cost accounting' and specific metrics like the LER are at hand (Biovision and IPES-Food 2020). Multi-criteria sustainability assessment tools for farms and food businesses are very helpful in assessing complexity and holistic sustainability and can accelerate transformation processes in agriculture and nutrition (Mottet et al. 2020).

7 Conclusions: Contribution of Agroecology to the SDGs

The SDGs recognize the strong interconnectivity among development goals and stress the need for holistic approaches and profound transformation of human activity across multiple dimensions and at multiple scales (Barrios et al. 2020).

Due to the fundamental importance of agriculture, the state of agriculture and food systems directly or indirectly affects all 17 of these goals. Agroecology provides one tool to help build sustainable food systems, and thus contribute to the ambitious targets laid out under the SDGs (Farrelly 2016). In particular, agroecology can contribute to no poverty (SDG 1), zero hunger (SDG 2), good health and wellbeing (SDG 3), gender equality (SDG 5), decent work and economic growth (SDG 8), responsible consumption and production (SDG 12), climate action (SDG 13) and life on land (SDG 15).

Agroecological approaches are increasingly called upon to play a greater role in contributing to the achievement of sustainable global food systems. Numerous promising examples demonstrating the potential of agroecology to stimulate and drive sustainable transition of food systems around the world were presented in a stakeholder paper (CNS-FAO 2021). If we implement the concept and, at the same time, apply a coherent policy set, agroecology will contribute to sustainable and resilient food production systems that help maintain ecosystems and progressively improve land and soil quality. It will further help in maintaining the genetic diversity of seeds, cultivated plants and domesticated animals. Through the promotion of reduced, alternative (non-chemical) and safe application of crop protection products, agroecology can reduce risks associated with agrochemical exposure, thus positively influencing the health of rural workers and consumers.

All of these potential benefits of agroecology mentioned above, combined with long-term productivity, social wellbeing and improved agency, reduced food waste and loss and a sufficiency-oriented agricultural production, require a rethinking of both the indicators and the way in which we measure performance of agricultural and food systems (Mottet et al. 2020). Additionally, a coherent policy framework is necessary that is able to break policy silos and improve governance structures in many countries to allow for increased self-control of the resource base, reduce the dependency of traditional market mechanisms controlled by capital through the construction of new, nested, markets, facilitate a strong backing reliance of high quality of labor, exchange of experiences and the availability of skill-oriented technologies, and establish a high degree of self-regulation at the territorial level (Van der Ploeg 2021). All of these elements are strengthening farming as an interesting, fulfilling profession that is attractive to young people. To allow agroecology to play a role in food system transformation, different governance levels and different departments, teams and stakeholder groups need to closely work together to define the key performance indicators for sustainable food systems and a policy frame aimed at reducing the amount of trade-offs. Promising examples of agroecological practices have developed and spread globally (CNS-FAO 2021), and the increasing awareness of society about the urgency of food system transformation increases the pressure on decision-makers to substantially support the development towards sustainable food systems. Strengthening knowledge systems, working with markets, enhancing collaboration among food system actors and creating an enabling policy environment will be crucial for this development.

References

Aboukhalil R (2014) The rising trend in authorship. Winnower 2(e141832):26907. https://doi.org/10.15200/winn.141832.26907

Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. Agron Sustain Dev 35(3):869–890. https://doi.org/10.1007/s13593-015-0285-2

Anderson CR, Bruil J, Chappell MJ, Kiss C, Pimbert MP (2021) Conceptualizing processes of agroecological transformations: from scaling to transition to transformation. In: Agroecology now! Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-61315-0_3

Armengot L, Barbieri P, Andres C, Milz J, Schneider M (2016) Cacao agroforestry systems have higher return on labor compared to full-sun monocultures. Agron Sustain Dev 36(4):1–10. https://doi.org/10.1007/s13593-016-0406-6

Barrios E, Gemmill-Herren B, Bicksler A, Siliprandi E, Brathwaite R, Moller S, Batello C, Tittonell P (2020) The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. Ecosyst People 16(1):230–247. https://doi.org/10.1080/26395916.2020.1808705

Beausang C, Hall C, Toma L (2017) Food waste and losses in primary production: qualitative insights from horticulture. Resour Conserv Recycl 126:177–185. https://doi.org/10.1016/j.resconrec.2017.07.042

Bellon MR, Ntandou-Bouzitou GD, Caracciolo F (2016) On-farm diversity and market participation are positively associated with dietary diversity of rural mothers in southern Benin, West Africa. PLoS One 11(9):e0162535. https://doi.org/10.1371/journal.pone.0162535

Beus C, Dunlap R (1991) Measuring adherence to alternative vs. conventional agricultural paradigm: a proposed scale. Rural Sociol 56(3):432–460. https://doi.org/10.1111/j.1549-0831.1991.tb00442.x

Bezner Kerr R, Kangmennaang J, Dakishoni L, Nyantakyi-Frimpong H, Lupafya E, Shumba L, Msachi R, Odei Boateng G, Snapp S, Chitaya A, Maona E, Gondwe T, Nkhonjera P, Luginaah I (2019) Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. Agric Ecosyst Environ 279:109–121. https://doi.org/10.1016/j.agee.2019.04.004

Bezner Kerr R, Madsen S, Stüber M, Liebert J, Enloe S, Borghino N, Parros P, Munyao Mutyambai D, Prudhon M, Wezel A (2021) Can agroecology improve food security and nutrition? A review. Glob Food Sec 29:100540. https://doi.org/10.1016/j.gfs.2021.100540

Biovision & IPES-Food (2020) Money flows: what is holding back investment in agroecological research for Africa? Biovision Foundation for Ecological Development & International Panel of Experts on Sustainable Food Systems. http://www.ipes-food.org/_img/upload/files/Money%20Flows_Full%20report.pdf

Bruinsma J (ed) (2003) World agriculture: towards 2015/2030; an FAO perspective. Earthscan Publications Ltd/Taylor & Francis Group, London/New York. http://www.fao.org/3/y4252e/y4252e.pdf

Chable V, Nuijten E, Costanzo A, Goldringer I, Bocci R, Oehen B, Rey F, Fasoula D, Feher J, Keskitalo M, Koller B (2020) Embedding cultivated diversity in society for agro-ecological transition. Sustain 12:784. https://doi.org/10.3390/su12030784

Chappell MJ, LaValle LA (2011) Food security and biodiversity: can we have both? An agroecological analysis. Agric Hum Values 28:3–26. https://doi.org/10.1007/s10460-009-9251-4

Clark M, Tilman D (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett 12:064016. https://doi.org/10.1088/1748-9326/aa6cd5

CNS-FAO (2016) Working towards sustainable agriculture and food systems. A discussion paper. Swiss National FAO Committee (CNS-FAO), September 2016

CNS-FAO (2019) Agroecology as a means to achieve the sustainable development goals. A discussion paper. Swiss National FAO Committee (CNS-FAO), February 2019

CNS-FAO (2021) Pathways to advance agroecology. Overcoming challenges and contributing to sustainable food systems transformation. Swiss National FAO Committee (CNS-FAO), March 2021
COAG (2018): Agroecology: from advocacy to action. Discussion paper for the twenty-sixth session of the FAO committee on agriculture on 1–5 October 2018. Rome
CSM (2016) Connecting smallholders to markets. The Civil Society Mechanism (CSM), An analytical guide. http://www.fao.org/family-farming/detail/en/c/1104374/
D'Annolfo R, Gemmill-Herren B, Gräub B, Garibaldi LA (2017) A review of social and economic performance of agroecology. Int J Agric Sustain 15:632–644. https://doi.org/10.1080/14735903.2017.1398123
Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE 7:e47149. https://doi.org/10.1371/journal.pone.0047149
Dury S, Bendjebbar P, Hainzelin E, Giordano T, Bricas N (eds) (2019) Food systems at risk: new trends and challenges. FAO/CIRAD and European Commission, Rome/Montpellier/Brussels. https://doi.org/10.19182/agritrop/00080
Edwards MA, Roy S (2017) Academic research in the 21st century: maintaining scientific integrity in a climate of perverse incentives and hypercompetition. Environ Eng Sci 34:51–61. https://doi.org/10.1089/ees.2016.0223
Eyhorn F, Muller A, Reganold JP, Frison E, Herren HR, Luttikholt L, Mueller A, Sanders J, Scialabba NEH, Seufert V, Smith P (2019) Sustainability in global agriculture driven by organic farming. Nat Sustain 2:253–255. https://doi.org/10.1038/s41893-019-0266-6
Fabregas R, Kremer M, Schilbach F (2019) Realizing the potential of digital development: the case of agricultural advice. Science 336:6471. https://doi.org/10.1126/science.aay3038
Fanzo J, Hunter D, Borelli T, Mattei F (eds) (2013) Diversifying food and diets – using agricultural biodiversity to improve nutrition and health. Taylor/Francis Group, London/New York. https://www.bioversityinternational.org/e-library/publications/detail/diversifying-food-and-diets/
FAO (2017) The future of food and agriculture – trends and challenges. Rome. http://www.fao.org/3/a-i6583e.pdf
FAO (2018a) FAO'S work on agroecology – a pathway to achieving the SDGs. http://www.fao.org/3/i9021en/I9021EN.pdf
FAO (2018b) The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems. Rome. http://www.fao.org/3/i9037en/i9037en.pdf
FAO (2018c) The future of food and agriculture: Alternative pathways to 2050. http://www.fao.org/3/CA1553EN/ca1553en.pdf
FAO (2019) TAPE tool for agroecology performance evaluation 2019 – process of development and guidelines for application. Test version, Rome. http://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1257355/
Farrelly M (2016) Agroecology contributes to the sustainable development goals. Farming Matters 32:32–34
Ferrero R, Lima M, Davis AS, Gonzalez-Andujar JL (2017) Weed diversity affects soybean and maize yield in a long term experiment in Michigan, USA. Front Plant Sci 8:236. https://doi.org/10.3389/fpls.2017.00236
Geels FW (2011) The multi-level perspective on sustainability transitions: responses to seven criticisms. Environ Innov Soc Trans 1:24–40. https://doi.org/10.1016/j.eist.2011.02.002
Gliessman SR (2015) Agroecology: the ecology of sustainable food systems, 3rd edn. CRC Press/Taylor & Francis Group, Boca Raton. ISBN 9781439895610
Godfray C, Garnett T (2014) Food security and sustainable intensification. Philos Trans R Soc Ser B Biol Sci 369:20120273. https://doi.org/10.1098/rstb.2012.0273
Hebinck P, Schneider S, Van Der Ploeg JD (eds) (2014) Rural development and the construction of new markets. Routledge, London. ISBN 9780367869298
HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf

HLPE (2020) Issues paper on the Impact of COVID-19 on Food Security and Nutrition (FSN) by the High-Level Panel of Experts on Food Security and Nutrition (HLPE). http://www.fao.org/3/cb1000en/cb1000en.pdf
IIED (2015) Summary report of the high-level workshop on scaling up agroecology to achieve the SDGs. https://infohub.practicalaction.org/bitstream/handle/11283/594772/Agroecology_Workshop.pdf?sequence=1&isAllowed=y
IPBES (2019) The global assessment report on biodiversity and ecosystems services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). https://ipbes.net/fr/node/35274
IPCC (2019) Climate change and land. IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/srccl/
Jones AD, Shrinivas A, Bezner Kerr R (2014) Farm production diversity is associated with greater household dietary diversity in Malawi: findings from nationally representative data. Food Policy 46:1–12. https://doi.org/10.1016/j.foodpol.2014.02.001
Khourya CK, Bjorkmanc AD, Dempewolfd H, Ramirez-Villegas J, Guarino L, Jarvis A, Rieseberg LH, Struik PC (2014) Increasing homogeneity in global food supplies. Proc Natl Acad Sci 111: 4001–4006. https://doi.org/10.1073/pnas.1313490111
Lechenet M, Dessaint F, Py G, Makowski D, Munier-Jolain N (2017) Reducing pesticide use while preserving crop productivity and profitability on arable farms. Nat Plants 3:17008. https://doi.org/10.1038/nplants.2017.8
Leclère D, Obersteiner M, Barrett M, Butchart SH, Chaudhary A, De Palma A, DeClerck FA, Di Marco M, Doelman JC, Dürauer M, Freeman R (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585:551–556. https://doi.org/10.1038/s41586-020-2705-y
Leippert F, Darmaun M, Bernoux M, Mpheshea M, Müller A, Geck M, Herren M, Irungu W, Nyasimi M, Sene JM, Sow M (2020) The potential of agroecology to build climate-resilient livelihoods and food systems. FAO/Biovision, Rome. https://doi.org/10.4060/cb0438en
Liebman MZ, Schulte-Moore LA (2015) Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. Elementa 3(000041). https://doi.org/10.12952/journal.elementa.000041
Lucas V, Gasselin P, Van Der Ploeg JD (2019) Local inter-farm cooperation: a hidden potential for the agroecological transition in northern agricultures. Agroecol Sustain Food Syst 43:145–179. https://doi.org/10.1080/21683565.2018.1509168
Mäder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. Science 296:1694–1697. https://doi.org/10.1126/science.1071148
Meemken EM, Qaim M (2018) Organic agriculture, food security, and the environment. Ann Rev Resour Econ 10:39–63. https://doi.org/10.1146/annurev-resource-100517-023252
Mottet A, Bicksler A, Lucantoni D, De Rosa F, Scherf B, Scopel E, López-Ridaura S, Gemmil-Herren B, Bezner Kerr R, Sourisseau J-M, Petersen P, Chotte J-L, Loconto A, Tittonell P (2020) Assessing transitions to sustainable agricultural and food systems: a Tool for Agroecology Performance Evaluation (TAPE). Front Sustain Food Syst 4:579154. https://doi.org/10.3389/fsufs.2020.579154
Müller A, Schader C, Scialabba NEH, Bruggemann J, Isensee A, Erb KH, Smith P, Klocke P, Leiber F, Stolze M, Niggli U (2017) Strategies for feeding the world more sustainably with organic agriculture. Nat Commun 8:1290. https://doi.org/10.1038/s41467-017-01410-w
Muthini D, Nzuma J, Nyikal R (2020) Farm production diversity and its association with dietary diversity in Kenya. Food Secur 12:1107–1120. https://doi.org/10.1007/s12571-020-01030-1
Nemes, N. (2009) Comparative analysis of organic and non-organic farming systems: a critical assessment of farm profitability. FAO. http://saveoursoils.com
Pan G (2016) The cost of malnutrition: why policy action is urgent. Tech Brief No 3. http://www.glopan.org/sites/default/files/pictures/CostOfMalnutrition.pdf

Pardey PG, Chan-Kang C, Dehrner SP, Beddow JM (2016) Agricultural R&D is on the move. Nat News 537(7620):301. https://doi.org/10.1038/537301a
Perotti, A. (2020): Moving towards a sustainable Swiss food system: an estimation of the true cost of food in Switzerland and implications for stakeholders. Master thesis, ETH Zurich. https://doi.org/10.3929/ethz-b-000473289
Piñeiro V, Arias J, Dürr J, Elverdin P, Ibáñez AM, Kinengyere A, Morales Opazo C, Owoo N, Page JR, Prager SD, Torero M (2020) A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nat Sustain 3:809–820. https://doi.org/10.1038/s41893-020-00617-y
Polimeni JM, Mayumi K, Giampietro M, Alcott B (2008) The Jevons paradox and the myth of resource efficiency improvements. Routledge. ISBN 978-1-84407-462-4
Pretty J, Morison JI, Hine RE (2003) Reducing food poverty by increasing agricultural sustainability in developing countries. Agric Ecosyst Environ 95:217–234. https://doi.org/10.1016/S0167-8809(02)00087-7
Pretty JN, Noble AD, Bossio D, Dixon J, Hine RE, Penning de Vries FWT, Morison JIL (2006) Resource-conserving agriculture increases yields in developing countries. Environ Sci Technol 40:1114–1119. https://doi.org/10.1021/es051670d
Rosset PM, Machín SB, Roque Jaime AM, Ávila Lozano DR (2011) The Campesino-to-Campesino agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable peasant agriculture and food sovereignty. J Peasant Stud 38:161–191. https://doi.org/10.1080/03066150.2010.538584
Salliou N, Muradian R, Barnaud C (2019) Governance of ecosystem services in agroecology: when coordination is needed but difficult to achieve. Sustain 11:1158. https://doi.org/10.3390/su11041158
Schader C, Müller A, Scialabba NE, Hecht J, Isensee A, Erb KH, Smith P, Makkar HPS, Klocke P, Leiber F, Schwegler P, Stolze M, Niggli U (2015) Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability. J R Soc Interface 12:20150891. https://doi.org/10.1098/rsif.2015.0891
Seibert, I.G., Sayeed, A.T., Georgieva, Z., and Guerra, A. (2019): Without feminism, there is no agroecology. https://www.righttofoodandnutrition.org/files/rtfn-watch11-2019_eng-42-50.pdf
Seufert V, Ramankutty N (2017) Many shades of gray—the context-dependent performance of organic agriculture. Sci Adv 3:e1602638. https://doi.org/10.1126/sciadv.1602638
Sibhatu KT, Qaim M (2018) Review: meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. Food Policy 77:1–18. https://doi.org/10.1016/j.foodpol.2018.04.013
Smith A, Raven R (2012) What is protective space? Reconsidering niches in transitions to sustainability. Res Policy 41:1025–1036. https://doi.org/10.1016/j.respol.2011.12.012
Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J (2008) Greenhouse gas mitigation in agriculture. Philos Trans R Soc B 363:789–813. https://doi.org/10.1098/rstb.2007.2184
Smolik JD, Dobbs TL, Rickerl DH (1995) The relative sustainability of alternative, conventional, and reduced-till farming systems. Am J Altern Agric 10:25–35. https://doi.org/10.1017/S0889189300006081
Tittonell PA (2013) Farming systems ecology. Towards ecological intensification of world agriculture. Inaugural lecture. Wageningen University. https://edepot.wur.nl/258457
Tittonell PA (2014) Ecological intensification of agriculture—sustainable by nature. Curr Opin Environ Sustain 8:53–61. https://doi.org/10.1016/j.cosust.2014.08.006
Triboulet P, Del Corso JP, Duru M, Galliano D, Gonçalves A, Milou C, Plumecocq G (2019) Towards an integrated framework for the governance of a territorialised Agroecological transition. In: Bergez JE, Audouin E, Therond O (eds) Agroecological transitions: from theory to practice in local participatory design. Springer, Cham. https://doi.org/10.1007/978-3-030-01953-2_7

Tuck SL, Winqvist C, Mota F, Ahnström J, Turnbull LA, Bengtsson J (2014) Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J Appl Ecol 51: 746–755. https://doi.org/10.1111/1365-2664.12219

UNCTAD/UNEP (2008) Organic agriculture and food security in Africa. United Nations, New York. https://unctad.org/en/Docs/ditcted200715_en.pdf

United Nations, Department of Economic and Social Affairs, Population Division (2019) World Urbanization prospects: the 2018 Revision (ST/ESA/SER.A/420). United Nations, New York. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

Uphoff N (2007) Agroecological alternatives: capitalising on existing genetic potentials. J Dev Stud 43(1):218–236. https://doi.org/10.1080/00220380601055700

Van der Ploeg JD (2021) The political economy of agroecology. J Peasant Stud 48:274–297. https://doi.org/10.1080/03066150.2020.1725489

Van der Ploeg JD, Barjolle D, Bruil J, Brunori G, Madureira LMC, Dessein J, Drąg Z, Fink-Kessler A, Gasselin P, de Molina MG, Gorlach K (2019) The economic potential of agroecology: empirical evidence from Europe. J Rural Stud 71:46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003

Wezel A (2020) Agroecological approaches and other innovations. In: Herren H, Haerlin B, IAASTD+10 Advisory group (eds) Transformation of our food systems. The making of a paradigm shift. https://www.globalagriculture.org/transformation-of-our-food-systems.html

Wezel A, Goris M, Bruil J, Félix GF, Peeters A, Bàrberi P, Bellon S, Migliorini P (2018) Challenges and action points to amplify agroecology in Europe. Sustain 10:1598. https://doi.org/10.3390/su10051598

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S, Murray CJL (2019) Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Wood S, Cowie A (2004) A review of greenhouse gas emission factors for fertiliser production. Research and Development Division, State Forests of New South Wales Cooperative Research Centre for Greenhouse Accounting. http://www.sciencetheearth.com/uploads/2/4/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf

World Resources Institute (2018): Creating a sustainable food future. Synthesis report, December 2018. https://www.wri.org/research/creating-sustainable-food-future-0

WWF (2021) Farming with biodiversity towards nature-positive production at scale. WWF International, Gland

A New Paradigm for Plant Nutrition

Achim Dobermann, Tom Bruulsema, Ismail Cakmak, Bruno Gerard, Kaushik Majumdar, Michael McLaughlin, Pytrik Reidsma, Bernard Vanlauwe, Eva Wollenberg, Fusuo Zhang, and Xin Zhang

1 Introduction and Background

World agricultural output has grown at an average annual rate of about 2.2% during the past 60 years, although with huge variations among countries (Fuglie 2018). Similar growth will be required in the near future to feed a growing world population and improve rural livelihoods. Over the longer term, slowing population growth, changing diets, reduced food losses and waste, and increased nutrient recycling will

Prepared by members of the Scientific Panel on Responsible Plant Nutrition France.

A. Dobermann (✉)
International Fertilizer Association, Paris, France
e-mail: adobermann@fertilizer.org

T. Bruulsema
Plant Nutrition Canada, Guelph, Canada

I. Cakmak
Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul, Turkey

B. Gerard
Mohammed VI Polytechnic University, Ben Guerir, Morocco

K. Majumdar
African Plant Nutrition Institute, Benguerir, Morocco

M. McLaughlin
Fertiliser Technology Research Centre, University of Adelaide, Adelaide, Australia

P. Reidsma
Plant Production Systems, Wageningen University & Research, Wageningen, The Netherlands

B. Vanlauwe
International Institute of Tropical Agriculture, Nairobi, Kenya

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_19

ease the pressure to produce more food and utilize more natural resources in that process.

Historically, economic development has been faster in regions of the world where fertilizer use and crop yields rose in parallel (McArthur and McCord 2017). The increasing access to mineral fertilizers has been one of the main factors in feeding the rapidly growing world population (Smil 2001). Rapid increases in crop yields also prevented a much larger expansion of agriculture into natural lands that would have otherwise occurred (Stevenson et al. 2013). On the other hand, in many regions, intensive farming to support the emerging food consumption patterns has resulted in nutrient-related externalities that are difficult to manage, such as land degradation, biodiversity loss, unsustainable water withdrawal, eutrophication of many freshwater and coastal marine ecosystems, increased greenhouse gas emissions or inequality among farmers (Balmford et al. 2018).

Anthropogenic perturbation levels of global nitrogen and phosphorus flows may already exceed limits that are deemed to be a safe operating space for humanity (Steffen et al. 2015). While agricultural activities at the farm level account for 9–4% of greenhouse gas (GHG) emissions from all human activities, a full accounting of the global food system, including land use change and fertilizer production, raises the figure to 21–37% (Rosenzweig et al. 2020). Human-induced emissions of nitrous oxide (N_2O), which are dominated by fertilizer additions to croplands, have increased by 30% since the 1980s (Tian et al. 2020). Current food systems also favor the cultivation of staple crops at the expense of more micronutrient-rich food crops. While hunger and malnutrition have significantly declined in recent decades, they have stubbornly persisted in sub-Saharan Africa and other regions, including micronutrient-related deficiencies that particularly affect women and children (Pingali et al. 2017). The number of people who do not have access to sufficient and nutritious food may continue to rise again due to conflict, climate extremes, economic downturns, or outbreaks of diseases (FAO, IFAD, UNICEF, WFP and WHO 2020).

It has been estimated that $12 trillion in hidden health, environmental and socio-economic costs are associated with the global food system, which is larger than the system's output at current prices (The Food and Land Use Coalition 2019). While food security through increasing crop and animal productivity will remain hugely important in light of an expected population of about 9.5 billion by 2050 (Vollset et al. 2020), it is no longer the only objective. The transition to a more sustainable global food system requires all stakeholders to manage nutrients and their entire life

E. Wollenberg
Alliance of Bioversity International and CIAT and Gund Institute for Environment, University of Vermont, Burlington, VT, USA

F. Zhang
China Agricultural University, Beijing, China

X. Zhang
University of Maryland Center for Environmental Science, Frostburg, MD, USA

cycle in a more holistic manner. Future plant nutrition solutions will have to address multiple global and regional challenges related to nutrients in the food system.

In that context, there are ten higher-level questions that need to be resolved within the next 20 years:

1. **How can we overcome the current global nutrient imbalance?** For many decades, rising crop and livestock production was closely coupled with increasing input of nitrogen and other nutrients, as well as international trade of feed and food. This has led to a global divide, ranging from large nutrient input-output surpluses and environmental pollution in some regions to large nutrient deficits in others (Fig. 2). On a global scale, how can future growth in primary crop production be decoupled from growth in fertilizer consumption? What are the country-specific targets and roadmaps for fertilizer use and nutrient use efficiency that will enable that?
2. **What are the key measures to double or triple crop yields in Africa with increasing and balanced nutrient inputs?** Africa has massive nutrient deficits that must be overcome in order to increase crop yields and achieve higher levels of food security within one generation (van Ittersum et al. 2016). The average fertilizer use in sub-Saharan Africa is about 20 kg nutrients/ha and exceeds 50 kg/ha in only few countries, which is far below what is required to boost crop production and replenish soil fertility after decades of depletion (Fig. 1). Fertilizer alone will not be sufficient to lift crop yields, but it is a key ingredient to trigger an African Green Revolution (Vanlauwe and Dobermann 2020), which must be based on good information, incentives for the efficient use of nutrients, and specific measures to tackle the persistent forms of malnutrition as well.
3. **What data-driven technologies, business solutions and policies will accelerate the adoption of more precise nutrient management solutions by farmers?** In many countries, farmers apply too great an amount of nutrients because they are relatively cheap or because they do not want to risk loss of yield. In other situations, farmers apply insufficient nutrients or in the wrong formulations because of lack of affordability, access, knowledge or data. Many good examples exist worldwide as to how to overcome this, but only a few have led to breakthroughs on a larger scale.
4. **Can nutrient losses and waste along the whole agri-food chain be halved within one generation?** Current estimates suggest that, at the global scale, only around 20% of applied nitrogen compounds may reach useful products, with up to 80% lost to the environment in different forms (Sutton et al. 2012). There are huge variations in nutrient losses among countries and their food systems that can be addressed through various means, including greater recovery of nutrients from various waste streams in forms that allow for safe recycling back to crop production.
5. **How can nutrient cycles in crop and livestock farming be closed?** Globally operating demand drivers and supply chains have caused a separation and

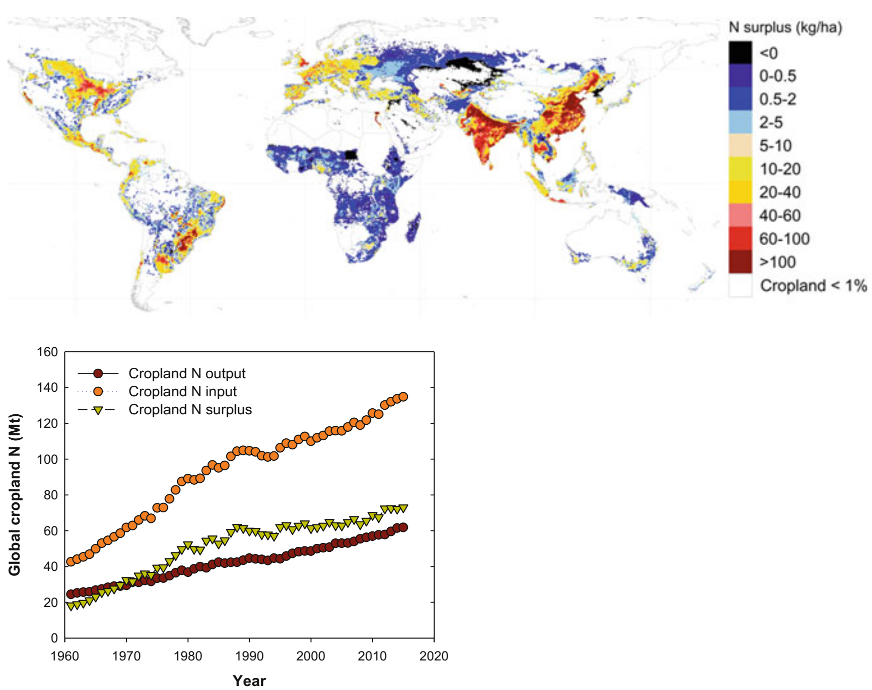


Fig. 1 Global trends in crop nitrogen output, input from fertilizer and other sources, and annual nitrogen surplus (left), and a map of nitrogen surplus or deficit in 2015 (top, kg N/ha). N surplus is defined as the total N input to cropland minus N harvested as crop products (Zhang et al. 2015); it is expressed as million tons (Mt) in the left panel, and as kg per hector land area in the top panel, indicating the potential pressure due to N lost from crop production. (Source: Xin Zhang and Guolin Yao, University of Maryland Center for Environmental Science)

concentration of crop and livestock farming, resulting in spatially disconnected, leaky nutrient cycles. The massive growth of the livestock sector has led to low nutrient use efficiency, increased waste and large greenhouse gas emissions. Global livestock supply chains account for one-third of all human-induced nitrogen emissions (Uwizeye et al. 2020). Sustainable livestock production includes more pasture-based systems and re-integration of crop and livestock farming to utilize animals for what they are good at: converting by-products from the food system and forage resources into valuable food and manure (van Zanten et al. 2019). What future farm structures, technologies and supply chains will enable that?

6. **How can we improve soil health?** Soils are vital for growing crops, but they also support other essential ecosystem services, such as water purification, carbon sequestration, nutrient cycling and the provision of habitats for biodiversity. Carbon and nutrient inputs are important triggers for improving soil health in crop production, which also increases the resilience of farming systems to extreme climatic events. Sequestration of atmospheric CO_2 in soils can

contribute to reducing global warming and improving soil health, but requires continuous organic matter inputs and nutrient inputs (particularly nitrogen and phosphorus) to form stable soil organic matter. How can a holistic plant nutrition approach manage macro- and micronutrients for high crop productivity and nutrient use efficiency, but also utilize biological N fixation, optimize carbon storage and turnover, increase soil biodiversity, and avoid soil acidification or other forms of degradation?

7. **How should we manage the nutrition of crops in changing climates?** Climate change has positive, as well as negative, impacts on the nutritional quality of crops, many of which are not yet well understood (Soares et al. 2019). Rising atmospheric carbon dioxide (CO_2) may increase crop yields, but also cause declining nutrient concentrations and nutrient use efficiency of food crops. Global warming will increase the risk of crop stresses such as drought, heat or high radiation, for which balanced plant nutrition plays particular roles in mitigation. Changes in seasonality, precipitation and extreme weather events will also affect the timing and efficiency of nutrient uptake, requiring integration of nutrient advisories with early warning and climate information systems.
8. **What are realistic options and targets for reducing fertilizer-related greenhouse gas emissions?** All pathways that limit global warming to 1.5 °C or well below 2 °C require land-based mitigation and land use change (IPCC 2019). Across the plant nutrition sector, low-emission "green" fertilizer production and transportation technologies, novel fertilizer formulations, inhibitors, and genetic solutions to nitrification inhibition or fixing atmospheric N, as well as more precise nutrient application and agronomic field management, offer numerous opportunities to reduce nutrient-related emissions of CO_2 and N_2O – provided that the surrounding policies and market conditions enable it.
9. **How can cropping systems deliver higher quality, more nutritious food?** More than two billion people in the world are affected by various forms of micronutrient malnutrition. The world's major cropping systems are designed to provide calories, protein and a number of other nutrients or bioactive compounds. A handful of micronutrient-poor crops dominate the global food and feed chains and have often decreased crop diversity or displaced traditional crops such as pulses. What agricultural practices can be deployed to improve human nutrition, including plant nutrition solutions (Welch et al. 2013)?
10. **How can we better monitor nutrients and implement high levels of sustainability stewardship?** Digital technologies offer great potential for better monitoring, analysis, benchmarking, reporting and certification of sustainability efforts across the entire nutrient chain. This would improve transparency, traceability, quality control, and sustainability assessment in the whole food sector, and it is also critical for public sector engagement and evidence-based policymaking. How, for example, can the International Code of Conduct for the Sustainable Use and Management of Fertilizers (FAO 2019) or criteria for Environmental, Social, and Governance (ESG) be implemented by countries and industry? Is there a need for a new standard on sustainable production and the use of nutrients?

2 What Can Be Done?

Human development, biological process requirements and mass balance principles make it clear that mineral nutrients, including fertilizers, will continue to be major ingredients of future food systems. **It is critical to develop integrated and targeted plant nutrition strategies and practices that minimize tradeoffs between productivity and the environment – and are viable in the farming and business systems of different regions, nations and localities.** Integration in this context has several dimensions, including a multi-nutrient food system approach, greater recycling and utilization of all available nutrient sources, alignment with other agronomic and stewardship practices, and compliance with high sustainability standards.

The new paradigm of **responsible plant nutrition** encompasses a broad array of scientific and engineering know-how, technologies, agronomic practices, business models and policies that directly or indirectly affect the production and utilization of mineral nutrients in agri-food systems. Following a food system approach, responsible plant nutrition aims to:

A. Improve income, productivity, nutrient efficiency and resilience of farmers and the businesses supporting them
B. Increase nutrient recovery and recycling from waste and other under-utilized resources
C. Lift and sustain soil health
D. Enhance human nutrition and health through nutrition-sensitive agriculture
E. Minimize greenhouse gas emissions, nutrient pollution and biodiversity loss

In a nutshell, responsible plant nutrition will contribute to a more nature-positive approach to food production and consumption. It does not aim to blindly copy nature, but, following science, it does adapt and integrate key agroecological principles (FAO 2018) in a tailored manner. Implementing the new paradigm involves six interdependent actions (Fig. 2):

Action 1: Sustainability-driven nutrient policies, roadmaps, business models and investments that create added value for all actors and beneficiaries in the nutrient chain. Nutrient policies and roadmaps must be tailored to the specific food systems in every country, including ambitious goals for nutrient use, losses and efficiency. Specific targets and priorities for managing nutrients will vary, depending on each country's history and sustainable development priorities. Progressive science-based monitoring, stewardship (International Plant Nutrition Institute 2016) and certification schemes will guide performance and reward farmers and businesses for innovation, reduction of nutrient losses, improvement of soil health,

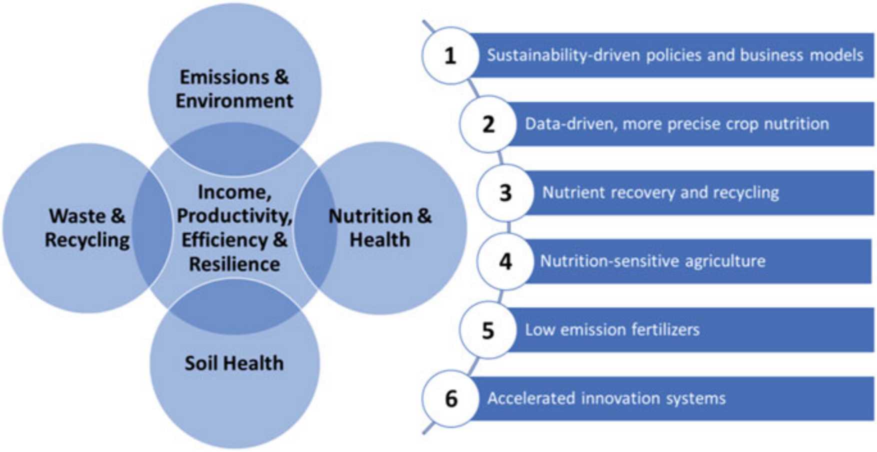


Fig. 2 The five interconnected aims of responsible plant nutrition, and six key actions to take

enhancement of biodiversity and provision of other ecosystem services. Differentiated strategies will also lead to regional shifts in global fertilizer use, reducing nutrient surpluses and ensuring that more nutrients are moved to where they are most lacking, particularly in many parts of Africa (Zhang 2017).

Action 2: Data-driven, more precise crop nutrition solutions. Knowledge-driven digital solutions and disruptive technologies will allow for tailoring nutrient applications to local needs in an increasingly precise manner. Besides high-tech solutions for commercial farming, "low-tech" site-specific nutrient management approaches have shown consistent, large increases in crop yields and profits and nutrient use efficiency in many crops grown by smallholder farmers in Asia and Africa (Dobermann et al. 2002; Rurinda et al. 2020). They now need to be upscaled to millions of farmers through digitally supported advisory systems and business solutions.

Action 3: Circular economy solutions for greater nutrient recovery and recycling. Crop-livestock integration, less food waste, use of by-products and increased nutrient recovery and recycling are key measures to optimize nutrient use efficiency across the full food chain (Fig. 3). Political incentives, novel technologies and shifts in behavior will drive greater nutrient recycling from multiple waste streams, as a key contribution to circular, bio-based economies. Such circular systems need to be safe and healthy for animals, humans and the environment, but they also allow for the creation of novel business models, including side-streams within the agricultural sector for the up-cycling of materials and the nutrients that they contain. Improved full-chain nutrient flow monitoring, life-cycle analysis, benchmarking and certification will support the development of such solutions.

Action 4: Nutrition-sensitive farming – producing food crops with higher nutritional value to address persistent, as well as emerging, mineral nutrient deficiencies. Besides dietary diversification and food interventions, plant nutrition

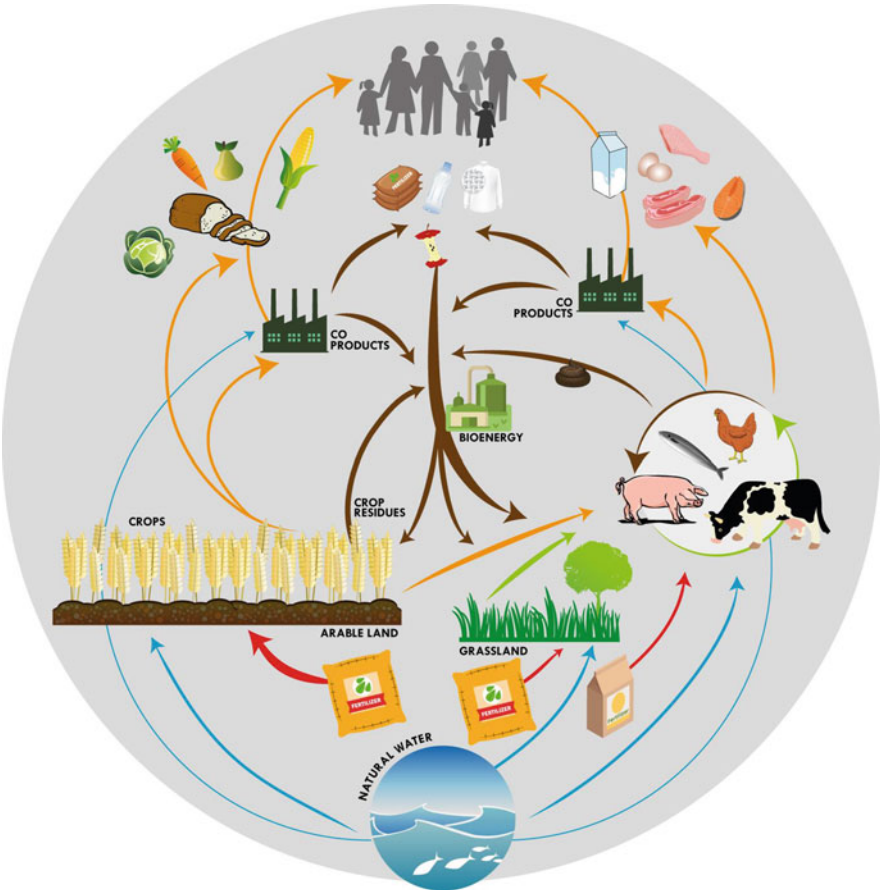


Fig. 3 Major nutrient flows in circular crop-livestock-human systems. Red arrows indicate fertilizer inputs into the system. Fertile land is primarily used to produce food for humans and some supplementary feed for livestock, as are crop residues (orange arrows). Grassland is primarily used for livestock, including grazing. By-products and waste are recycled back to agriculture or used to make new bio-based products (brown arrows). Leakages out of the circular system are minimized. (Source: Re-drawn and modified from van Zanten et al. 2019)

solutions are part of strategies for addressing the triple burden of undernutrition, micronutrient malnutrition, overweight/obesity and other non-communicable diseases. Depending on the local context, nutrition-sensitive crop production may include more diverse crop rotations, as well as biofortification of staple crops with micronutrients through breeding and/or fertilizers (Cakmak and Kutman 2018). The latter involves the targeted use of fertilizer products that deliver micronutrients of importance to crops, animals and humans. Besides essential plant nutrients such as iron or zinc, this may also include nutrients that are of particular importance to animals and humans, such as iodine (Fuge and Johnson 2015) or selenium (Alfthan et al. 2015).

Action 5: Energy-efficient, low-emission fertilizers. Fertilizers will increasingly be produced in an environmentally-friendly manner, and they will embody greater amounts of knowledge as to how to control the release of nutrients to the plant. Significant reductions in pre-farm greenhouse gas emissions can be achieved through low-carbon emission fertilizer production. Various new technologies are already being piloted to produce "green ammonia" from renewable, carbon-neutral energy sources, as well as to use it for energy storage and transport. A new "ammonia economy" could feed and power the world in a whole new, decentralized manner (Rouwenhorst et al. 2019). Innovation in fertilizer formulation will lead to environmentally-friendly fertilizers that maximize nutrient capture by the crop and minimize losses of nutrients (Chen et al. 2018).

Action 6: Accelerated, more open innovation systems for faster translation of new ideas into practice. Future research and innovation systems need to foster the co-creation and sharing of knowledge for rapid development and deployment of new know-how and technologies. This requires more openness and coordinated action from public and private sector players. A massive cultural change is needed in science and science funding, towards a problem-focused and leaner science approach, transdisciplinary collaboration, entrepreneurship, and early engagement with users – including the full diversity of farmers.

Who needs to do what?

Responsible plant nutrition is a complex and global challenge, which can only be tackled through concrete action by all those directly involved in the nutrient cycle, as well as those influencing it (Fig. 4).

Policymakers at all levels need to create clear, science-based and harmonized regulatory frameworks for nutrients, but also dynamic policies that incentivize innovation in technologies, practices and business models. They must set out a clear vision for national or regional roadmaps with sound targets for nutrients, nutrition and environmental indicators. They can drive changes in food consumption, as well as provide progressive incentives for the adoption of better practices by

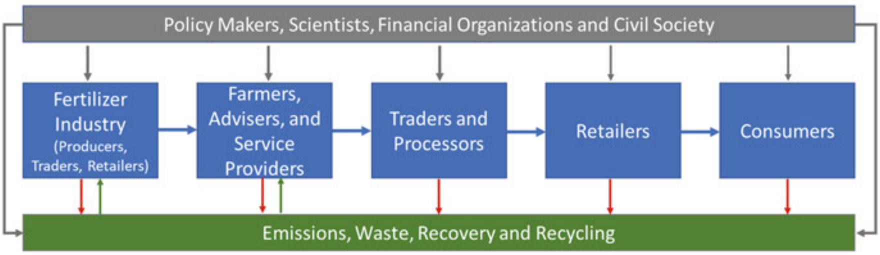


Fig. 4 The agri-food chain from a nutrient management perspective. Blue boxes show actors who directly contribute to nutrient use and losses at different stages. Red arrows indicate greenhouse gas emissions, nutrient losses into the environment and waste that can happen along all parts of the chain. All opportunities to reduce emissions and losses must be exploited, while also increasing nutrient recovery and return to farming and industry (green arrows). The grey box shows actors who influence the major actors, drive innovation or set the societal framework for action. (Source: Modified from Kanter et al. 2020)

farmers. Policies need to properly balance food production and environmental goals. Technical assistance and extension services must be supported adequately to promote sustainable practices. Policymakers also need to ensure that farmers all over the world have affordable access to the internet and digital services.

The global fertilizer industry has recently recognized the need for a sustainability- and innovation-driven plant nutrition approach as its core business strategy (International Fertilizer Association (IFA) 2018). Fertilizer companies will have to increasingly become providers of integrated plant nutrition solutions based on new business models that do what is right for people and the planet. Sustainability and innovation, including transparent monitoring and reporting, will drive the transformation strategy for the entire industry, for every product and solution sold. Revenue growth primarily needs to be driven by growth in the performance value offered to farmers and society, not in the volume of fertilizers sold.

Farmers, farm advisers and service providers carry the primary responsibility for improving nutrient use efficiency, reducing nutrient losses, recycling nutrients and promoting soil health at the farm scale, which has huge implications at larger scales. They need to be able to fully adapt and adopt new knowledge, technology, and services, and they need to be rewarded for good practices. Many farmers are entrepreneurs, and thus willing to change, and they are also aware of their role as stewards of land, water, climate and biodiversity. But doing things differently requires lowering risks and other adoption barriers.

Food traders, processors and retailers have enormous power to influence nutrient cycles, both through influencing what consumers eat or drink and how it is being produced. Vertically integrated, data-driven and more transparent supply chains that meet sustainable production standards and reduce production losses will become more widespread, including more direct sourcing from farmers. These developments offer numerous opportunities for implementing more holistic approaches to nutrient management. Monetizing such sustainable production practices is both a key challenge and an opportunity.

Consumers will drive significant changes in plant nutrition through changes towards healthier diets, as well as an increasing emphasis on food that is produced in a more sustainable manner. Specific trends will differ among regions and income groups. On a global scale, changes in food behavior may be relatively slow and will also be partly compensated for by growing food consumption due to rising populations and income growth in low and middle income countries. However, an immediate responsibility of consumers is to reduce excessive meat consumption, waste less food and ensure recycling of the waste that does occur.

Utility service providers and waste processors are an important and relatively new category of actors in the nutrient cycle, but their role will increase substantially in the coming years. Particularly in densely populated areas, their needs and actions will increasingly co-define how farming and nutrient management will be effected. This requires deepening the collaboration with other groups of actors and jointly developing a common understanding, as well as common standards to meet.

Investors: Investment in plant nutrition research and innovation will need to increase massively in order to meet the complex plant nutrition challenges we face.

Public, private and philanthropic investors should increasingly invest in technologies, businesses and organizations that support key elements of the new paradigm, including creating a growing ecosystem of startup companies and other enterprises. Use of blended public and private capital can de-risk and leverage more private investment.

Scientists: Science and engineering will underpin all efforts to achieve the multiple objectives of the new plant nutrition paradigm, but the entire science culture must change too, towards new ways of working that stimulate new discoveries and achieve faster translation into practice. Greater focus on explicit pathways to agronomic applications, reality checks and rigor in claims of utility are needed, as well as more sharing of know-how and critical resources, more open innovation and more entrepreneurship.

Civil society organizations play significant roles in the new paradigm through informing the public, grassroots mobilization, monitoring, alerting and influencing, and inclusive dissemination of new technologies and practices. This is a big responsibility, which should follow an evidence-based approach. The co-development of concrete solutions in partnership with government, industry, science and farmers should replace the all too prevalent emphasis on single issues or controversial debates.

What will success look like?

Compared to where we are in 2020, the following concrete outcomes can be achieved within one generation, by 2040:

1. Widely accepted standards for quantifying and monitoring nutrients along the food supply chain inspire solutions for improving overall nutrient use efficiency, increasing recycling and reducing nutrient waste across the whole agri-food system. Ambitious targets, policies and investments stimulate collective actions by governments, businesses, farmers and other stakeholders towards sustainable, integrated, and tailored plant nutrition solutions.
2. On a global scale, crop yield growth meets food, feed and bio-industry demand and outpaces growth in mineral fertilizer consumption, while cropland expansion and deforestation have been halted. Global crop nitrogen use efficiency – the nitrogen output in products harvested from cropland as a proportion of nitrogen input – increases to 70%.
3. Through responsible consumption, increased recycling, and better management practices, nutrient waste along the food system is halved. Nitrogen and phosphorus surpluses in hotspots are reduced to safe levels that minimize eutrophication and other environmental harm.
4. Soil nutrient depletion and carbon loss are halted. Forward-looking policies and investments trigger changes in farming systems and management practices that increase soil health, including soil organic matter. Regional soil nutrient deficits are reduced substantially, particularly in sub-Saharan Africa, where fertilizer use has tripled and crop yield has at least doubled, including improved nutritional outputs. Millions of hectares of degraded agricultural land are restored, including

through the use of mineral and organic fertilizers and nutrient-containing waste or by-products.

5. Extreme forms of chronic hunger and nutrient-related malnutrition are eradicated through integrated strategies that include the targeted use of micronutrient-enriched fertilizers and nutrient-biofortified crops. A new generation of more nutritious cereals and other staple crops is increasingly grown by farmers, driven by consumer and market demand. Policy and decision-makers support mineral fertilization strategies for meeting specific human nutritional needs where markets do not provide the needed incentives.
6. The fertilizer industry follows rigorous and transparent sustainability standards for the entire life cycle of its products and business operations. Greenhouse gas emissions from fertilizer production and use are reduced by at least 30% through increased energy efficiency, carbon capture and storage and other novel technologies and products. At least 10% of the world's fertilizer-N is produced from green ammonia with very low or zero carbon emission.
7. R&D investments in plant nutrition research and innovation by public and private sector are tripled compared to present levels. Many companies spend 5% or more of their gross revenue on research and innovation. Collaborative, open innovation approaches allow for scientific discoveries to become quickly translated into practical solutions and knowledge. Innovative, value-oriented business models drive growth throughout the industry.
8. Consumers appreciate the benefits of plant nutrients, including mineral fertilizers as a primary nutrient source. A nutrient footprint standard with high visual recognition informs consumer choices. Information on improvement of soil health and nutrient balances is widely available, and their linkage to the mitigation of air, water and climate issues will be broadly acknowledged.
9. Farmers all over the world have access to affordable, diverse and appropriate plant nutrition solutions, and they are being rewarded for implementing better nutrient management and stewardship practices that increase their prosperity and enable them to exit poverty traps. Customized crop nutrition products and solutions account for at least 30% of the global crop nutrition market value.

So far, we have failed to achieve the goals stated above, despite many scientific and technical solutions that have existed for decades. Achieving it now, within one generation, will require a far more concerted effort by everyone involved, from the fertilizer industry to farmers and consumers of food and other agricultural products. Fast action – grounded in long-term sustainability thinking – is needed to facilitate the transition towards a new paradigm for plant nutrition.

References

Alfthan G et al (2015) Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: from deficiency to optimal selenium status of the population. J Trace Elem Med Biol 31:142–147. https://doi.org/10.1016/j.jtemb.2014.04.009

Balmford A et al (2018) The environmental costs and benefits of high-yield farming. Nat Sustain 1: 477–485. https://doi.org/10.1038/s41893-018-0138-5
Cakmak I, Kutman UB (2018) Agronomic biofortification of cereals with zinc: a review. Eur J Soil Sci 69:172–180. https://doi.org/10.1111/ejss.12437
Chen J et al (2018) Environmentally friendly fertilizers: a review of materials used and their effects on the environment. Sci Total Environ 613–614:829–839. https://doi.org/10.1016/j.scitotenv.2017.09.186
Dobermann A et al (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res 74:37–66
FAO (2018) The 10 elements of agroecology. Guiding the transition to sustainable food and agricultural systems. Available at http://www.fao.org/3/i9037en/i9037en.pdf
FAO (2019) International code of conduct for the sustainable use and management of fertilizers. Available at http://www.fao.org/3/ca5253en/ca5253en.pdf
FAO, IFAD, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world 2020. Available at http://www.fao.org/documents/card/en/c/ca9692en/
Fuge R, Johnson CC (2015) Iodine and human health, the role of environmental geochemistry and diet, a review. Appl Geochem 63:282–302. https://doi.org/10.1016/j.apgeochem.2015.09.013
Fuglie KO (2018) Is agricultural productivity slowing? Glob Food Sec 17:73–83. https://doi.org/10.1016/j.gfs.2018.05.001
International Fertilizer Association (IFA) (2018) IFA 2030 scenarios. Digging deeper, thinking harder, planning further. Available at https://www.fertilizer.org/Public/About_IFA/IFA2030.aspx
International Plant Nutrition Institute (2016) 4R plant nutrition manual: a manual for improving the management of plant nutrition, metric version. IPNI, Norcross
IPCC (2019) Climate change and land. IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Available at https://www.ipcc.ch/srccl/
Kanter DR et al (2020) Nitrogen pollution policy beyond the farm. Nat Food 1:27–32. https://doi.org/10.1038/s43016-019-0001-5
McArthur JW, McCord GC (2017) Fertilizing growth: agricultural inputs and their effects in economic development. J Dev Econ 127:133–152. https://doi.org/10.1016/j.jdeveco.2017.02.007
Pingali P, Mittra B, Rahman A (2017) The bumpy road from food to nutrition security – slow evolution of India's food policy. Glob Food Sec 15:77–84. https://doi.org/10.1016/j.gfs.2017.05.002
Rosenzweig C et al (2020) Climate change responses benefit from a global food system approach. Nat Food. 1:94–97. https://doi.org/10.1038/s43016-020-0031-z
Rouwenhorst KHR, van der Ham AGJ, Mul G, Kersten SRA (2019) Islanded ammonia power systems: technology review & conceptual process design. Renew Sust Energ Rev 114:109339. https://doi.org/10.1016/j.rser.2019.109339
Rurinda J et al (2020) Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa. Agric Syst 180:102790
Smil V (2001) Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production. The MIT Press, London
Soares JC, Santos CS, Carvalho SMP, Pintado MM, Vasconcelos MW (2019) Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. Plant Soil 443:1–26. https://doi.org/10.1007/s11104-019-04229-0
Steffen W et al (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:1259855. https://doi.org/10.1126/science.1259855
Stevenson JR, Villoria N, Byerlee D, Kelley T, Maredia M (2013) Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proc Natl Acad Sci 110:8363–8368. https://doi.org/10.1073/pnas.1208065110

Sutton M A et al. (2012) Our nutrient world: the challenge to produce more food and energy with less pollution. Available at https://www.unenvironment.org/resources/report/our-nutrient-world-challenge-produce-more-food-and-energy-less-pollution
The Food and Land Use Coalition (2019) Growing better: ten critical transitions to transform food and land use. Available at https://www.foodandlandusecoalition.org/global-report/
Tian H et al (2020) A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586:248–256. https://doi.org/10.1038/s41586-020-2780-0
Uwizeye A et al (2020) Nitrogen emissions along global livestock supply chains. Nat Food 1(7): 437–446. https://doi.org/10.1038/s43016-020-0113-y
van Ittersum MK et al (2016) Can sub-Saharan Africa feed itself? Proc Natl Acad Sci 113:14964–14969. https://doi.org/10.1073/pnas.1610359113
van Zanten HHE, van Ittersum MK, de Boer IJM (2019) The role of farm animals in a circular food system. Glob Food Sec 21:18–22. https://doi.org/10.1016/j.gfs.2019.06.003
Vanlauwe B, Dobermann A (2020) Sustainable intensification of agriculture in sub-Saharan Africa: first things first! Front Agr Sci Eng 7:376–382. https://doi.org/10.15302/J-FASE-2020351
Vollset SE et al (2020) Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the global burden of disease study. Lancet 396(10258):1285–1306. https://doi.org/10.1016/S0140-6736(20)30677-2
Welch R M, Graham RD, Cakmak I (2013) Linking agricultural production practices to improving human nutrition and health. Expert paper written for ICN2 Second International Conference on Nutrition Preparatory Technical Meeting, 13–15 November, Rome, Italy. Available at http://www.fao.org/3/a-as574e.pdf
Zhang X (2017) A plan for efficient use of nitrogen fertilizers. Nature 543:322–323. https://doi.org/10.1038/543322a
Zhang X et al (2015) Managing nitrogen for sustainable development. Nature 528:51–59. https://doi.org/10.1038/nature15743

Livestock and Sustainable Food Systems: Status, Trends, and Priority Actions

Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen, Ty Beal, Carlos Gonzalez, and Margaret Gill

1 Introduction

There is growing global consensus of the need to transform food systems in order to achieve critical global goals at the intersection of human and planetary well-being. The Sustainable Development Goals (SDGs) stress that, to meet future needs, we need to use land more sustainably, minimise negative impacts on the environment, and seek opportunities to restore lands that have lost nutrients and/or biodiversity. Simultaneously, it is crucial to provide all people with access to a more nutritious

M. Herrero (✉)
Cornell Global Development, Cornell Atkinson Centre for Sustainability. College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA
e-mail: Mario.Herrero@cornell.edu

D. Mason-D'Croz
Cornell Global Development, College of Agriculture and Life Sciences, Cornell University. Agricultural Economics and Rural Policy Group, Wageningen University & Research, Wageningen, the Netherlands

P. K. Thornton
CGIAR Research Programme on Climate Change Agriculture and Food Security, ILRI, Nairobi, Kenya

J. Fanzo · A. Bellows
Bloomberg School of Public Health and the Nitze School of Advanced International Studies, Johns Hopkins University, Baltimore, MD, USA

J. Rushton
Department of Livestock and One Health, Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, Liverpool, UK

C. Godde · J. Palmer
Commonwealth Scientific and Industrial Research Organisation, Canberra, Australia

A. de Groot
Impact Institute, Amsterdam, the Netherlands

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_20

diet, and hence future food systems must provide a diverse range of affordable foods to enable all people to have access to diets of high nutritional quality.

The livestock sector is an important part of these challenges, since, on one hand, it is a major user of land, but, on the other hand, it provides micronutrient-dense food with high-quality protein. Here, we provide a synthesis of the current understanding of the dynamics of the livestock sector in terms of use of natural resources, trade between countries and the synergies and trade-offs caused by the changing nature of the demand and supply of ASF (including milk, meat, eggs, and fish in this study). We discuss the kinds of policies, governance processes and institutions that might minimise negative interactions and maximise positive synergies. We conclude with a brief exposition of the possible implications for the international agricultural research agenda, along with eight priority actions that need to be deployed simultaneously and in combination to ensure that livestock contribute to sustainable food systems, leaving no one behind.

2 Background and Trends

Analyses of trends of the livestock sector suggest that, as incomes increase and societies urbanise, per capita consumption of livestock products increases (Delgado et al. 1999). This, together with increases in population, means that the total demand for livestock products would grow substantially. This phenomenon, while mostly true, hides substantial heterogeneity in terms of the types of livestock products that

J. Chang
College of Environmental and Resource Sciences, Zhejiang University, Zhejiang, China

H. van Zanten
Farming Systems Ecology Group, Wageningen University & Research, Wageningen, the Netherlands

B. Wieland
International Livestock Research Institute, Addis Ababa, Ethiopia and Institute of Virology and Immunology, University of Bern, Bern, Switzerland

F. DeClerck
Agricultural Biodiversity and Ecosystem Services, Bioversity International, Rome, Italy

EAT Norway, Oslo, Norway

S. Nordhagen · T. Beal
Global Alliance for Improved Nutrition (GAIN), Geneva, Switzerland

C. Gonzalez
Cornell Global Development, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA

M. Gill
School of Biological Science, University of Aberdeen, Aberdeen, UK

are likely to increase in demand and the locations of consumption growth. Below, we provide clarity on the dynamics of ASF demand and supply.

2.1 Trends in Animal Source Food Demand: 1990–2015

Averaged globally, over the last 25 years, per capita food demand of all ASF increased by more than 40 kg/person/year (FAOSTAT 2018). However, this number hides substantial variation across regions and by commodity within ASFs, with several different trends operating in opposing directions (Fig. 1). For example, while there was a nearly 35% increase in per capita meat demand (+11.27 kg/person/year) and total per capita meat demand increased for all regions between 1990 and 2015, this increase was driven by large increases in demand for poultry and pork, which saw increases of 106 and 26%, respectively.

Global demand for ruminant meat (beef and mutton), however, has followed a different trajectory, with per capita demand having remained near 1990 levels

	Fish, Seafood	Milk - Excluding Butter	Eggs	Meat	Bovine Meat	Mutton & Goat Meat	Pigmeat	Poultry Meat
Europe	4.5	25.2	0.6	1.8	-8.8	-1.4	0.8	10.6
Northern Africa	8.7	47.8	1.3	12.2	3.3	1.9	0.0	6.5
Western Africa	6.8	6.6	0.3	2.8	0.2	1.2	0.4	1.6
Eastern Africa	-0.9	17.3	-0.1	0.5	-0.2	-0.1	0.4	0.4
Middle Africa	3.6	-5.5	0.4	8.4	-1.1	0.4	2.2	7.2
Southern Africa	-1.9	8.4	3.3	23.2	-1.2	-1.1	2.4	22.3
Eastern Asia	19.0	29.7	11.2	35.7	3.9	2.2	18.2	10.4
China	24.1	35.6	13.0	38.8	4.6	2.6	19.5	11.1
Central Asia	0.7	44.1	2.2	9.2	1.7	-0.5	2.0	5.4
Southern Asia	3.0	34.8	1.4	1.4	-0.5	-0.5	-0.2	2.6
India	2.0	35.3	1.6	0.2	-1.2	-0.1	-0.2	1.7
South-Eastern Asia	17.0	7.6	2.5	16.6	1.3	0.2	7.5	7.6
Western Asia	2.0	7.4	0.9	16.1	2.2	-1.4	0.1	15.4
Americas	0.9	12.3	2.9	19.2	-0.8	-0.2	1.5	18.6
United States of America	0.5	-3.6	1.1	5.8	-5.8	-0.3	-1.6	13.4
South America	2.0	33.4	2.7	31.2	3.8	-0.3	3.9	23.9
Brazil	4.7	57.0	1.1	44.0	11.8	-0.2	4.2	28.1
Oceania	8.2	-30.6	-2.1	7.6	-6.6	-13.5	6.5	22.4
Australia	9.1	-17.4	-1.5	6.9	-6.5	-13.9	6.2	23.0
World	7.0	18.9	3.1	11.3	-0.6	0.2	3.3	8.1

Change in kg/person/year between 1990-2015

-60.0 60.0

Fig. 1 Change in animal source food demand in the period 1990–2015 (kg/person/year). (Source: Based on authors' calculations from FAOSTAT (2018). All regional definitions follow FAOSTAT definitions. Regions are inclusive of selected countries (i.e., Eastern Asia includes China), which are reported individually to highlight key trends) (changing by less than 1 kg/person/year on average globally). Within the beef trend, we still see substantial variation regionally, with most regions exhibiting much bigger declines in beef demand than the global number would suggest.

There is much less diversity of trajectories in the trends for poultry. Per capita poultry demand has increased, with different magnitudes, in all regions. The smallest increase was in Eastern Africa and the United States of America, 27% and 32%, respectively, in per capita demand of poultry meat. All other regions experienced double the per capita demand of poultry meat. Regional pork demand trends are more variable, but resemble poultry more so than beef.

Figure 1 shows the changes in animal source food demand in the period 1990–2015 (kg/person/year) in various regions.

2.2 The Role of Trade in Meeting Demand for Animal Source Foods

The last few decades have seen substantial increases in international trade in ASF, with important regional differences. The value of exports globally has nearly tripled, from around 59 in 1990 to almost 174 billion US$ by 2010, although total trade value represents less than 20% of global production (FAO 2019). Meat, in value terms, has contributed nearly two-thirds of the value of exports of livestock products globally.

Most trade in ASFs is within the same region of origin, with most imports coming from nearby countries, for example, Europe exports to Europe, as shown in Fig. 2. There are, however, a number of dominant trading countries that trade between continents (Fig. 2; for example, intraregional bovine meat exports are dominated by the Southern Cone of South America (most of the green outside of the Latin American region row in Fig. 2), particularly Brazil, Australia (in the East Asian and Pacific region, which is blue), and the United States of America (in the North American region, which is red)). Small ruminant export is dominated by Australia and New Zealand (in the East Asian and Pacific region, which is blue), which are the primary sources of imports for most countries. Europe and, to a lesser extent, North America are the primary exporting regions supplying the bulk of traded intraregional pork. Intraregional trade in poultry is dominated by Brazil (in Latin America, which is green) and the United States of America (in the North American region, which is red).

Trade in ASF, in volume terms, is small compared to trade of feed. Trade in meat and processed meat products accounted for less than one tenth of the volume of trade in feed grains (Galloway et al. 2007). These dynamics are likely to intensify as more feed will be necessary to respond to growing demand for pork and poultry in regions currently importing feeds. This comes with substantial consequences for land use and environmental impacts, as, depending on the land used to produce the feed, it could lead to substantial embedded environmental impacts in overall ASF production. A clear example: if imports of soybeans increase in Asia, this could fuel

Fig. 2 Composition of 2010 regional imports of meat commodities by source of imports. The source of imports follow the colours given in the final column (i.e., imports from Europe are coloured orange, those from North America are red, etc.), so, for example, 91% of imports of bovine meat in Europe comes from other countries in Europe, whereas 62% of imports of bovine meat in the former Soviet Union comes from countries in Latin America (FAO 2019)

deforestation in Brazil, a primary soybean provider. In other regions, other environmental dimensions would take precedence over emissions, with the potential for substantial losses of biodiversity and disruption of water cycles in places (see Searchinger et al. 2015, for example for Sub-Saharan Africa).

2.3 The Response of Production to Meet the Increase in Demand: The Monogastric "Explosion," Intensification, and Expansion Dynamics

Since the 1970s, there has been a 'monogastric explosion,' with rates of growth in animal numbers often exceeding 4% per year, and meat and egg production, in cases, reaching over 6–7% per year, globally. Improvements in crop yields, improved feeding rations with high-quality feedstuffs, higher production efficiency, favourable prices and the involvement of private industry in driving these dynamics all played a significant role, initially in Europe, North America, and Oceania, and later in Latin America and parts of Asia (FAO 2006).

Since 1990, global production of ASF (kg) has increased by more than 60%, an increase of almost 2% per year (FAOSTAT 2018). Figure 3 shows the regional variations in these patterns. The largest production increases were observed in Africa and Asia. Higher-income regions, on the other hand, grew at a slower rate, with ASF production in Europe actually declining by about 15% from 1990 levels.

Across ASF commodities, the fastest growth in production was for poultry meat, which has nearly tripled globally since 1990 (Fig. 3). All regions, on average, saw increased production, with the global median increase in production across all countries being 125% above 1990 levels (~3.3%/year growth).

Eggs, pork, and dairy production grew at a slower pace, with production increasing by 103%, 72%, and 56%, respectively. Beef and lamb production globally grew by about 1/4 and 1/3 the rate of poultry, respectively, since 1990. Lamb production in low-and middle-income regions grew at a much faster rate than the global average, with small ruminant production increasing at rates similar to pork in Africa and Asia. However, in developed countries in North America, Europe, and Oceania, there were declines in production.

Substantial increases in production efficiency, often associated with intensification, have also taken place. Intensification occurred at different rates in different parts of the world and, in some cases, led to reductions in animal numbers. For example, the United States of America produces 60% more milk with 80% fewer cows now than it did in the 1940s (Capper et al. 2009) through a substantial change in genetics, feeding and housing systems. Substantial intensification, as well as expansion, of the livestock sector has occurred primarily in Latin America and Asia. This is in stark contrast with Sub-Saharan Africa, where productivity has remained stagnant for decades, with all of the growth in production being due to increases in animal numbers. These general observations hide substantial heterogeneity, which we disentangle below.

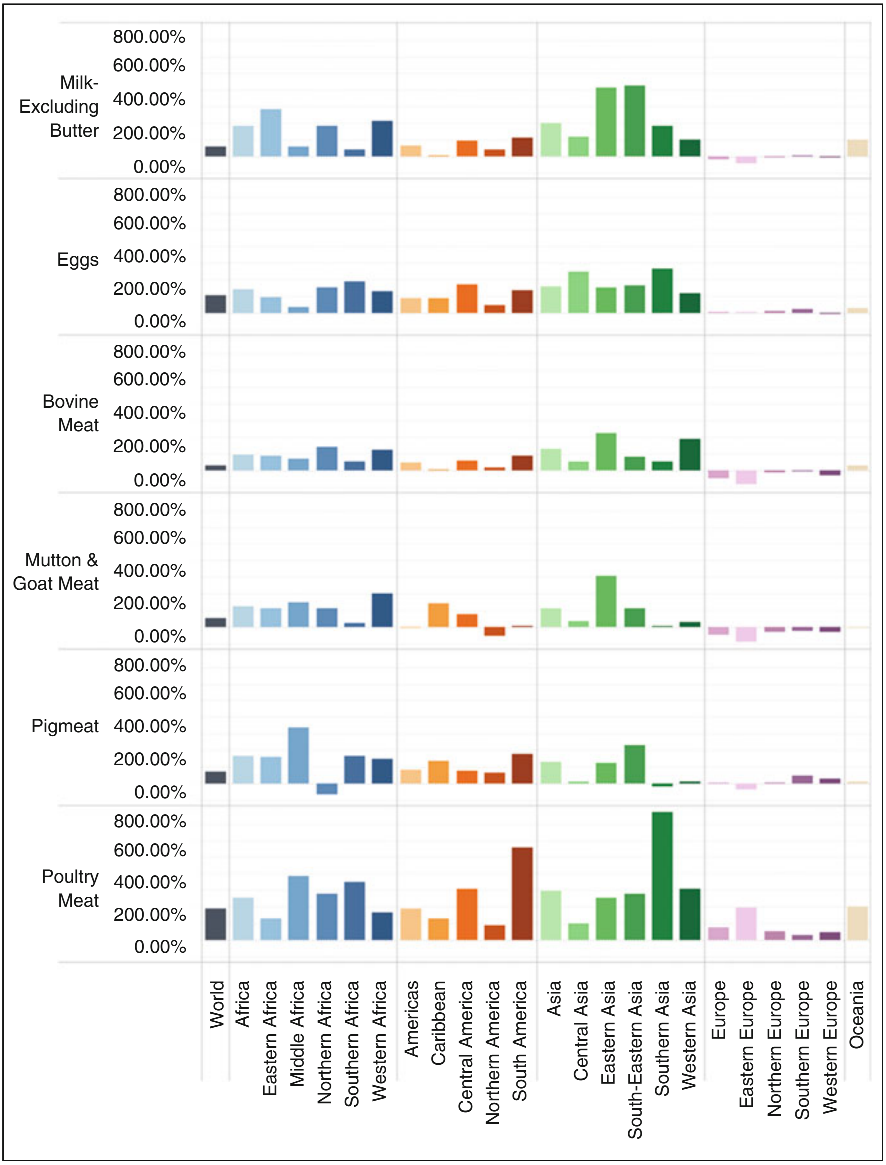


Fig. 3 Production trends of animal products (kg) from 1990 to 2015. (Source: Based on authors' calculations from FAOSTAT 2018)

2.4 Different Livestock Products and Production Systems, Different Dynamics

The production increases in the past few decades follow different trajectories for ruminants than for pork and poultry in smallholder or industrial operations (Fig. 4). Between 2000 and 2011, global milk and meat production increased by 28% and 11%, respectively (Fig. 4). Mixed crop-livestock systems contributed to the majority of bovine milk and meat production.

At the global level, these increases in total production were mainly driven by the increases in animal numbers (dairy: +19%, meat: +10%), followed by the increases in animal productivities (kg of livestock products/TLU/year, milk: +9%, meat: +1%). In arid and humid regions, or in low-income countries, total production increases were mainly driven by the increases in animal numbers, rather than the increases in productivity. This reflects that the feeding systems have remained static, being reliant on animals grazing and harvesting energy from available land, instead of greater utilisation of new forage crops or concentrate feeds. Similarly,

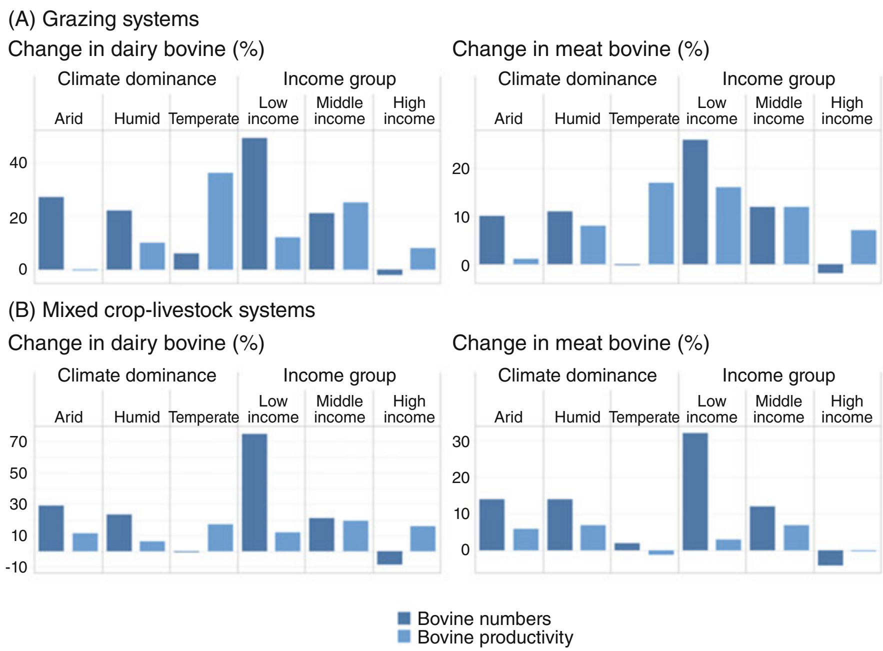


Fig. 4 Average changes in dairy bovine milk and meat bovine productivities (kg/TLU/year) and animal numbers in grazing systems (**a**) and mixed crop-livestock systems (**b**) by climate and income group. Period: 2000–2011. Data calculated based on productivity and animal number estimates by country, livestock system and climate type from (Herrero et al. 2013b). The climate category Arid includes semi-arid systems such as northern Australia. Grazing and mixed crop-livestock systems as defined by (Robinson et al. 2011), income groups as defined by (World Bank 2016). (Figure adapted from Godde et al. 2018)

improvements in animal health services in these production systems have been limited by patchy disease control, in particular, over remote areas.

In contrast, in temperate regions and high-income countries, total production increases were mainly driven by the increases in productivity, rather than the increases in animal numbers. On average, high-income countries showed a decrease in total animal numbers (−4%) while maintaining modest productivity increases (under 1% per year).

Increases in dairy productivity (28%) only outstripped growth in animal numbers (9%) as the source of growth in dairy production between 2000 and 2011 in the highlands of low-and middle-income countries. This evidence of intensification is unsurprising, considering that the majority of Research and Development and extension efforts have been directed towards these smallholders, mostly mixed dairy systems (Waithaka et al. 2006; Herrero et al. 2010, 2014).

2.5 The Role of Smallholders in the Production of ASF

Livestock production supports about 650 million low-income small-scale producers in lower-and middle-income countries (FAO 2009). Livestock are responsible for 17–47% of the value of agricultural production in the regions of lower-and middle-income countries (Herrero et al. 2013a) and contribute income to 68% of lower-and middle-income country households (FAO 2009), while also playing important cultural roles (Thornton 2010; Herrero et al. 2013a). While men are often most represented in livestock production and fishing, women tend to be highly active in the processing and sale of animal products (Herrero et al. 2013a). At the same time, ASF-related livelihoods do not necessarily entail high-quality jobs. For example, ASF producers and fishing communities in lower-and middle-income countries sometimes do not earn enough to eat their own production (Thow et al. 2017; Annan et al. 2018; Ravuvu et al. 2018). Women in livestock value chains in particular may lack appropriate recognition and remuneration (Agarwal 2018), and denial of women's access to shared ASF resources, such as fisheries, creates power imbalances that expose women to abuse (Fiorella et al. 2019). A move towards healthier, more plant-rich diets could create more jobs than animal agriculture-based employment, with potential improvements in gender equality and occupational safety (Saget et al. 2020).

Bovine Milk and Meat Globally, farms smaller than 20 ha produce 45% of bovine milk and close to 37% of bovine meat (Herrero et al. 2017) (Fig. 5). However, important regional differences exist. Large farms (>50 ha) dominate bovine milk (>75%) and meat (>80%) production in North America, South America, and Australia and New Zealand, which are regions with high levels of exports of these products.

Conversely, farms smaller than 20 ha produce the majority (>75%) of bovine milk and meat in China, East Asia Pacific, South Asia, Southeast Asia, Sub-Saharan

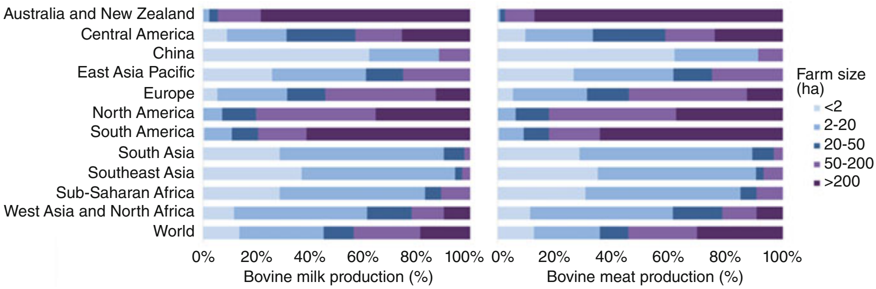


Fig. 5 The production of bovine milk and meat by farm size and region. (Source: Data from Herrero et al. 2017)

Africa, and West Asia and North Africa. Very small farms (<2 ha) are of particular importance in China, where they still produce more than 60% of bovine milk and meat. These very small farms are also of importance in East Asia Pacific, South Asia, Southeast Asia, and Sub-Saharan Africa, where they contribute more than 25% of bovine milk and meat production.

The role of smallholders in the future is uncertain. For dairy, a sustainably intensified smallholder sector could be the engine of production growth, as there are still large yield gaps in these systems. Furthermore, with demand both growing and primarily satisfied by local markets (formal and informal), smallholders should benefit from improved cash flow derived from growth in dairy. For intensification to occur, the growth of markets, improved access to inputs and services, and increased adoption of key technological packages need to happen at a faster pace than previously anticipated (McDermott et al. 2010; Godde et al. 2018).

For beef, the situation is different. In the absence of a clear increase in demand per capita, and with small farm output largely dependent on increased numbers of animals, it is likely that operation size will be more of a constraint. Nevertheless, smaller scale production resulting from culled animals in diversified farming systems may continue to be economically viable, even if it is unlikely to be the main source of income or livelihoods.

Pigs and poultry The contribution of smallholder systems to monogastric production, based on data from Herrero et al. (2013b), shows the importance of smallholder monogastric systems as a source of pork, poultry and eggs in several regions, notably, South and Southeast Asia and Sub-Saharan Africa (Fig. 6).

Gilbert et al. (2015) found a negative relationship between the proportion of extensively raised chickens and pigs and the GDP per capita of different countries. Although there are large variations between countries, this suggests that, as economies grow, the smallholder monogastric sector, while still important in some countries, will tend to reduce in importance as income grows and conditions become more favourable for private industry to industrialise the sector. The reduction in transaction costs and vertical integration will drive this transition, as it has in other regions.

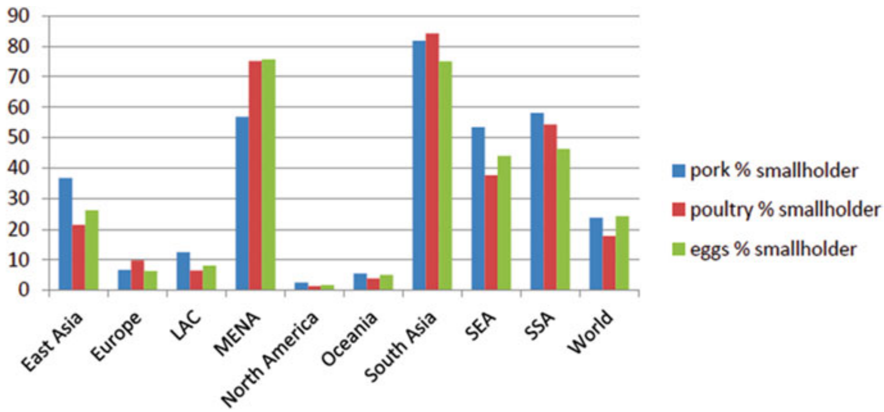


Fig. 6 The proportion of pork, poultry and eggs from smallholder systems in different global regions. (Herrero et al. 2013b)

3 Implications of the Historical Supply and Demand Dynamics of ASF for Land Use and Other Environmental Metrics

Livestock account for the majority of greenhouse gas emissions from food systems, through methane from enteric fermentation and manure management, carbon dioxide from land use change, and nitrous oxide from manure management (Herrero et al. 2016; Tubiello et al. 2021). However, livestock now use 62% less land and emit 46% fewer greenhouse gas emissions to produce one kilocalorie compared with 1961. Nevertheless, improved livestock productivity has required an increase of 188% in the use of nitrogen fertilisers derived from fossil fuels to increase feed production (Davis et al. 2015). Despite productivity improvements, due to increased demand, the aggregate environmental impacts of livestock have continued to grow, which will require substantial further reductions in the sector's environmental footprint.

Animal production practices, depending on type and location, can have beneficial or detrimental effects on biodiversity (Herrero et al. 2009; Barange et al. 2018). In particular, livestock-induced land use conversion is a major environmental and human rights concern in some areas (De Sy et al. 2015). Many intact ecosystems, notably, carbon-dense and biodiversity-rich tropical forest biomes, have been converted to pasture and feed crops for animals (FAO and UNEP 2020). These ecosystems are essential to climate change mitigation (Lennox et al. 2018). Intact ecosystems currently occupy half of the ice-free surface of the Earth (Dinerstein et al. 2017), and this degree of intactness has been proposed as a global limit (Newbold et al. 2016; Dinerstein et al. 2017; Leclère et al. 2018; Willett et al. 2019a, b), implying that an urgent halt to land use conversion is needed. In extensive rangeland practices in grassland and savanna biomes, where large grazers (e.g., bison) have been lost, ruminant livestock can be an important means of biodiversity conservation and climate mitigation (Olff and Ritchie 1998; Griscom et al. 2017).

Resource use varies widely by type of ASF and production practice. Beef production tends to be the greatest user of land and energy, followed by pork, poultry, eggs, and milk production (de Vries and de Boer 2010).

Resource use also varies by production system and setting. In many cases, livestock can be reared on lands of low opportunity cost, without competing with croplands or other land uses (van Zanten et al. 2018). Keeping livestock in grazing systems may have some environmental benefits, such as conservation of grassland biodiversity, although such relationships are complex and context-specific (FAO 2009). Animal production systems are often essential to circular production systems (Poux and Aubert 2018). However, the intensive production of any animal, including pigs and poultry, has substantial environmental impacts, especially for surrounding communities and waterways, that must be considered (Wing and Wolf 2000; Burkholder et al. 2007; Godfray et al. 2018).

3.1 Animal Source Food Consumption Trends: The Three Key Storylines

We review the 2020 projections made by Delgado and others towards the end of the 1990s, contrasted against what is happening currently in the livestock sector. We also summarise the storylines that emerge from these trends. Globally, their projections of total meat and milk production saw a difference of only −12% and −5% from what current trends in FAOSTAT suggest. By commodity, the projections were particularly accurate for pork, with larger deviations for beef and poultry. We observe a similar story with the per capita demand projections. Overall, the projections are good, with a difference of only 4 and 10 kg/person/year for meat and milk, respectively. However, we can see that, similar to the beef and poultry projections, there are offsetting deviations that are masked when we only look at the global number (Table 1). Here, the key deviations are in projections for China and India (Table 2).

Table 1 Comparing global animal source food production (million metric tonnes) in Delgado et al. (1999) to FAOSTAT (2018)

	FAOSTAT			Delgado et al. (1999)	% Difference
	1990	2013	2020[a]	2020	2020
Beef	55	68	72	82	14%
Pork	69	113	125	122	−2%
Poultry	41	109	127	83	−35%
Meat	178	309	346	304	−12%
Milk	538	753	813	772	−5%

[a]2020 projection is a linear regression based on FAO production values from 1990–2013

Table 2 Comparing per capita consumption of animal source food (kg/person/year) in Delgado et al. (1999) to FAOSTAT (2018)

	FAOSTAT						Delgado et al. (1999)		% Difference	
	Meat			Milk			Meat	Milk	Meat	Milk
	1990	2013	2020[a]	1990	2013	2020[a]	2020	2020	2020	2020
China	25	62	73	6	33	43	60	12	−18%	−72%
India	4	4	4	53	85	92	6	125	44%	36%
World	33	43	46	77	90	95	39	85	−16%	−11%

[a] 2020 projection is a linear regression based on FAO production values from 1990–2013

Reviewing these projections highlights the fact that the evolution of the global livestock sector over the past couple of decades can be summarised in a few storylines:

(a) First, demand for poultry has been the main global driver of increased meat consumption, with per capita consumption having nearly doubled since 1990. This represents a mix of changes in demand and supply.
(b) Second, per capita dairy consumption in high-income regions has stayed constant since 1990, with any growth in total consumption being driven by changes in population. Low-and middle-income regions have seen substantial increases in dairy consumption, with this being driven by increases both in population and in per capita consumption of dairy products, with the largest increase observed in China.
(c) Finally, increases in global beef demand is a story of two countries, China and Brazil, which account for nearly 93% of the 11 million metric tonne increase in global beef demand, even as, globally, per capita beef consumption has been declining or become stagnant in most countries. The key role of China and Brazil in the global beef sector was already identified by Delgado (2003) in an update of their 1999 projections.

3.2 *Animal Source Foods and Human Nutrition and Health: The Need for Moderation, Not Avoidance*

In general, healthy plant-rich diets, including flexitarian, or vegetarian options, have lower climate and land impact than those high in ASF; their water and nutrient impacts depend on the practices used (Hallström et al. 2015; Aleksandrowicz et al. 2016; Frehner et al. 2021). Reduction in ASF, notably red meat consumption has been shown to reduce environmental impacts (e.g., on climate, land, and biodiversity), with some studies suggesting that global climate and biodiversity targets are only achievable through reduced consumption (Tilman and Clark 2014; Leclère et al. 2018; Springmann et al. 2018; Clark et al. 2020). For example, transition to healthy plant-rich diets that include some meat could reduce food-related emissions by nearly half, setting them on track to meet the 1.5 °C climate target (Clark et al. 2020). In contrast, a global transition to increased consumption of ASF, notably red meat, is not feasible within recommended environmental limits (Springmann et al. 2018).

Diets that include few or no ASFs, including vegetarian and vegan diets, have been shown to reduce the risk of non-communicable diseases (Tilman and Clark 2014; Springmann et al. 2016). Diets with diverse plant-sourced foods can meet protein requirements (Young and Pellett 1994), and vegetarian diets can meet adult micronutrient needs (Walker et al. 2005). However, plant-based foods do not necessarily equal healthy foods: many highly processed foods are fully plant-based (e.g., highly processed snack foods and sugar-sweetened beverages), yet have been associated with poor health outcomes (Hu 2013; Marlatt et al. 2016; Mozaffarian 2016).

Controversy exists regarding dietary recommendations for some ASF, and this has had a polarising effect on many scientific and food sector discussions. Confounding this debate are statements regarding global calls to reduce ASF consumption (Willett et al. 2019a, b), masking regions where increased intake would have positive impacts on health; creating confusion in the health impacts of a diversity of ASF; causing a lack of clarity (and sometimes unrealistic assumptions) on which foods would be replacing ASF in diets; and, finally, leading to the under-consumption of health-promoting foods (Afshin et al. 2019).

While ASF consumption and its subtypes are highly variable geographically, the under-consumption of whole grains, fruits, nuts and seeds, vegetables, and seafood, together with excess sodium, remains the largest risk of disease and mortality attributed to diets, according to the Global Burden of Disease Dietary Risk Factors study (Afshin et al. 2019). For many in high-income settings, increasing the consumption of protective foods while remaining within caloric recommendations may require reduced consumption of some ASF. For others, particularly resource-constrained populations in low-and middle-income countries, increasing consumption of certain ASF (alongside consumption of these other protective foods) could have health benefits. However, there are limitations within the underlying data, uncertainty regarding these estimates and significant heterogeneity in consumption among subpopulations (Beal et al. 2019).

3.3 Animal Source Foods and Undernutrition

ASFs are considered complete sources of protein that provide all nine essential amino acids in adequate quantities and are the only dietary source of vitamin B12. In addition, ASFs are nutrient dense and have higher bioavailability of key nutrients such as iron, vitamin A, and zinc compared to plant source foods, although nutrient content may vary depending on the type of ASF. Consumption of these foods may be particularly essential for young children, adolescent girls, and pregnant or lactating women, as these individuals have increased nutrient requirements due to biological processes (Neumann et al. 2002; Murphy and Allen 2003; Semba et al. 2016; Beal et al. 2017). With regards to undernutrition, a number of studies have assessed the role of ASFs in linear growth for children under the age of five and micronutrient deficiencies in both women and children. Recent systematic reviews have identified limited evidence regarding the association between consumption of ASF and linear growth during early childhood (Eaton et al. 2019; Pimpin et al. 2019; Shapiro et al. 2019). These reviews concluded that substantial heterogeneity in definitions of ASFs might have led to inconsistent results. On the other hand, a cross-sectional analysis of Demographic Health Surveys found a strong association between ASF consumption and reduced incidence of stunting, and consumption of a diversity of ASF had an additive effect on that relationship (Headey et al. 2018). Another study found a strong correlation between ASF intake and reductions in stunting in Nepal and Uganda, with dairy consumption having the strongest correlation (Zaharia et al. 2021). In addition, in a longitudinal sample of children in rural Nepal, increased ASF consumption was associated with greater child development scores (Miller et al. 2020). Of the ASF, small pelagic fish, molluscs, large pelagic fish, salmonids and carp tend to have higher nutritional density than most terrestrial ASF, with ruminant meats following (Golden et al. 2021). A diversity of foods, including of ASF, within healthy ranges remains a standard recommendation, particularly for nutritionally vulnerable populations.

3.4 Animal Source Foods and the Risk of Non-communicable Diseases

The relationship between ASF and chronic diseases is highly dependent on the type of ASF and what other foods are substituted for ASF in the diet (e.g., red meat vs. other lean protein or red meat vs. ultra-processed plant-based foods). Cohort studies provide modest evidence that increased consumption of low-fat dairy and seafood may be protective against cardiovascular disease (Bernstein et al. 2010; Soedamah-Muthu et al. 2011; Schwingshackl et al. 2017a, b). On the other hand, the association between unprocessed and processed red meat consumption and diet-related chronic diseases is still debated among scientists. In 2015, the International Agency for Research on Cancer classified processed meat as a group 1 carcinogen (other examples: tobacco smoking and outdoor air pollution) and unprocessed red meat as a probable carcinogen (IARC 2015). There is strong evidence to suggest that consumption of processed meat (cured, salted, preserved) is associated with increased risk of cancer on average (Bouvard et al. 2015), although the precise mechanisms and differences among subtypes require more study. The relationship between unprocessed (fresh) red meat and health is more controversial and needs further research. Some epidemiological cohort studies have found positive associations between unprocessed red meat consumption and, respectively, overall mortality (Schwingshackl et al. 2017a, b; Zheng et al. 2019), type-2 diabetes (Pan et al.

2011; Schwingshackl et al. 2017a, b), cardiovascular disease (Qian et al. 2020), and cancer (Chan et al. 2011; Bouvard et al. 2015), while other studies have not found any relationship between unprocessed red meat and adverse health outcomes (Johnston et al. 2019; Iqbal et al. 2021). While more research is needed, most studies that do suggest higher adverse health risk with red meat consumption find an association at doses exceeding 1–2 servings/week (Mozaffarian 2016), which is consistent with many national dietary recommendations (Gonzalez Fischer and Garnett 2016; Herforth et al. 2019; USDA and USHHS 2020).

In summary, populations consuming high amounts of red meat, particularly in processed forms, would benefit from reduced consumption to improve health and sustainability. This mostly applies to consumers in higher-income countries, but also to a growing number in lower-and middle-income countries, where the burden of diet-related non-communicable diseases is growing rapidly. For those vulnerable to undernutrition (whether in lower-and middle-income countries or higher-income countries), the nutrient contribution of minimally processed ASF may be beneficial in reducing risk of micronutrient deficiency and promoting growth (Murphy and Allen 2003).

4 Essential Actions for Ensuring Livestock's Contribution to Sustainable Food Systems

This section examines some alternative or additional actions that would need to take place for livestock to contribute to sustainable food systems, while addressing critical aspects of social equity, poverty and other social goals. As discussed, this will require different actions depending on the context, including:

- Consumption of ASF at a level appropriate to meet nutritional needs.
- A reduction in consumption of red and processed meat for populations with high risks of diet-related non-communicable diseases or in the context of an unbalanced diet.
- The enabling of increased consumption by nutritionally vulnerable populations that need higher levels of nutrients, including pregnant women, the elderly, children and undernourished populations, particularly those in lower-and middle-income countries.

Several studies have quantified the potential environmental gains of changing dietary patterns. This area of work started from the need to quantify the greenhouse gas mitigation potentials of changing diets (Stehfest et al. 2009), and has been expanded considerably to include health impacts and several additional environmental metrics (Tilman and Clark 2014; Leclère et al. 2018; Springmann et al. 2018; Willett et al. 2019a, b). As an example, Fig. 7 summarises the technical mitigation potential of changing diets.

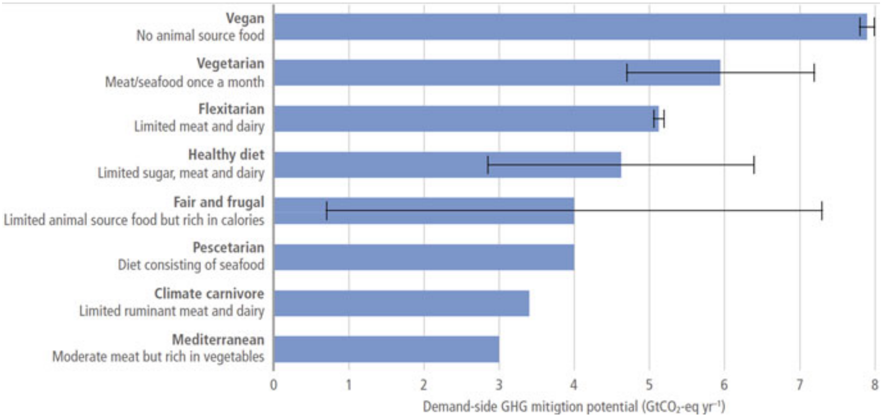


Fig. 7 The technical greenhouse gas mitigation potential of changing diets according to a range of scenarios examined in the literature. (Mbow et al. 2019)

The features of these studies show that:

1. The upper bound of the technical mitigation potential of demand-side options is about 7.8 Gt CO_2-eq per year (no consumption of animal products scenario) (Stehfest et al. 2009).
2. Many dietary scenario variants have been tested. Key variants include target kilocalorie levels (i.e., 2500 kcal per capita per day), notions of healthy diets, swaps between animal products (red vs. white meat) and/or vegetables, and stylised diets (Mediterranean, flexitarian, etc.). All fit roughly between the current emissions and the Stehfest et al. (2009) upper boundary.
3. The main impact of reducing the consumption of ASFs is to reduce the land footprint of livestock. This land-sparing effect, coupled with alternative uses of the land (i.e., negative emissions technologies), leads to a large mitigation potential. Many of the other environmental impacts are also associated with the land-sparing effect (i.e., biodiversity, Leclère et al. 2018).
4. The largest technical potential comes from reductions in ruminant meat consumption (the most inefficient sub-sector), as most scenarios try to trigger land sparing (reduction of carbon dioxide emissions) as the key mechanism for reducing emissions.
5. Reductions in livestock product consumption, especially red meats, could have both environmental and health benefits (Tilman and Clark 2014; Willett et al. 2019a, b).
6. Fully vegan diets could meet calorie and protein requirements, but can also be deficient in key nutrients (vitamin B12, folate, Zinc), a concern for vulnerable groups, in particular, those without access to dietary supplements. Therefore, diets with some level of animal products may be necessary.
7. The economic mitigation potential of changing diets is not known. This is a crucial research area, together with mechanisms for eliciting behavioural changes.

8. Most scenarios so far have taken kilocalories as the currency for changing diets; few have dealt with protein or micronutrients, a factor that, from the livestock and healthy diet perspectives, seems like a necessary step.
9. Very few key examples of legislation and policy-induced shifts in consumption exist. There are some examples that have been shown to promote increases in the consumption of fruits and vegetables (Garnett et al. 2015).
10. The social and economic costs of reduced demand for ASFs are unknown. Notably, there is little information on the impacts on farmers' income, employment, alternative labour markets, reductions in agricultural GDP, etc.
11. Methodological advances are needed to elicit simultaneously the environmental, health and socio-economic impacts of reduced consumption.

Attached to livestock production is an enormous amount of wealth generation, employment, value chains and famers' livelihoods. Impacts on these are seldomly studied, yet they are crucial to creating convincing policy cases for a contraction of livestock product demand. Global studies that have begun to include some of these critical feedbacks are only now starting to emerge (Mason-D'Croz et al. 2020).

From a nutritional perspective, livestock's contribution to healthy diets is not so much about their kilocalories as their micronutrients and protein. It is essential to include these in future research. Diets in these scenarios are also too 'globalised,' and more realistic, and culturally sensitive, regional variants will need to be examined. The differentiated impacts of ASF consumption and production across population cohorts will require that future analysis begin to better recognise the heterogeneity of populations (rural/urban, under-or over-nourished, gender, age, or by age groups), if they are to provide necessary information to improve the targeting of future food policies.

Mitigating greenhouse gases from livestock systems is more feasible in some contexts than in others, and this largely depends on the livelihood objectives of livestock farmers (Herrero et al. 2016). Nonetheless, many practices that improve productivity or the production system as a whole can lead to direct and indirect greenhouse gas mitigation co-benefits. These should be pursued.

The supply side options for mitigating greenhouse gases in the livestock sector have been the subject of recent reviews (Smith et al. 2007, 2014; Hristov et al. 2013; Herrero et al. 2016; Roe et al. 2019). These options look to:

– Reduce the enteric methane of ruminants.
– Reduce nitrous oxide through manure management of both ruminants and monogastrics.
– Implement best animal husbandry and management practices (all), which would have an effect on major greenhouse gases (carbon dioxide, methane and nitrous oxide).
– Directly sequester carbon from pastures (ruminants)
– Generally improve land use practices that also help in enhancing soil carbon sequestration.

Excluding land use practices, Herrero et al. (2016) found that these options have a technical mitigation potential of 2.4 $GtCO_2eq$/year. However, they also found that the economic feasibility of these practices is low (10–15% of the technical potential, or less than 0.4 $GtCO_2eq$/year). The largest mitigation opportunities for the livestock sector occur when livestock are considered holistically as part of the agriculture, forestry and land use sectors (Havlík et al. 2014).

5 Concluding Remarks and Recommendations in the Context of the Food Systems Summit

Our study has demonstrated that the dynamism of the livestock sector provides a range of avenues for change, some more relevant to smallholders than others, some more amenable to public funding than others, and some more likely to alleviate negative environmental impacts than others. Picking the most effective and desirable solutions will be essential for stakeholders associated with the livestock sector to achieve the desired impacts on sustainable food systems. The balance between social and environmental goals will need to be carefully evaluated. The avenues for growth, the trade-offs and the potential actions can be summarised below.

Smallholder dairy: The evidence suggests that demand for milk is growing fast, and that, at least in highland or high potential areas, productivity per animal is increasing due to the adoption of better practices, like feeds, animal health management and genetics. These systems can be competitive, but issues surrounding land fragmentation and feed availability need closer attention. Testing and implementing transformational feed technologies or engaging in developing systems that could increase in circularity, such as through increased biomass recycling, sound like important next steps to ensure high-quality feed at low environmental costs in these systems. This needs to go beyond previous work on crop residues (e.g., Blummel and colleagues) and may need transdisciplinary partnerships with other sectors to develop these new biomass streams and to adjust breeding and feeding strategies. This, in turn, would also lead to reduced pressures on land and to the exploration of other greenhouse gas mitigation avenues, beyond those explored to date (improved feeds, manure management). Eventually, this could contribute to the national mitigation action plans of specific countries.

The smallholder pork and poultry sector: our synthesis has shown that, while there are countries where smallholder pork and poultry makes an important contribution to the supply of these products, in the coming decades, much of the growth in production is likely to come from industrial production, as integrated supply chains emerge and private sector engagement increases. This suggests that investing in these smallholder systems is, at best, a medium-term strategy that could provide livelihood benefits as these producers diversify or identify new exit strategies. Identifying transition options for these producers in the future seems necessary.

From an international public good perspective, the future of feed in fuelling the large demand for pork and poultry is a critical researchable issue, if the feed is to be sourced sustainably. Biomass value chains, old and new, need to be evaluated, developed and promoted to ensure that competition for food with humans is minimised. Here, again, circular feed sources, regulations for including a minimum amount of recycled feed, and new feed sources (superfeeds from industrial production or others) need to be developed, along with professional arguments in favour of local industries taking on these enterprises in a well-planned manner.

For monogastrics, there are a lot of researchable issues, including on antimicrobial resistance, with priority areas being:

1. Monitoring inputs: what inputs are used in the system in terms of feed, antimicrobials and other aspects that affect the health of the animals and have implications for the health of producers, consumers and those working in the food chain.
2. Surveillance: establishing systems that generate information on current and emerging diseases, antimicrobial use and antimicrobial resistance.
3. Assessment: the economic burden of livestock health and wealth (see https://animalhealthmetrics.org) as a basis to identify interventions that impact positively on the economic outcomes of livestock production, as well as minimising impacts on the environment and public health.

A central element of a livestock agenda in relation to environmental trade-offs is related to the identification of entry points for engaging in the beef sector. On one hand, the existing data show that most of the growth in red meat production has been obtained through increases in animal numbers, while intensification has been influential in only a few countries. Consumption per capita is stagnant, or decreasing, in most countries, and most of the demand is driven by population growth. At the same time, reducing red meat consumption could lead to substantial greenhouse gas mitigation, as well as reductions in pressure on land and biodiversity. Producing red meat only on lands of low opportunity costs, or as a by-product of the dairy industry, would have the lowest environmental impacts.

Identifying the best levels of consumption in relation to other dietary elements for different population groups should be a high priority for the Food Systems Summit, as well as identifying ways to decouple red meat production from land, or create niche products for very specific sets of consumers through labelling systems and certification.

The livestock sector will change, voluntarily, or as a result of forces external to it. If sustainability concerns are of paramount importance, a critical research area is to develop economic incentive systems (price premiums) and regulations to pay for reduced emissions, watershed protection, biodiversity protection and others; and to internalise these in true cost or true-pricing schemes, supported by adequate regulatory and fiscal measures.

References

Afshin A et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393(10184):1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Agarwal B (2018) Gender equality, food security and the sustainable development goals. Curr Opin Environ Sustain 34:26–32. https://doi.org/10.1016/j.cosust.2018.07.002

Aleksandrowicz L et al (2016) The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLoS ONE 11(11):e0165797. https://doi.org/10.1371/journal.pone.0165797

Annan RA et al (2018) Public awareness and perception of Ghana's restrictive policy on fatty meat, as well as preference and consumption of meat products among Ghanaian adults living in the Kumasi Metropolis. BMC Nutrition 4(1):1–8. https://doi.org/10.1186/s40795-018-0209-z

Barange B et al (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, Rome

Beal T et al (2017) Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PLOS ONE 12(4):e0175554. https://doi.org/10.1371/journal.pone.0175554

Beal T, Neufeld LM, Morris SS (2019) Uncertainties in the GBD 2017 estimates on diet and health. Lancet 394(10211):1801–1802. https://doi.org/10.1016/S0140-6736(19)32502-4

Bernstein AM et al (2010) Major dietary protein sources and risk of coronary heart disease in women. Circulation 122(9):876–883. https://doi.org/10.1161/CIRCULATIONAHA.109.915165

Bouvard V et al (2015) Carcinogenicity of consumption of red and processed meat. Lancet Oncol 16(16):1599–1600. https://doi.org/10.1016/S1470-2045(15)00444-1

Burkholder JA et al (2007) Impacts of waste from concentrated animal feeding operations on water quality. Environ Health Perspect 115(2):308–312. https://doi.org/10.1289/ehp.8839

Chan DSM et al (2011) Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies. PLOS ONE 6(6):e20456. https://doi.org/10.1371/JOURNAL.PONE.0020456

Clark MA et al (2020) Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370(6517):705–708. https://doi.org/10.1126/science.aba7357

Davis KF et al (2015) Historical trade-offs of livestock's environmental impacts. Environ Res Lett 10(12):125013. https://doi.org/10.1088/1748-9326/10/12/125013

De Sy V et al (2015) Land use patterns and related carbon losses following deforestation in South America. Environ Res Lett 10(12):124004. https://doi.org/10.1088/1748-9326/10/12/124004

de Vries M, de Boer IJM (2010) Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest Sci 128(1–3):1–11. https://doi.org/10.1016/J.LIVSCI.2009.11.007

Delgado CL (2003) Rising consumption of meat and milk in developing countries has created a new food revolution. J Nutr 133:3965–3971. https://doi.org/10.1093/jn/133.11.3907S.

Delgado CL et al (1999) The coming livestock revolution, Commission on Sustainable Development, New York. https://doi.org/10.1007/s10680-008-9165-7

Dinerstein E et al (2017) An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67(6):534–545. https://doi.org/10.1093/biosci/bix014

Eaton JC et al. (2019) Effectiveness of provision of animal-source foods for supporting optimal growth and development in children 6 to 59 months of age. Cochrane Database of Systematic Reviews (5). https://doi.org/10.1002/14651858.CD012818.PUB2/MEDIA/CDSR/CD012818/IMAGE_N/NCD012818-CMP-003-02.PNG

FAO (2006) Livestock report, Rome

FAO (2009) The state of food and agriculture: livestock in balance, Food and Agriculture Organisation of the United Nations. Rome 2009. https://doi.org/10.1016/S0140-6736(75)92740-3

FAO (2019) FAOSTAT. Available at http://www.fao.org/faostat/en/#data/TM. Accessed 2 July 2021

FAO and UNEP (2020) The state of the World's forests 2020: forests, biodiversity and people, Rome

FAOSTAT (2018) FAOSTAT food balance sheets. Available at http://www.fao.org/faostat/en/#data/FBS. Accessed 16 June 2021

Fiorella KJ et al (2019) A review of transactional sex for natural resources: under-researched, overstated, or unique to fishing economies? Glob Public Health 14(12):1803–1814. https://doi.org/10.1080/17441692.2019.1625941

Frehner A et al (2021) How food choices link sociodemographic and lifestyle factors with sustainability impacts. J Clean Prod 300:126896. https://doi.org/10.1016/j.jclepro.2021.126896

Galloway JN et al (2007) International pork chop trade in meat: the tip of the. Ambio 36(8): 622–629. https://doi.org/10.1579/0044-7447(2007)36[622:ITIMTT]2.0.CO;2

Garnett T et al (2015) Policies and actions to shift eating patterns: what works? FCRN/Chatham House, p 85

Gilbert M et al (2015) Income disparities and the global distribution of intensively farmed chicken and pigs. PLoS One 10(7):1–14. https://doi.org/10.1371/journal.pone.0133381

Godde CM et al (2018) Grazing systems expansion and intensification: drivers, dynamics, and trade-offs. Glob Food Sec 16(November):93–105. https://doi.org/10.1016/j.gfs.2017.11.003

Godfray HCJ et al (2018) Meat consumption, health, and the environment. Science 361(6399). https://doi.org/10.1126/science.aam5324

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF et al (2021) Aquatic foods to nourish nations. Nature 598(7880):315–320

Gonzalez Fischer C, Garnett T (2016) Plates, pyramids, planet: developments in national healthy and sustainable dietary guidelines: a state of play assessment. FAO, Rome. Available at www.fao.org/. Accessed 3 Jan 2019

Griscom BW et al. (2017) Natural climate solutions. In: Proceedings of the National Academy of Sciences, Early edit, pp 1–6. https://doi.org/10.1073/pnas.1710465114

Hallström E, Carlsson-Kanyama A, Börjesson P (2015) Environmental impact of dietary change: a systematic review. J Clean Prod 91:1–11. https://doi.org/10.1016/j.jclepro.2014.12.008

Havlík P et al (2014) Climate change mitigation through livestock system transitions. Proc Natl Acad Sci USA 111(10):3709–3714. https://doi.org/10.1073/pnas.1308044111

Headey D, Hirvonen K, Hoddinott J (2018) Animal sourced foods and child stunting. Am J Agric Econ 100(5):1302–1319. https://doi.org/10.1093/ajae/aay053

Herforth A et al (2019) A global review of food-based dietary guidelines. Adv Nutr 10(suppl_2): S224–S238. https://doi.org/10.1093/advances/nmy130

Herrero M et al (2009) Livestock, livelihoods and the environment: understanding the trade-offs. Curr Opin Environ Sustain 1(2):111–120. https://doi.org/10.1016/j.cosust.2009.10.003

Herrero M et al (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science 327(5967):822–825. https://doi.org/10.1126/science.1183725

Herrero M, Grace D et al (2013a) The roles of livestock in developing countries. In: Animal. Elsevier, pp 3–18. https://doi.org/10.1017/S1751731112001954

Herrero M, Havlík P et al (2013b) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc Natl Acad Sci USA 110(52):20888–20893. https://doi.org/10.1073/pnas.1308149110

Herrero M et al (2014) Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. Glob Environ Chang 24(1):165–182. https://doi.org/10.1016/j.gloenvcha.2013.12.008

Herrero M et al (2016) Greenhouse gas mitigation potentials in the livestock sector. Nat Clim Chang 6(5):452–461. https://doi.org/10.1038/nclimate2925

Herrero M, Thornton PK et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4

Hristov AN et al (2013) Mitigation of greenhouse gas emissions in livestock production. A review of technical options for non-CO2 emissions. In: Gerber PJ, Henderson B, Makkar HPS (eds) FAO animal production and health paper. Rome. https://doi.org/10.1016/j.agee.2005.08.009
Hu FB (2013) Resolved: There is sufficient scientific evidence that decreasing sugar-sweetened beverage consumption will reduce the prevalence of obesity and obesity-related diseases. Obes Rev 14(8):606–619. https://doi.org/10.1111/obr.12040
IARC (2015) IARC monographs evaluate consumption of red meat and processed meat, The Lancet Oncology. Lancet Publishing Group. https://doi.org/10.1016/S1470-2045(15)00444-1
Iqbal R et al (2021) Associations of unprocessed and processed meat intake with mortality and cardiovascular disease in 21 countries [Prospective Urban Rural Epidemiology (PURE) Study]: a prospective cohort study. Am J Clin Nutr 114(3):1049–1058. https://doi.org/10.1093/AJCN/NQAA448
Johnston BC, Zeraatkar D, Han MA, Vernooij RWM, Valli C, el Dib R et al (2019) Unprocessed red meat and processed meat consumption: dietary guideline recommendations from the nutritional recommendations (NUTRIRECS) consortium. Ann Intern Med 171(10):756–764. https://doi.org/10.7326/M19-1621/SUPPL_FILE/M19-1621_SUPPLEMENT.PDF
Leclère D et al. (2018) Towards pathways bending the curve of terrestrial biodiversity trends within the 21st century [Preprint]. https://doi.org/10.22022/ESM/04-2018.15241
Lennox GD et al (2018) Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Glob Chang Biol 24(12):5680–5694. https://doi.org/10.1111/gcb.14443
Marlatt KL et al (2016) Breakfast and fast food consumption are associated with selected biomarkers in adolescents. Prev Med Rep 3:49–52. https://doi.org/10.1016/j.pmedr.2015.11.014
Mason-D'Croz D et al (2020) Modelling the global economic consequences of a major African swine fever outbreak in China. Nature Food 1(4):221–228. https://doi.org/10.1038/s43016-020-0057-2
Mbow C et al (2019) Food Security. In: IPCC special report on climate change and land. IPCC, pp 1–200
McDermott JJ et al (2010) Sustaining intensification of smallholder livestock systems in the tropics. Livest Sci 130(1–3):95–109. https://doi.org/10.1016/j.livsci.2010.02.014
Miller LC et al (2020) Diet quality over time is associated with better development in rural Nepali children. Matern Child Nutr 16(3):e12964. https://doi.org/10.1111/MCN.12964
Mozaffarian D (2016) Dietary and policy priorities for cardiovascular disease, diabetes, and obesity. Circulation 133(2):187–225. https://doi.org/10.1161/CIRCULATIONAHA.115.018585
Murphy SP, Allen LH (2003) Nutritional importance of animal source foods. J Nutr 133(11): 3932S–3935S. https://doi.org/10.1093/JN/133.11.3932S
Neumann C, Harris DM, Rogers LM (2002) Contribution of animal source foods in improving diet quality and function in children in the developing world. Nutr Res 22(1–2):193–220. https://doi.org/10.1016/S0271-5317(01)00374-8
Newbold T et al (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353(6296):291–288. https://doi.org/10.1126/science.aaf2201
Olff H, Ritchie ME (1998) Effects of herbivores on grassland plant diversity. Trends Ecol Evol 13(7):261–265. https://doi.org/10.1016/S0169-5347(98)01364-0
Pan A et al (2011) Red meat consumption and risk of type 2 diabetes: 3 cohorts of US adults and an updated meta-analysis. Am J Clin Nutr 94(4):1088–1096. https://doi.org/10.3945/AJCN.111.018978
Pimpin L et al (2019) Effects of animal protein supplementation of mothers, preterm infants, and term infants on growth outcomes in childhood: a systematic review and meta-analysis of randomized trials. Am J Clin Nutr 110(2):410–429. https://doi.org/10.1093/AJCN/NQY348
Poux X, Aubert P (2018) An agroecological Europe in 2050: multifunctional agriculture for healthy eating findings from the ten years for agroecology (TYFA) modelling exercise, Paris

Qian F et al (2020) Red and processed meats and health risks: how strong is the evidence? Diabetes Care 43(2):265–271. https://doi.org/10.2337/DCI19-0063
Ravuvu A et al (2018) Protocol to monitor trade agreement food-related aspects: the Fiji case study. Health Promot Int 33(5):887–900. https://doi.org/10.1093/heapro/dax020
Robinson TP et al (2011) Global livestock production systems, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI)
Roe S et al (2019) Contribution of the land sector to a 1.5°C world. Nat Clim Chang 9(11):817–828. https://doi.org/10.1038/s41558-019-0591-9
Saget C, Vogt-Schilb A, Luu T (2020) Jobs in a net-zero emissions future in Latin America and the Caribbean, Washington, DC/Geneva
Schwingshackl L, Hoffmann G et al (2017a) Food groups and risk of type 2 diabetes mellitus: a systematic review and meta-analysis of prospective studies. Eur J Epidemiol 32(5):363–375. https://doi.org/10.1007/S10654-017-0246-Y/TABLES/1
Schwingshackl L, Schwedhelm C et al (2017b) Food groups and risk of all-cause mortality: a systematic review and meta-analysis of prospective studies. Am J Clin Nutr 105(6):1462–1473. https://doi.org/10.3945/AJCN.117.153148
Searchinger TD et al (2015) High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. Nat Clim Chang 5:481–486. https://doi.org/10.1038/NCLIMATE2584
Semba RD et al (2016) Child stunting is associated with low circulating essential amino acids. EBioMedicine 6:246–252. https://doi.org/10.1016/J.EBIOM.2016.02.030
Shapiro MJ et al (2019) A systematic review investigating the relation between animal-source food consumption and stunting in children aged 6–60 months in low and middle-income countries. Adv Nutr 10(5):827–847. https://doi.org/10.1093/ADVANCES/NMZ018
Smith P et al (2007) Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric Ecosyst Environ 118(1–4):6–28. https://doi.org/10.1016/j.agee.2006.06.006
Smith P et al. (2014) Agriculture, forestry and other land use. In (ed) Intergovernmental panel on climate change working group, Change 2014 Mitigation of Climate Change, p 94. https://doi.org/10.1016/j.phrs.2011.03.002
Soedamah-Muthu SS et al (2011) Milk and dairy consumption and incidence of cardiovascular diseases and all-cause mortality: dose-response meta-analysis of prospective cohort studies. Am J Clin Nutr 93(1):158–171. https://doi.org/10.3945/AJCN.2010.29866
Springmann M et al (2016) Analysis and valuation of the health and climate change cobenefits of dietary change. Proc Natl Acad Sci U S A 113(15):4146–4151. https://doi.org/10.1073/pnas.1523119113
Springmann M et al (2018) Options for keeping the food system within environmental limits. Nature 562(7728):519–525. https://doi.org/10.1038/s41586-018-0594-0
Stehfest E et al (2009) Climate benefits of changing diet. Clim Chang 95(1–2):83–102. https://doi.org/10.1007/s10584-008-9534-6
Thornton PK (2010) Livestock production: recent trends, future prospects. In: Philosophical Transactions of the Royal Society B: Biological Sciences. Royal Society, pp 2853–2867. https://doi.org/10.1098/rstb.2010.0134
Thow AM et al (2017) Food supply, nutrition and trade policy: reversal of an import ban on Turkey tails. Bull World Health Organ 95(10):723–725. https://doi.org/10.2471/BLT.17.192468
Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515(7528):518–522. https://doi.org/10.1038/nature13959
Tubiello FN et al (2021) Carbon emissions and removals from forests: new estimates, 1990-2020. Earth System Science Data 13(4):1681–1691. https://doi.org/10.5194/essd-13-1681-2021
USDA and USHHS (2020) Dietary guidelines for Americans, 2020–2025, 9th edn. Washington, DC. Available at https://www.DietaryGuidelines.gov. Accessed 24 Mar 2022
van Zanten HHE et al (2018) Defining a land boundary for sustainable livestock consumption. Glob Chang Biol 24(9):4185–4194. https://doi.org/10.1111/gcb.14321

Waithaka MM et al (2006) Bio-economic evaluation of farmers' perceptions of viable farms in western Kenya. Agric Syst 90(1–3):243–271. https://doi.org/10.1016/j.agsy.2005.12.007
Walker P et al (2005) Public health implications of meat production and consumption. Public Health Nutr 8(4):348–356. https://doi.org/10.1079/phn2005727
Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S et al (2019a) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–429. https://doi.org/10.1016/S0140-6736(18)31788-4
Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen SJ et al (2019b) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 6736(18):3–49. https://doi.org/10.1016/S0140-6736(18)31788-4
Wing S, Wolf S (2000) Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ Health Perspect 108(3):233–238. https://doi.org/10.1289/ehp.00108233
World Bank (2016) List of economies
Young V, Pellett P (1994) Plant protein in relation to human protein and amino acid nutrition. Am J Clin Nutr 59:1203S–1212S
Zaharia S et al (2021) Sustained intake of animal-sourced foods is associated with less stunting in young children. Nat Food 2(4):246–254. https://doi.org/10.1038/s43016-021-00259-z
Zheng Y et al (2019) Association of changes in red meat consumption with total and cause specific mortality among US women and men: two prospective cohort studies. BMJ, p 365. https://doi.org/10.1136/BMJ.L2110

The Vital Roles of Blue Foods in the Global Food System

Jim Leape, Fiorenza Micheli, Michelle Tigchelaar, Edward H. Allison, Xavier Basurto, Abigail Bennett, Simon R. Bush, Ling Cao, Beatrice Crona, Fabrice DeClerck, Jessica Fanzo, Stefan Gelcich, Jessica A. Gephart, Christopher D. Golden, Christina C. Hicks, Avinash Kishore, J. Zachary Koehn, David C. Little, Rosamond L. Naylor, Elizabeth R. Selig, Rebecca E. Short, U. Rashid Sumaila, Shakuntala H. Thilsted, Max Troell, and Colette C. C. Wabnitz

1 Introduction

Debates and decisions about food systems generally focus on agriculture and livestock. Blue foods – fish, invertebrates, algae and aquatic plants captured or cultured in freshwater and marine ecosystems – are perennially neglected (Bennett et al. 2021). Yet, blue foods play a central role in food and nutrition security for billions of people and may be ever more important as the world seeks to create just

J. Leape (✉) · M. Tigchelaar · J. Z. Koehn · E. R. Selig
Center for Ocean Solutions, Stanford University, Stanford, CA, USA
e-mail: jleape@stanford.edu

F. Micheli
Center for Ocean Solutions, Stanford University, Stanford, CA, USA

Hopkins Marine Station, Stanford University, Stanford, CA, USA

E. H. Allison · S. H. Thilsted
WorldFish, CGIAR, Penang, Malaysia

X. Basurto
Nicholas School of the Environment, Duke University, Durham, NC, USA

A. Bennett
Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA

S. R. Bush
Environmental Policy Group, Wageningen University, Wageningen, the Netherlands

L. Cao
School of Oceanography, Shanghai Jiao Tong University, Shanghai, China

B. Crona · R. E. Short · M. Troell
Stockholm Resilience Centre, Stockholm, Sweden

F. DeClerck
EAT Forum and One CGIAR, Oslo, Norway

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_21

food systems that support the health of people and the planet (HLPE 2014; Bennett et al. 2018; FAO 2020a; Hicks et al. n.d.; Golden et al. 2021). It is thus paramount that governments bring blue food systems into their food-related decision-making.

Last year, the UN Committee of World Food Security High Level Panel of Experts called for a transformation of the food system, moving "from a singular focus on increasing the global food supply through specialized production and export to making fundamental changes that diversify food systems, empower vulnerable and marginalized groups, and promote sustainability across all aspects of food supply chains, from production to consumption" (HLPE 2020). Properly understood and managed, many blue foods are profoundly suited to that shift.

The blue food portfolio is highly diverse. There are more than 3000 species of marine and freshwater animals and plants used for food (Golden et al. 2021; Thilsted et al. 2016). Blue food systems are supported by a wide range of ecosystems, cultures and production practices – from large-scale trawlers on the high-seas to small-scale fishponds integrated within agricultural systems – supporting access to

J. Fanzo
Berman Institute of Bioethics, Johns Hopkins University, Baltimore, MD, USA

S. Gelcich
Instituto Milenio en Socio-ecologia Costera & Center of Applied Ecology and Sustainability, Pontificia Universidad Catolica de Chile, Santiago, Chile

J. A. Gephart
Department of Environmental Science, American University, Washington, DC, USA

C. D. Golden
Department of Nutrition, Harvard T.H. Chan School of Public Health, Boston, MA, USA

C. C. Hicks
Lancaster Environment Centre, Lancaster University, Lancaster, UK

A. Kishore
International Food Policy Research Institute, Washington, DC, USA

D. C. Little
Institute of Aquaculture, University of Stirling, Stirling, Scotland

R. L. Naylor
Center on Food Security and the Environment, Stanford University, Stanford, CA, USA

U. R. Sumaila
Institute for the Oceans and Fisheries, University of British Columbia, Endowment Lands, Canada

School of Public Policy and Global Affairs, University of British Columbia, Endowment Lands, Canada

C. C. C. Wabnitz
Center for Ocean Solutions, Stanford University, Stanford, CA, USA

Institute for the Oceans and Fisheries, University of British Columbia, Endowment Lands, Canada

nutritious food for communities through global and local markets alike. This diversity supports resilience that can help local food systems withstand shocks like COVID-19 and climate extremes (Troell et al. 2014; Béné 2020; Love et al. 2021) and offers many possibilities for governments and communities seeking to build food systems that are healthy, sustainable, and just.

Blue foods can be a cornerstone of good nutrition and health. Many of them are rich in bioavailable micronutrients that help prevent maternal and infant mortality, stunting, and cognitive deficits. And blue foods can be a healthier animal-source protein than terrestrial livestock: they are rich in healthy fats and can help reduce obesity and non-communicable diseases. In many parts of the world, blue foods are also more accessible and affordable than other animal-source foods (Ryckman et al. 2021a, b). Aquatic plants, including seaweeds, are a traditional presence in diets in the Asia-Pacific region and may offer a variety of possibilities for low-carbon, nutritious food. Coastal and riparian Indigenous Peoples, from the Arctic to the Amazon, have traditionally had among the highest per capita aquatic food consumption rates in the world (Bayley 1981; Cisneros-Montemayor et al. 2016).

Blue foods generally have smaller environmental footprints than many other animal-source foods (Gephart et al. 2021a). However, across a diverse sector, the details matter: greenhouse gas emissions and wildlife and biodiversity impacts can be quite high for some blue food systems, such as bottom trawling or aquaculture systems with low feed efficiencies, especially when they are poorly sited or poorly managed. But many fisheries and aquaculture systems offer footprints that are much smaller than that of beef, with the potential to be improved further (Gephart et al. 2021a). Unfed aquaculture (such as filter-feeding shellfish and seaweeds) also has the potential to improve the water quality of the environment it occupies (Naylor et al. 2021a).

Blue foods are important to livelihoods in many vulnerable communities. The FAO estimates that about 800 million people make their living in blue food systems (FAO 2012), mostly in small-scale fisheries and aquaculture. These systems produce a wide variety of blue foods, supporting healthy diets and resilience in the face of climate change and market fluctuations.

To capitalize on the potential of blue foods, decision-makers must address significant challenges. Wild capture fisheries, both marine and freshwater, need to be better managed (Hilborn et al. 2020; Melnychuk et al. 2021), as many fish stocks have become severely depleted and some technologies have high environmental footprints. Although aquaculture is becoming increasingly sustainable, the growing use of feed in some sectors is putting pressure on the environment through overfishing, deforestation for feed crops and intensification of agricultural production. Intensification of aquaculture can concentrate nutrient pollution and exacerbate risks associated with pathogens and high dependence on antibiotics (Naylor et al. 2021a; Henriksson et al. 2018).

Environmental stressors can also limit blue food production. Climate change will increasingly affect the health and productivity of fish stocks and aquatic ecosystems

(FAO 2018) with implications for food security, livelihoods and economies worldwide, and especially in wild capture fisheries in Africa, East and South Asia, and small island developing states (Tigchelaar et al. 2021; Golden et al. 2016). Other kinds of pollution, from agricultural nutrient runoff to plastics, further threaten productivity and the safety of foods harvested from polluted waters (Bank et al. 2020; Garrido Gamarro et al. 2020).

Like all food systems, blue food systems are beset by inequities. Wealth-generating activities are often favored over those important to nutrition and health, livelihoods and culture. The aquatic resource management systems, knowledge and rights of Indigenous Peoples and traditional small-scale fisherfolk have often been undermined or overlooked in fisheries, water management and ocean governance (Ratner et al. 2014). Although blue food value chains employ roughly equal numbers of men and women (FAO 2020a), their roles, influence over value chains, and benefits can be highly unequal. Progress toward gender equality is critical for the development of more equitable and efficient blue food systems (Hicks et al. n.d.; Lawless et al. 2021).

Blue foods are globally the most traded food products – for developing countries, net revenues from trade of blue foods exceed those of all agricultural commodities combined (Gephart and Pace 2015; Sumaila et al. 2016; FAO 2020b). Global supply chains are complex and often opaque, however, making it difficult or impossible for buyers to ascertain environmental impacts and human rights abuses in production. In some places, the harvesting and trade of fish for high monetary-value global markets have undermined production that is important for local food security and livelihoods (Hicks et al. 2019).

There is every reason to expect that total demand for blue foods will grow substantially in the years ahead – as population and incomes increase, and as attention toward healthy and sustainable food expands (Naylor et al. 2021b) – with growth in supply primarily expected to come from aquaculture (Naylor et al. 2021a). If produced responsibly, blue foods have essential roles to play in ending malnutrition and in building healthy, nature-positive and resilient food systems, including for people living on lands that are marginal for agricultural production (particularly forests, wetlands and small islands), many of whom are Indigenous (Azam-Ali et al. 2021). Realizing that potential, however, will require that governments be thoughtful about how to develop those roles. Here, we focus on three central imperatives for policymakers:

I. Integrate blue foods into decision-making about food system policies, programs and budgets, so as to enable effective management of production, consumption and trade, as well as interconnections with terrestrial food production;
II. Understand, protect and develop their potential in ending malnutrition, fostering the production of accessible, affordable nutritious foods; and
III. Support the central role of small-scale actors, with governance and finance that are responsive to their diverse needs, circumstances and opportunities.

The Bangladesh Story

The proliferation of diverse, freshwater aquaculture supply chains in Bangladesh in recent decades illustrates the potential for blue foods to meet domestic demand, improve food and nutrition security, and reduce rural poverty (Hernandez et al. 2018). This “hidden aquaculture revolution” has involved the participation of hundreds of thousands of small- to medium-scale actors along the supply chain, acting independently and in response to urbanization, growing incomes, and rising fish demand. Approximately 94% of the fish produced in freshwater aquaculture in Bangladesh is directed towards domestic markets and is not traded internationally. Although mostly small-scale, freshwater aquaculture systems have become increasingly intensive and commercial in their operations (Belton et al. 2018). Aquaculture growth and its contribution to food and nutrition security in Bangladesh have resulted from public investment in infrastructure, a positive business environment for small- and medium-size entrepreneurs, and ‘light touch’ government control over the types of systems and species produced (Hernandez et al. 2018).

2 Policy Recommendations

2.1 *Bring Blue Foods into the Heart of Food System Decision-Making*

2.1.1 The Problem: Fisheries and Aquaculture Are Typically Ignored in the Management of Food Systems

Blue foods are deeply interconnected with the rest of the food system – in diets, in supply chains, and in the environment. Aquatic and terrestrial foods appear on the same plate and are often substitutes for each other in household food choices. Capture fisheries provide feed inputs for aquaculture and livestock; terrestrial crops provide feed inputs for aquaculture. Excess nutrients from agriculture and aquaculture can pollute rivers and cause coastal dead zones, undermining fisheries; cultivation of filter-feeding fish and seaweeds takes up nutrients and, if properly managed and scaled, can help protect ecosystem health. Genetic advances in crops and livestock have had positive spillover effects on aquaculture through selection and breeding and through improvements in nutritional performance and feed efficiency.

Yet, blue foods are generally ignored in food system discussions and decision-making (Bennett et al. 2021). Blue foods receive little attention in development assistance – the World Bank, the Bill and Melinda Gates Foundation, and other major development funders have largely neglected the roles of fish, shellfish and aquatic plants in human nutrition and health. Blue foods also tend to be left out of food system policymaking at the national level (Koehn et al. 2021). Ministries or agencies dedicated to capture fisheries and aquaculture tend to manage them as a natural resource, with a focus on economic interests – production and trade. In many countries, the result is that both fisheries and aquaculture are managed with an emphasis on high-monetary-value, export-oriented production. That orientation is reinforced by the market and naturally favors investments in innovations and enterprises that offer the highest financial return. Critical welfare functions are often neglected; indeed, fishery agencies often lack the mandate to address the potential contributions of blue foods to food security and public health, to livelihoods and communities, and to cultural traditions and diets.

When fisheries and aquaculture are siloed and managed as a natural resource, policymakers miss vital opportunities for advancing their goals for nutrition, sustainability, resilience, and livelihoods, and they make unwitting trade-offs among those interests. Fisheries that have sustained communities for generations are depleted by distant water fleets or outcompeted in the market by large volumes of inexpensive farmed fish. The farming of species that could remedy pressing nutrient deficiencies remains undeveloped because management and investment are directed to high-revenue products. Small-scale producers who are central to local diets, livelihoods and community resilience lose out to large commercial concessions.

The African Great Lakes

The small pelagic fisheries of the African Great Lakes region illustrate the opportunities in bringing blue foods into food system policymaking. These fisheries produce huge volumes of affordable, micronutrient-rich food traded throughout the region, but they have been given low priority for investment and management because they are seen as having low economic value. Food system policymaking approaches could include investments to (a) reduce post-harvest loss, which can be substantial, and improve food quality and safety; (b) strengthen domestic and intra-regional trade institutions to enhance small-scale trader market access; (c) address the challenges, risks and opportunities of female fish traders, who comprise a substantial portion of the post-harvest sector; and (d) manage trade-offs between sale for animal feed industries and that for direct human consumption.

2.1.2 The Solution: Governments Should Fully Integrate Blue Foods into their Governance of Food Systems

The potential of blue foods will only be realized if they are brought into food system decision-making. That requires integrated governance, systematic inclusion in policy, and a basic change in the way we think about fish. Specifically, governments should:

(a) Create a governance structure that integrates green and blue

Governments should create a Ministry of Food or other structure that can govern the entire food system, managing synergies and trade-offs in production, consumption and trade. Ministries of agriculture and of fisheries typically focus on production – generally on increasing volume – and often are captured by entrenched interests. A Ministry of Food or similar entity could manage the disparate interests of producers, consumers, and other stakeholders for improved nutritional, environmental, economic, and social outcomes. It could, for example, manage production and consumption to create markets for more nutritious species (see Sect. 2.2). It could also expand the capabilities of small-scale producers, through investment and the allocation of resource rights to support livelihoods and community resilience (see Sect. 2.3). More broadly, it enables decision-makers to govern blue foods as a food system, and to ensure blue foods are fully included in all food system policies.

(b) Govern blue foods as a food system

At the most basic level, integrating blue foods into food system decision-making also recognizes that fisheries and aquaculture should themselves be managed as food systems – they should be managed to deliver society's goals for nutrition, health and equity, as well as for economics and sustainability. Government policy and management should embrace all aspects of the blue food sector – including fisheries, aquaculture development, distribution, exports and imports, and consumption.

Promoting a systems approach means that governments can ensure that nutrient-rich aquatic foods are available and affordable to those for whom they are most important, both nutritionally and culturally. It can work across the value chain to identify and address the many threats to the supply of blue foods, from overfishing to pollution to waste and loss in harvesting, processing and distribution (see Sect. 2.2). It can build a system that is just, ensuring equitable participation in production, accessibility for consumption, and broad representation in decision-making. By managing blue foods as a system, governments can also create policies and incentives across the value chain to shift both production and consumption to species and technologies that have lighter footprints and to foster diversity in production systems.

Looking at the whole system also enables the government to make public investments where markets fail. Private investment goes to blue food systems and enterprises that offer high financial returns. Governments can allocate public funds to develop innovations in fisheries and aquaculture that offer lower returns but are important for nutrition, livelihoods, and sustainability, and it can provide capital for small- and medium-sized enterprises to take those innovations to scale.

To realize this vision, governments will need to collect data that enable good decisions – including data that enable the monitoring of fisheries and supply chains, that capture the vital diversity of species that are produced and consumed, that survey the demographic diversity of participants in the sector, and that reflect the frequently profound heterogeneity in consumption across different regions of the country and between different ethnic and religious groups. They will also need to redesign policies to enable and incentivize the capabilities of key actors – from producers to consumers – to adopt transformative practices in the food system as a whole, in value chains, and in the places where they live (see Sect. 2.3).

(c) Include blue foods in all food system policies

Structural reform must be followed by policy inclusion – governments should integrate blue foods into the policies that regulate, guide and support the food sector. Government strategies to meet the Human Right to Food, for example (see Sect. 2.2), should embrace the potential of blue foods to offer accessible, affordable sources of key nutrients. Dietary guidelines should include the nutritional contributions of different blue foods, so as to help consumers understand their value for addressing nutrient deficiencies and obesity, diabetes and coronary disease. Safety net programs for children and pregnant and lactating women should also include blue foods, as fish can be a rich source of essential micronutrients for those most vulnerable populations, helping to prevent stunting and cognitive deficits. The food systems and food sovereignty of Indigenous Peoples must be supported.

Including blue foods in policymaking for the food system allows governments to better manage the interconnections between terrestrial and aquatic food systems. That includes the regulation of agricultural and inland aquaculture runoff and other land-based pollution that can undermine coastal fisheries and marine aquaculture, such as nutrients that cause coastal dead zones and toxins that can compromise food safety. Governments can also better manage the allocation of crops and fish to competing uses – for food or feed – and support the development of a circular economy in which wastes or by-products from one part of the food system are used as feed inputs for another.

2.2 *Protect and Develop the Potential of Blue Foods to Help End Malnutrition*

2.2.1 The Problem: Blue Food Systems Are Not Managed for Nutrition

Many blue foods contain high concentrations of bioavailable minerals and vitamins, essential fatty acids (in particular, EPA and DHA), and animal protein (Thilsted et al. 2016) – globally, roughly 8% of zinc and iron, 13% of protein, and 27% of vitamin B12 are derived from aquatic foods (Golden et al. 2021). Blue foods can therefore make key contributions to diet-related health challenges. They can reduce micronutrient deficiencies that lead to disease; improve heart, brain and eye health by uniquely providing omega-3 fatty acids; and replace the consumption of less healthy red and processed meats (Golden et al. 2021). The micronutrient contributions of blue foods are especially important for childhood development, pregnant women and women of childbearing age (Kawarazuka and Béné 2011; Bogard et al. 2015; Starling et al. 2015), and can reduce nutritional inequities for girls and women (Golden et al. 2021).

Not all fish are equal. For example, a single serving of small indigenous species in Bangladesh, eaten whole, contributes more than five times as much vitamin B12 as a single serving of tilapia fillet (Thilsted et al. 2016). Which blue foods are on a plate, and in what form, therefore matters as much as the amount of food (Golden et al. 2021; Hicks et al. 2019). Yet, blue food policy often considers blue foods only as a protein source, which neglects the nutrient diversity of fish (in terms of micronutrients and fatty acids) and excludes the contributions of aquatic plants altogether. In the Bangladesh case discussed above, for example, growth in (farmed) fish consumption has led to an increase in total protein consumption, but also a decrease in consumption of certain micronutrients, highlighting the challenge of balancing high nutrient content provided by small native fish with employment and revenue generation offered by tilapia and pangasius production (Bogard et al. 2017). Adopting a nutrition-sensitive approach to aquaculture and fisheries, rather than just a production focus, can address these issues (Bennett et al. 2021; Thilsted et al. 2016; Gephart et al. 2021b).

In many countries, ministries manage blue foods for their wealth-generating benefits, focusing policy on high economic value blue food production, often for export. Such a focus risks undermining the critical welfare functions of blue foods by neglecting the nutritional characteristics, livelihood contributions, accessibility, and cultural patterns of blue food consumption (Bennett et al. 2021; Hicks et al. n.d.; Thilsted et al. 2016; Hicks et al. 2019). Nutrient-dense blue foods are regularly exported from nutritionally vulnerable countries to serve either as a high-quality product for wealthy consumers or to be reduced to fishmeal to feed farmed fish for high-income countries (Isaacs 2016). Orientation towards export markets not only affects coastal and riparian populations, but also inland communities who have historically depended on richly nutritious dried or smoked fish transported from the coast (Gordon et al. 2013).

The quantity, quality and safety of blue food supply are threatened by food loss and waste (amounting to 35% of fish harvested globally (FAO 2020a)), management failures (including overfishing and Illegal, Unreported, and Unregulated fishing), environmental degradation, and climate change (FAO 2018). It is estimated that declines in marine fish catch over the next three decades could subject an additional 845 million people (11% of the world's population) to vitamin A, zinc, or iron deficiencies (Golden et al. 2016). Though all of these pressures occur globally, their effects are highest and most strongly felt in tropical and low-income countries with high dependence on blue foods for nutrition and health, livelihoods and income (Tigchelaar et al. 2021; Golden et al. 2016).

Finally, blue food policy misses opportunities to support nutrition goals when it fails to address unequal distribution of the benefits from blue food systems or the concentration of power. Women, in particular, are underrepresented in policies and decision-making (Hicks et al. n.d.; Lawless et al. 2021; Udo and Okoko 2014). Where gender equality is lacking, blue foods are less affordable (Hicks et al. n.d.) and blue food waste and losses are greater (Kaminski et al. 2020).

2.2.2 The Solution: Sustain and Enhance the Nutritional Benefits of Blue Food Systems

To manage blue food systems for the benefit of nutrition and health, governments should:

(a) Recognize the centrality of the right to food in blue food trade and domestic policy

The right to food states that everyone is entitled to adequate, accessible and safe food that corresponds to their cultural traditions in a fulfilling and dignified manner (Fakhri 2020). A Right to Food means that governance of and investment in blue food systems should seek balance between economic opportunities and local rights to food provisioning (Bennett et al. 2021; Hicks et al. n.d.), aiming to sustain and innovate with the full diversity of species, production and harvest methods, product forms and distribution channels in mind (Golden et al. 2021). Recognizing the right to food requires taking a food systems approach in which nutrition, sustainability, climate-resilience and equity can be considered together (see Sect. 2.1) and which ensures that all actors are represented, including through engagement with grassroots and civil society organizations (see Sect. 2.3) (Bennett et al. 2021; Hicks et al. n.d.). Recognizing the food rights of Indigenous Peoples who harvest aquatic foods is of particular importance, whether such Peoples have Nation status or not. At a national level, blue foods should explicitly be included in food and nutrition policy (see Sect. 2.1) (Bennett et al. 2021; Thilsted et al. 2016; Koehn et al. 2021). Internationally, blue foods should be positioned as a vital food source in the context of the UN Sustainable Development Goals, health national adaptation plans (HNAPs), and other international efforts to alleviate malnutrition (Bennett et al. 2021).

(b) Harness the nutritional diversity of blue foods

Governments should ensure that the nutritional potential of blue foods serves to improve the health and diets of nutritionally vulnerable people. They should recognize and harness the diversity of local blue food nutritional profiles, preparation methods and dietary practices (Hilborn et al. 2020).

Governments should manage capture fisheries so as to optimize them for nutritional benefits, not just for maximum sustainable yield, which can uncover opportunities to diversify fish production without increasing pressure on existing stocks (Golden et al. 2021; Bernhardt and O'Connor 2021). Aquaculture development should foster the sustainable production of native small fish species that can supply context-specific nutrient needs. As an example, *mola*, a fish species from the Gangetic floodplains, can easily be produced in homestead ponds and offers 80 times more vitamin A than commonly farmed silver carp (Thilsted et al. 2016).

Governments should evaluate exports and licenses to distant water fleets to ensure that they don't compromise nutritional goals. In some cases (e.g., Namibia), retaining just a small portion of current exports could meet local nutrition goals

(Hicks et al. 2019), though this requires infrastructure to support equitable distribution and access to blue foods locally (see Sect. 2.3).

Public health policies and investments focused on reducing malnutrition should include blue foods in programs to address the specific nutritional needs of pregnant and lactating women, young children and the elderly – with appropriate consideration of food safety and pollutants – as was done with the introduction of dried small fish powder in Myanmar to support children's health (Dried small fish powder provides opportunity for child health in Myanmar 2020).

(c) Halt loss of nutrients from blue food systems

To ensure that blue foods important for nutrition are available, accessible and affordable, governments should take steps to reduce losses in the system. Improved processing methods can preserve and concentrate nutrients and increase availability, as well as improve nutritional quality (Siddhnath et al. 2020).

In many places, better management of capture fisheries through harvest controls or spatial restrictions, for example, can restore fish stocks and increase yields (Hilborn et al. 2020; Melnychuk et al. 2021; Anderson et al. 2018). Better regulation of economic development in floodplains, riparian, coastal, and ocean ecosystems can help protect blue food production and reduce risks to food safety (Niane et al. 2015; de Oliveira Estevo et al. 2021).

Fisheries and aquaculture policy should also anticipate and adapt to projected impacts from climate change (FAO 2018; Tigchelaar et al. 2021). Governments should consider nature-based solutions like mangrove and seagrass restoration and restorative aquaculture that can help strengthen the resilience of aquatic ecosystems (Gattuso et al. 2018; Hoegh-Guldberg et al. 2019). Additional climate adaptation options are context-specific, but include shifting to offshore resources (McDonald and Torrens 2020), devising climate-smart agreements for transboundary resources (Oremus et al. 2020) and investing in climate information systems, including early warning systems for extreme events (Cinner et al. 2018; Turner et al. 2020). Place-based responses to climate change are particularly important for Indigenous Peoples whose cultures and identities are closely linked to their local environments (Whitney et al. 2020).

(d) Improve the distributional equity of blue food production and consumption

Participation in activities along the value chain is often socially differentiated; for example, men dominate blue food production and women blue food processing. Governments thus need to collect data on what roles, from fish producers to post-harvest processors, traders, and consumers, different groups in society hold and why. When divisions of labor exist because of unequal opportunities to participate across the value chain, they are likely to result in distributional and nutritional inequities (Udo and Okoko 2014). Investments to address the drivers of unequal opportunities, such as through strengthening women's empowerment, are known to lead to improvements in outcomes for women and their families. For example, in Zambia, strategies to uncover underlying structural barriers that limit participation, such as unequal norms and attitudes, increased women's participation in production processes, and their control over resources (Kaminski et al. 2020). Governments need to ensure that the full diversity of actors, across social groups, including gender, class, and ethnicity, and along the value chain and scale of production, are fairly represented in decision-making processes (Hicks et al. n.d.) (see Sect. 2.3). In addition, governments should recognize subnational differences in nutritional vulnerability and blue food access in national policy and align subnational policies and instruments with nutritional goals.

2.3 Support the Central Role of Small-Scale Actors in Fisheries and Aquaculture

2.3.1 The Problem: Limited Recognition and Support for the SSFA Sector in Supporting Equitable and Sustainable Food Systems

Small-scale fisheries and aquaculture (SSFA) have been marginalized in dialogues about sustainable and equitable food system transformation, despite being central to it in many contexts (Bennett et al. 2021). SSFA play a key role in supplying nutrition and supporting local economies in many countries. They produce more than half of the global fish catch and contribute over two-thirds of aquatic foods destined for direct human consumption (FAO 2020a), with the potential for lower environmental footprints (e.g., lower fuel use than in large-scale operations (Gephart et al. 2021a)). In addition, the value chains that process and sell their products support about 800 million full- and part-time jobs, half of which are occupied by women (FAO 2012, 2020a). SSFA produce a high diversity of aquatic foods. This diversity underpins healthy diets, and resilience in the face of shocks, climate and market changes (Hicks et al. 2019; Gephart et al. 2021b; Bennett et al. 2020; Campbell et al. 2021). SSFA also contribute to intra-regional trade, especially in smoked and dried products, which can have more direct impacts on food security and poverty alleviation than the globalized system (Béné et al. 2010).

SSFA worldwide face a growing range of threats and challenges, including resource over-exploitation, habitat degradation, poor political representation, market-driven competition for resources (e.g., patterns of trade and foreign fishing), assumed links between informality and illegality (Song et al. 2020), climate change (Monnier et al. 2020), and shocks such as the current COVID-19 pandemic (Bennett et al. 2020; Farmery et al. 2021; Short et al. 2021). Cumulatively, SSFA are being 'squeezed out' of the spaces they occupy on the land-water margins by other more powerful sectors, such as tourism, residential and industrial land use, oil and gas exploration, industrial fisheries and aquaculture (Cohen et al. 2019). Within SSFA, inequitable access to resources and opportunities and limited gender and social inclusion are key threats. Indigenous Peoples whose lands and waters have been colonized by others, and whose harvesting activities tend to be small-scale, continue to be marginalized by public policy. Finally, pervasive data and monitoring limitations pose major challenges to understanding the status of SSFA (Pauly and Zeller

2016), as a lack of data leads to underestimating SSFA contributions and marginalizing SSFA in policy and decision-making, while aggregated and categorical data fail to represent the diversity of SSFA actors and benefits.

Governments and policies predominantly focus on industrialized, large-scale fisheries and aquaculture, leading to a lack of voice and support for SSFA. One reason for this persistent neglect is that policymakers struggle with the diversity, dynamism and perceived informality of SSFA and their associated cultures (Hicks et al. n.d.). Most policies affecting the sector make unrealistic assumptions that SSFA are a homogenous group limited to producers (Gelcich et al. 2018; Johnson 2006). In contrast, the sector is extraordinarily diverse along many dimensions (Short et al. 2021). Successful transformations of SSFA require supporting current activities while exploring new opportunities and encouraging both the entry of new actors into the sector and the redeployment of some current actors to opportunities outside it.

2.3.2 The Solution: Support SSFA Capabilities and Diversity Through Inclusive Blue Food Policy

Governments of countries where SSFA operate should place this sector at the center of their national human development and food security strategies, creating initiatives that support the capabilities of the diverse SSFA actors. Supporting the viability of SSFA requires governments to:

(a) **Include actors from SSFA in decision-making and policy development**

Inclusion of SSFA in decision-making is essential to enable more adaptive governance mechanisms and policies that build on the strengths of the diversity of SSFA, acknowledge the cultural importance and specific roles of blue foods for diverse actors and steer food systems towards a more equitable distribution of blue food benefits.

Women are greatly underrepresented in policy and decision-making, even though they make up half of the workforce in SSFA globally. Recent efforts to improve gender equity in blue food policy have tended to adopt a narrow focus on women, overlooking men or gender relations (Lawless et al. 2021). Such a narrow focus risks exacerbating inequities by placing the blame, or burden for change, on women (Hicks et al. n.d.). Blue food policy development therefore not only needs to involve more input and leadership from women, but also should take a gender transformative approach to improving intersectional equity in SSFA (Hicks et al. n.d.; Lawless et al. 2021; Cole et al. 2020).

Indigenous coastal and riparian Peoples tend to be more blue food-dependent than the wider population in the countries they live in (Bayley 1981; Cisneros-Montemayor et al. 2016). They also have proven systems for food system governance – including knowledge systems – that, if recognized and supported, could enable the 'decolonization' of their food systems (Coté 2016). As access to traditional food sources has been lost, adoption of unhealthy diets based on processed foods have led to high rates of diet-related non-communicable diseases (Kuhnlein and Receveur 2003; Hawley and McGarvey 2015). Thus, by supporting Indigenous Peoples' food (and wider) sovereignty claims, governments could contribute to transformative health benefits in these communities and nations.

Governments should support and strengthen multi-stakeholder initiatives that have the benefits of SSFA at their core, including organizations of fish workers, harvesters and producers at the global, regional, and national levels, such as the World Forum of Fish Harvesters and Fish Workers (WFF), the World Forum of Fisher Peoples (WFFP), and the International Collective in Support of Fish Workers (ICSF).

(b) **Expand capabilities through investment in institutions and human capital, and investment in environmental protection and restoration**

Securing the future of SSFA requires adaptive action that supports the capabilities of SSFA to deliver both market and non-market societal benefits. Positive environmental outcomes, for example, require engagement of SSFA actors to co-produce knowledge, forge strategies for sustainability and climate adaptation, and participate in and lead environmental restoration, conservation and adaptation efforts.

Governments should create space for SSFA as they expand agricultural and industrial aquaculture and fishery sectors. They should use public and private regulation and financial mechanisms to enable SSFA actors – including Indigenous Peoples – to (re)gain control over the resources, rights, skills and knowledge necessary for environmentally resilient and socially equitable production and trade (including insurance, credit, and market mechanisms to buffer against extreme events).

Governments should also allocate and enforce land, water and labor rights to SSFA through user rights-based systems, the creation of preferential access areas, coastal and inland land use zoning, or other measures. To support the roles of SSFA in creating livelihoods and resilient and equitable food systems, governments should also provide capital, through public and private financial mechanisms that empower, rather than undermine, SSFA actors. In the case of Indigenous Peoples, recognition of their collective sovereign rights is the key starting point.

(c) **Support diversification and sustainable intensification**

For many SSFA producers, it will be crucial to find pathways for sustainable intensification or expansion of their operations or for diversification into other SSFA products or other sources of livelihood. To that end, governments should invest in R&D and facilitate access to venture capital to support innovation in species/production systems that are of high value for nutrition, livelihoods, and justice. They should also support the development of complementary livelihoods, which are often critical to continued participation by SSFA actors, their control of the resource base and its sustainability.

Costs, trade-offs, and potential environmental and social impacts of intensification and diversification should be carefully considered, and diversification should be proactively designed and monitored. To this end, efforts should be made towards better integration of different data types and sources and enabling the effective and timely access to and use of data by relevant actors. Investment is needed in monitoring systems for catch, effort, production and consumption, and in national surveys of engagement in SSFA that are fully gender-inclusive, and that reflect intersections of gender, age and ethnicity. Promotion of R&D towards technological solutions to data collection, storage and communication/accessibility barriers would effectively support these needs.

(d) **Secure economic and nutritional benefits through trade policies and the development and protection of local and national markets**

Governments, in particular, those in low-income food insecure nations, need to be able to regulate the activities of large corporate actors and trade to protect the rights (e.g., labor rights, human rights, right to food) of SSFA workers, to ensure that terms, conditions, and revenues from trade are transparent and fair, do not impact local food security, and, where needed, retain high nutritional value products for local consumption. Regulation should consider the potential trade-offs and linkages between nutritional and economic value of resources. It should establish transparent processes, monitoring systems, and accountability mechanisms to ensure the traceability and visibility of social impacts. Market-based approaches that encourage actors to add value to products through processing, marketing or certification need to carefully consider trade-offs in economic, social, environmental, and public health outcomes (see Sect. 2.1).

Governments should also explore opportunities to support "alternative" systems based on short supply chains for products with strong local identities and local, decentralized production and processing. Diversity, deeply embedded in these food systems, could be supported by policies mandating or incentivizing local retention of SSFA products to ensure food self-sufficiency, for example, the development or control of local markets and school feeding programs.

3 Conclusion

Blue foods have vital roles to play in the transformation of the global food system. In the face of growing challenges and rising demand, governments must act now to support and expand these roles. They should bring blue foods into the heart of their food decision-making, by creating a Ministry of Food or other governance structures that integrate blue foods fully into food policies, budgets and programs, managing the terrestrial and aquatic food systems as a whole. They should recognize the right to food and harness the nutritional diversity of blue foods in ways that ensure the equitable distribution of blue food production and consumption. And they should empower and support the millions of small-scale actors in fisheries and aquaculture who produce, process, distribute and trade most of the food we eat, and can be the key to a vibrant, sustainable, healthy, and equitable blue food economy. Recognizing and acting upon the potential role of blue foods in all dimensions of food policy would be a clear win for the 2021 UN Food Systems Summit and achieving the 2030 Agenda for Sustainable Development.

Acknowledgments This chapter was prepared by researchers who are part of the Blue Food Assessment (BFA; https://www.bluefood.earth/), a comprehensive examination of the role of aquatic foods in building healthy, sustainable, and equitable food systems. The key messages and recommendations in this chapter were derived from several papers that are part of the BFA, as well as related materials. A complete list of BFA papers can be found at https://www.bluefood.earth/science/.

Funding: the BFA was supported by the Builders Initiative, the MAVA Foundation, the Oak Foundation and the Walton Family Foundation.

References

Anderson CM et al (2018) How commercial fishing effort is managed. Fish Fish 20:268–285

Azam-Ali S et al (2021) Marginal areas and indigenous people: priorities for research and action

Bank MS, Metian M, Swarzenski PW (2020) Defining seafood safety in the Anthropocene. Environ Sci Technol 54:8506–8508

Bayley PB (1981) Fish yield from the Amazon in Brazil: comparison with African River yields and management possibilities. Trans Am Fish Soc 110:351–359

Belton B, Bush SR, Little DC (2018) Not just for the wealthy: rethinking farmed fish consumption in the Global South. Glob Food Sec 16:85–92

Béné C (2020) Resilience of local food systems and links to food security - a review of some important concepts in the context of COVID-19 and other shocks. Food Secur 1–18

Béné C, Lawton R, Allison EH (2010) "Trade matters in the fight against poverty": narratives, perceptions, and (lack of) evidence in the case of fish trade in Africa. World Dev 38:933–954

Bennett A et al (2018) Contribution of fisheries to food and nutrition security: current knowledge, policy, and research

Bennett NJ et al (2020) The COVID-19 pandemic, small-scale fisheries and coastal fishing communities. Coast Manage:1–11

Bennett A et al (2021) Recognize fish as food in policy discourse and development funding. Ambio. https://doi.org/10.1007/s13280-020-01451-4

Bernhardt JR, O'Connor MI (2021) Aquatic biodiversity enhances multiple nutritional benefits to humans. Proc Natl Acad Sci U S A 118

Bogard JR et al (2015) Inclusion of small indigenous fish improves nutritional quality during the first 1000 days. Food Nutr Bull 36:276–289

Bogard JR et al (2017) Higher fish but lower micronutrient intakes: temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. PLoS One 12:e0175098

Campbell SJ et al (2021) Immediate impact of COVID-19 across tropical small-scale fishing communities. Ocean Coast Manag 200:105485

Cinner JE et al (2018) Building adaptive capacity to climate change in tropical coastal communities. Nat Clim Chang 8:117–123

Cisneros-Montemayor AM, Pauly D, Weatherdon LV, Ota Y (2016) A global estimate of seafood consumption by coastal indigenous peoples. PLoS One 11:e0166681

Cohen P et al (2019) Securing a just space for small-scale fisheries in the blue economy. Front Mar Sci 6:171

Cole SM et al (2020) Gender accommodative versus transformative approaches: a comparative assessment within a post-harvest fish loss reduction intervention. Gend Technol Dev 24:48–65

Coté C (2016) "Indigenizing" food sovereignty. Revitalizing indigenous food practices and ecological Knowledges in Canada and the United States. Humanit Rep 5:57

de Oliveira Estevo M et al (2021) Immediate social and economic impacts of a major oil spill on Brazilian coastal fishing communities. Mar Pollut Bull 164:111984
Dried small fish powder provides opportunity for child health in Myanmar (2020) WorldFish Blog. http://blog.worldfishcenter.org/2020/11/dried-small-fish-powder-provides-opportunity-for-child-health-in-myanmar/
Fakhri M (2020) The right to food in the context of international trade law and policy. https://undocs.org/A/75/219
FAO (2012) The state of world fisheries and aquaculture 2012. http://www.fao.org/3/i2727e/i2727e.pdf
FAO (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. vol 627
FAO (2020a) The state of world fisheries and aquaculture 2020. Sustainability in action. http://www.fao.org/3/ca9229en/ca9229en.pdf. https://doi.org/10.4060/ca9229en
FAO (2020b) FAO Yearbook. Fishery and Aquaculture Statistics 2018/FAO annuaire. Statistiques des pêches et de l'aquaculture 2018/FAO anuario. Estadísticas de pesca y acuicultura 2018. https://doi.org/10.4060/cb1213t
Farmery AK et al (2021) Blind spots in visions of a "blue economy" could undermine the ocean's contribution to eliminating hunger and malnutrition. One Earth 4:28–38
Garrido Gamarro E, Ryder J, Elvevoll EO, Olsen RL (2020) Microplastics in fish and shellfish – a threat to seafood safety? J Aquat Food Prod Technol 29:417–425
Gattuso J-P et al (2018) Ocean solutions to address climate change and its effects on marine ecosystems. Front Mar Sci 5:337
Gelcich S, Reyes-Mendy F, Arriagada R, Castillo B (2018) Assessing the implementation of marine ecosystem based management into national policies: insights from agenda setting and policy responses. Mar Policy 92:40–47
Gephart JA, Pace ML (2015) Structure and evolution of the global seafood trade network. Environ Res Lett 10:125014
Gephart JA et al (2021a) Environmental performance of blue foods. Nature 597:360–365
Gephart JA et al (2021b) Scenarios for global aquaculture and its role in human nutrition. Rev fish sci aquac 29:122–138
Golden CD et al (2016) Nutrition: fall in fish catch threatens human health. Nature 534:317–320
Golden CD et al (2021) Aquatic foods to nourish nations. Nature. https://doi.org/10.1038/s41586-021-03917-1
Gordon A, Finegold C, Crissman CC, Pulis A (2013) Fish production, consumption, and trade in Sub-Saharan Africa: a review analysis. https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/884/WF-3692.pdf?sequence=1&isAllowed=y
Hawley NL, McGarvey ST (2015) Obesity and diabetes in Pacific Islanders: the current burden and the need for urgent action. Curr Diab Rep 15:29
Henriksson PJG et al (2018) Unpacking factors influencing antimicrobial use in global aquaculture and their implication for management: a review from a systems perspective. Sustain Sci 13: 1105–1120
Hernandez R et al (2018) The "quiet revolution" in the aquaculture value chain in Bangladesh. Aquaculture 493:456–468
Hicks CC et al (2019) Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574: 95–98
Hicks CC et al (n.d.) Towards justice in blue food systems. Nat Food
Hilborn R et al (2020) Effective fisheries management instrumental in improving fish stock status. Proc Natl Acad Sci U S A 117:2218–2224
HLPE (2014) Sustainable fisheries and aquaculture for food security and nutrition. http://www.fao.org/3/a-i3844e.pdf
HLPE (2020) Impacts of COVID-19 on food security and nutrition: developing effective policy responses to address the hunger and malnutrition pandemic. http://www.fao.org/3/cb1000en/cb1000en.pdf, https://doi.org/10.4060/cb1000en

Hoegh-Guldberg O et al (2019) The ocean as a solution to climate change: five opportunities for action. http://oceanpanel.org/sites/default/files/2019-10/HLP_Report_Ocean_Solution_Climate_Change_final.pdf
Isaacs M (2016) The humble sardine (small pelagics): fish as food or fodder. Agric Food Security 5:27
Johnson DS (2006) Category, narrative, and value in the governance of small-scale fisheries. Mar Policy 30:747–756
Kaminski AM et al (2020) Fish losses for whom? A gendered assessment of post-harvest losses in the Barotse floodplain fishery, Zambia. Sustain Sci Pract Policy 12:10091
Kawarazuka N, Béné C (2011) The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. Public Health Nutr 14:1927–1938
Koehn JZ et al (2021) Fishing for health: do the world's national policies for fisheries and aquaculture align with those for nutrition? Fish Fish. https://doi.org/10.1111/faf.12603
Kuhnlein HV, Receveur O (2003) Dietary change and traditional food systems of indigenous peoples. https://doi.org/10.1146/annurev.nu.16.070196.002221
Lawless S, Cohen PJ, Mangubhai S, Kleiber D, Morrison TH (2021) Gender equality is diluted in commitments made to small-scale fisheries. World Dev 140:105348
Love DC et al (2021) Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. Glob Food Sec 28:100494
McDonald J, Torrens SM (2020) Governing Pacific fisheries under climate change. In: Research handbook on climate change, oceans and coasts. Edward Elgar Publishing
Melnychuk MC et al (2021) Identifying management actions that promote sustainable fisheries. Nat Sustain:1–10
Monnier L et al (2020) Small-scale fisheries in a warming world: exploring adaptation to climate change
Naylor RL et al (2021a) A 20-year retrospective review of global aquaculture. Nature 591:551–563
Naylor RL et al (2021b) Blue food demand across geographic and temporal scales. Nat Commun 12:5413
Niane B et al (2015) Human exposure to mercury in artisanal small-scale gold mining areas of Kedougou region, Senegal, as a function of occupational activity and fish consumption. Environ Sci Pollut Res Int 22:7101–7111
Oremus KL et al (2020) Governance challenges for tropical nations losing fish species due to climate change. Nat Sustain 3:277–280
Pauly D, Zeller D (2016) Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nat Commun 7:10244
Ratner BD, Åsgård B, Allison EH (2014) Fishing for justice: human rights, development, and fisheries sector reform. Glob Environ Change 27:120–130
Ryckman T, Beal T, Nordhagen S, Chimanya K, Matji J (2021a) Affordability of nutritious foods for complementary feeding in eastern and southern Africa. Nutr Rev 79:35–51
Ryckman T, Beal T, Nordhagen S, Murira Z, Torlesse H (2021b) Affordability of nutritious foods for complementary feeding in South Asia. Nutr Rev 79:52–68
Short RE et al (2021) Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. Nat Food 2:733–741
Siddhnath et al (2020) Dry fish and its contribution towards food and nutritional security. Food Rev Int:1–29
Song AM et al (2020) Collateral damage? Small-scale fisheries in the global fight against IUU fishing. Fish Fish 21:831–843
Starling P, Charlton K, McMahon AT, Lucas C (2015) Fish intake during pregnancy and foetal neurodevelopment--a systematic review of the evidence. Nutrients 7:2001–2014
Sumaila UR, Bellmann C, Tipping A (2016) Fishing for the future: an overview of challenges and opportunities. Mar Policy 69:173–180
Thilsted SH et al (2016) Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61:126–131

Tigchelaar M et al (2021) Compound climate risks threaten aquatic food system benefits. Nat Food 2:673–682

Troell M et al (2014) Does aquaculture add resilience to the global food system? Proc Natl Acad Sci 111:13257–13263

Turner R, McConney P, Monnereau I (2020) Climate change adaptation and extreme weather in the small-scale fisheries of Dominica. Coast Manage 48:436–455

Udo IU, Okoko AC (2014) Seafood processing and safety: a veritable tool for transformation and empowerment of rural women in Nigeria. Nigerian J Agric Food Environ 10:8–17

Whitney C et al (2020) "Like the plains people losing the buffalo": perceptions of climate change impacts, fisheries management, and adaptation actions by indigenous peoples in coastal British Columbia, Canada. Ecol Soc 25:33

Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation

Rui Benfica, Judith Chambers, Jawoo Koo, Alejandro Nin-Pratt, José Falck-Zepeda, Gert-Jan Stads, and Channing Arndt

1 Introduction

Food systems are a powerful lever for countries to overcome poverty, hunger, and malnutrition. In the next few decades, low- and middle-income countries (LMICs) will need to respond to numerous challenges, including rising food demand, shifts toward healthier diets, deleterious climate change effects, and the need to preserve biodiversity. Accelerated efforts to raise agricultural yields (Alexandratos and Bruinsma 2012) and increase productivity in agricultural value chains are needed, especially for vulnerable populations in LMICs. Innovations in food systems, facilitated by improved technology for more precise breeding and input use efficiency, the enabling of policy and regulatory environments, increased investments, and enhanced individual and institutional capacities (Fuglie 2018) in research development and delivery can significantly contribute to those goals.

Currently, many LMICs lack the capacity to innovate and/or benefit from global developments in agricultural innovations and digital technologies. Several factors are at play. First, while advanced and high-middle-income countries use R&D investments to catalyze technological and economic transformation (Ruttan 1982), many LMICs lag in both investment and human/institutional capacity (Beintema et al. 2012). Second, many countries are constrained by the inherent characteristics of their agrifood system operating environments, which are mostly rural, remote, and dominated by small farms, making it hard for innovations to take hold. They are

R. Benfica (✉) · J. Koo · A. Nin-Pratt · J. Falck-Zepeda · G.-J. Stads
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: R.Benfica@cgiar.org

J. Chambers
Program for Biosafety Systems, IFPRI, Washington, DC, USA

C. Arndt
Environment and Production Technology Division, IFPRI, Washington, DC, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_22

hampered by limited infrastructure density (roads, telecommunications, weather stations, energy grid, etc.); poorly developed markets and value chains; and inadequate financial services. They also lack efficient mitigation systems to address risks arising from climate change, global trade, and invasive species. Finally, they lack supportive enabling policies and regulations to facilitate the discovery, development, and delivery of food system and digital innovations.

Promising advancements in bioscience and digital technologies offer opportunities to address the innovation challenges and close the productivity gap for LMICs. Applications of biotechnology research have led to more precise introduction and enhancement of essential traits in crops, animals, and micro-organisms. The CRISPR-Cas9 genome editing system has become a viable tool for targeting specific genomic changes (Es et al. 2019), producing results similar to those achieved through conventional plant and animal breeding methods, but with more efficient, timely, and cost-effective R&D trajectories (Gao 2018). Likewise, digital technologies are contributing to accelerated food system transformation, optimizing management decisions (Basso and Antle 2020), facilitating information flows across food-land-water systems (von Braun et al. 2017), and facilitating regional and global trade (Jouanjean 2019).

Accordingly, this brief focuses on agricultural bio-innovations and digital technologies as important drivers of food system transformation over the next decade, and outlines elements relevant for all types of innovation to succeed. Taking a systems landscape perspective, it highlights R&D and economic viability, and environmental and social effects, while addressing enabling factors, such as R&D investment, institutional and human capacity, infrastructure, and the variety of socioeconomic, regulatory, and political economy factors that affect development, delivery, and adoption pathways for new technologies.

1.1 Agricultural Bio-Innovations

Agricultural bio-innovations comprise a broad suite of technologies, including conventional and marker-assisted breeding in crops, livestock, fish, and microorganisms, as well as biofertilizers and precision agriculture. Newer improvement techniques include genetic modifications (GM) and new breeding techniques (NBTs) such as genome editing. These confer protection from pests, diseases, and weeds, and offer other novel uses and applications that address environmental conditions and climate change effects.[1] This paper highlights crop bio-innovations, as these have advanced significantly but are still facing challenges that could

[1] New bio-innovations also revolutionized livestock and fish breeding, including aquaculture and embryo transplantation (Belton et al. 2020). Genome editing and other biotechnology-based livestock transformation technologies have vast potential to help address human and animal needs, as well as environmental challenges. R&D areas under development in the livestock sector include disease models, xenotransplantation, vaccine production, enhanced animal breeding and

constrain their use and viability. Some of those challenges are also relevant for other bio-innovations.

Historically, investments in crop improvement research, dominated by conventional breeding, have led to gains in agricultural productivity. In a comprehensive assessment, Evenson and Gollin (2003) documented high growth rates in the productivity of most cereals. Their analysis suggests that at least half of all total factor productivity (TFP) gains between 1960 and 2000 were attributable to crop genetic improvements. They also found that countries without genetic improvements were less likely to realize TFP gains from other sources (Evenson and Gollin 2003). A study by Lantican et al. (2015), covering three-quarters of the world's wheat area, shows that genetic improvement contributed to an increase in wheat yields from 2.5 tons/ha (hectare) in 1995 to 2.8 tons/ha in 2015, an increase of 0.6% annually. In the case of maize, Krishna et al. (2021) find that genetic improvement efforts in 10 major maize-producing countries in Africa[2] increased yields from 1.4 tons/ha in 1995 to 1.7 tons/ha in 2015, an average annual increase of 1.0%.

Despite this, in the absence of infusions of new technology, conventional breeding has limited the potential to address increasing demand for food and biomass or to mitigate agro-environmental challenges in a timely manner (Gao 2018). Recent biotechnology applications offer multiple benefits to LMICs, given the array of biophysical, climate, and socioeconomic challenges these countries face. However, their adoption varies across developing economies. Differences in R&D capacity, delivery, adoption, and benefits often reflect disparities in the socioeconomic and political factors that affect public perceptions, and in the prevailing policy and governance environments. If such factors are limiting, they can restrict the technology frontier and constrain farmers' access to potential solutions.

Consequently, more emphasis should be put on interventions that address the mix of research and enabling policy factors necessary to realize the pro-poor benefits of bio-innovations. To illustrate this consideration, we focus on genome editing, specifically CRISPR-Cas9, given its transformative potential and the urgent need to develop the enabling R&D and policy trajectories required for impact.

CRISPR-Cas9 uses targeting technologies that can produce new varieties that resemble "nature-identical" variants (Gao 2018). These varieties may be more resistant to disease, poor environmental conditions, and climate change; include desired agronomic and nutritional traits; and require fewer inputs. Compared to other methods, CRISPR-Cas9 is more targeted, faster, more efficient, more and cost-effective, making it a viable technology choice for revenue-stressed countries. Additionally, regulators who have evaluated the science recognize the need to examine those technologies and make decisions on a case-by-case basis, as gene editing can generate products that do not result in transgenic events, and thus do not necessarily require regulatory scrutiny. All of this makes CRISPR-Cas9 agricultural

---

improvement, and bioreactors (Zhao et al. 2019). Some livestock technologies have been already deployed commercially (Perisse et al. 2021; Yum et al. 2018).

[2]Benin, Cameroon, Ghana, Guinea, Madagascar, Mali, Rwanda, Senegal, Uganda, and Zambia.

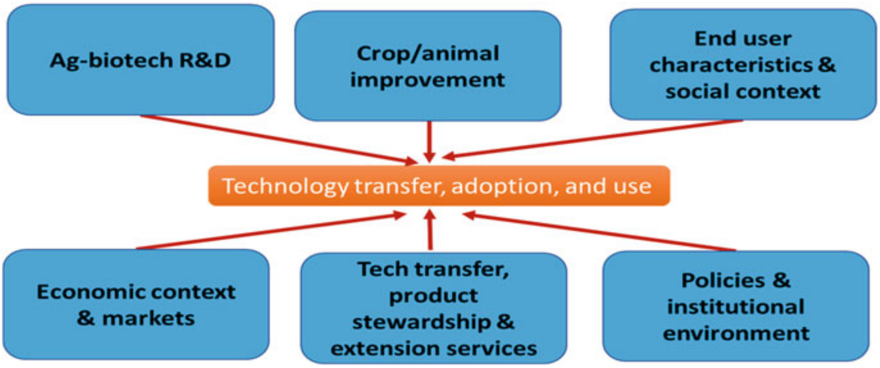


Fig. 1 The enabling environment for technology transfer, adoption, and use. (Source: Based in part on Falck-Zepeda 2021)

applications attractive investment options for global public goods research (Gao 2018; Pixley et al. 2019). Despite these advantages, however, poor enabling environments could still limit the value of and access to CRISPR-Cas9 agricultural bio-innovations for resource-poor farmers, traders, and consumers. Figure 1 illustrates the complex relationships among the factors required for the successful adoption and diffusion of bio-innovations.

The elements shown in Fig. 1 help determine whether a technology will succeed, including decision-maker support through enabling policies, economic benefits and functioning markets, and effective extension services. Some elements may be more relevant to genome editing bio-innovations, depending on the context in which these technologies operate. A discussion of factors most relevant to genome editing follows.[3]

- **Intellectual property (IP) considerations.** Evolving trends in IP rights and restrictions related to genome editing may drive technology access across organizations and influence the reach of public goods R&D efforts. Results of an analysis triangulating patents, published research, and public news searches reveal some important findings (Martin-Laffon et al. 2019; IPStudies 2019, 2020; Brinegar et al. 2017; Zambrano et al. 2021). First, globally, the public sector leads in the foundational CRISPR-Cas9 IP landscape. China leads in published research and patent filings, followed by the United States. Public institutions lead in both areas in China, while in the United States, the public sector dominates research, but the private sector dominates patent filings. Second, research and patent filings are dominated by rice, driven by China, with additional research focused on 17 other crops/plants across 24 countries. In the United States, the patent landscape is notable for its growing and diversified set of commodities and institutions. Third, foundational patent-holders are explicitly

[3] These likely apply to crops, animals, fish, and microorganisms.

licensing their proprietary positions and providing incentives for strategic alliances that promote access to IP-protected R&D inputs. In that context, international and national agriculture research organizations (IARCs and NAROs) have successfully negotiated licensing agreements for CRISPR-Cas9. Finally, more private sector licensors of genome editing technologies are negotiating multiple-partner IP licenses for the development of agricultural and industrial applications. Major biotechnology firms are negotiating licenses with several CGIAR centers, small private firms, and start-ups.

This evolving IP landscape points to the critical need to ensure and secure continued development of novel, productive mechanisms to facilitate IP access for pro-poor innovations to guarantee freedom to operate technology product development and deployment. Despite the positive trends in licensing for public good genome editing technologies, the CGIAR centers, IARCs, and NAROs still lack sufficient capacity to ensure and self-determine their equitable access to these technologies.

- **Regulatory considerations**. The costs of regulatory delays in the approval of innovations may reduce access to potentially valuable technologies and affect market entry, and thus the realization of potential benefits. Feasible regulatory frameworks are those that consider evidence-based scientific approaches balancing safety, time, and costs, and that are both risk-proportional and fair (Arndt et al. 2020; Falck-Zepeda et al. 2016), generally leading to valuable technologies being approved for potential producer use. Without this solid foundation for decision-making, regulatory frameworks could create large opportunity costs, as an examination of regulatory delays associated with GM crops has demonstrated.[4] In the face of a similar regulatory environment, these opportunity costs could be even higher for genome editing, given the expanded licensing and R&D efforts across a growing array of food-security-relevant traits and crops (Chen et al. 2019). Conversely, the wider range of applications for genome editing, combined with lower development costs and enabling policy factors, implies greater potential for positive economic benefits. In fact, given that potential, the opportunity costs of excluding genome editing from the technology options available to improve agricultural productivity are quite significant (Wesseler and Zilberman 2014; Wesseler et al. 2017).
- **Socioeconomic and political economy issues.** It is widely recognized that socioeconomic and political economy factors can promote or prevent the successful deployment of bio-innovations. Current research indicates that GM crops can potentially address critical biotic and abiotic constraints in agriculture and livestock production efficiently but lack broad-based public acceptance (Ahmed

[4] The cost of regulatory delays for GM crops is well documented (Wesseler et al. 2014; Smyth et al. 2016). Costs of regulatory delays in livestock and fisheries sectors are also significant (Van Eenennaam et al. 2021).

et al. 2021; Gouse et al. 2016; Chen et al. 2019).[5] NBTs, including CRISPR-Cas9, risk facing the same impediments to adoption as GM crops, though many NBTs will not include foreign DNA. Extrapolation of results from economic impact assessments for conventional and GM-assisted plant breeding suggests that returns from genome editing technologies may be significant, with important implications for LMICs. It is therefore critical to develop science-based regulatory guidance that promotes the use of this technology to address the needs of the poor.

1.2 Digital Technologies in Agricultural Value Chains

Digital innovation is transforming lives worldwide. We work, learn, communicate, shop, and entertain online. More than half of the world's population uses the Internet, with the 4G mobile network now covering about 85% of the global population (ITU 2020). Digital technologies catalyze development and accelerate economic growth. The digital economy is now equivalent to 15.5% of global gross domestic product (GDP) and has grown 2.5 times faster than global GDP over the past fifteen years (Huawei and Oxford Economics 2017). The agriculture sector is no exception. For family farmers in Africa, digital technologies revolutionize livelihoods by overcoming isolation, as they connect farmers to markets and financial institutions, speeding up change through digital extension and taking success to scale by using granular data to better target innovations (Annan and Dryden 2015). Research shows that innovative applications of digital technologies in agriculture enable more productive, efficient, resilient, and sustainable food systems (Basso and Antle 2020).

Digital technologies in agriculture leverage digitally collected data and analytics to guide decisions along agricultural value chains. *Farmers* can access high-frequency, high-resolution data to make customized decisions. *Traders* can predict food supply and demand dynamically and connect producers and markets at the right time with the right volume. *Policymakers* can make informed decisions related to investments, smart subsidies, and risk management. The following are examples of promising digital applications that address challenges along agricultural value chains:

- **Remote sensing.** The rapid technological improvement of remote sensing makes the precise and timely monitoring of agriculture and natural resources possible, providing actionable information for farmers, traders, and policymakers. For large areas (for example, a country or region), satellite remote sensing can be used to manage food-land-water systems in an integrated and efficient way (Sheffield et al. 2018), including monitoring potential risks to crop yields

[5] Projections of potential for technologies already advanced in the regulatory pipeline include: Dzanku et al. 2018; Kikulwe et al. 2020; Phillip et al. 2019; Ruhinduka et al. 2020; and Yirga et al. 2020.

(Burke et al. 2021), flash floods (Liu et al. 2018), landslides (Casagli et al. 2017), and locust infestations (Piou et al. 2019). Crop and livestock insurance providers increasingly rely on information from remote sensing to profile the risks and damages to production (Benami et al. 2021). When used in small areas, unmanned aircraft vehicles (UAVs or drones) can capture very high-resolution imagery on demand and provide farmers and extension services with useful and timely monitoring information.

- **Connected sensors.** Low-cost, Internet-connected sensors can directly monitor crop and environmental field conditions with speed and precision. These data help farmers make real-time informed and customized management decisions. Antony et al. (2020) conducted an extensive review of the literature and expert interviews on the use of Internet of Things (IoT) devices for smallholder agriculture, including automated solar-powered drip irrigation for vegetables, water-level sensors in rivers for flood alerts, automatic climate control systems, and in-field multiparameter sensors to monitor real-time crop conditions, providing extension agents with information to advise farmers.
- **Artificial intelligence.** As large amounts of data from multiple sources become available in real time, artificial intelligence (AI) helps combine data streams from multiple sources, analyzes them quickly, and generates timely, actionable insights. In addition to processing remote-sensing and IoT data, AI could revolutionize farm mechanization in the near future, with the use of agricultural robots that can apply fertilizer, remove weeds, and harvest crops (Torero 2021).
- **Digital advisory services.** Resource-poor farmers often lack access to information and advisory services at times of critical need. While developing country extension services are improving, with the number of extension agents now exceeding one million, insufficient and unsustainable financing for extension services remains an information constraint (Davis et al. 2020). Through digital channels (for example, mobile phones, interactive voice response, and the Internet), farmers and extension agents can directly access timely agricultural information customized for individual farmers' needs.

  Many private companies offer subscription-based information services through mobile phones. In sub-Saharan Africa, CTA (2019) identified 390 digital agriculture services, of which 15 reached more than one million farmers. There is evidence of some positive impacts. Fabregas et al. (2019) conducted a meta-analysis of studies in sub-Saharan Africa and India, finding that farmers who subscribed to digital services increased their adoption of recommended agro-chemical inputs by 22% and their yields by 4%. CTA (2019) analyzed 50 impact studies in sub-Saharan Africa and found that subscribers' income increased by 20–40%. In Ethiopia, video-mediated extension was shown to reach wider audiences, enhancing agricultural knowledge and the uptake of technologies compared with conventional approaches (Abate et al. 2019).
- **Digital financial services.** Farmers often use cash in financial transactions, and are excluded from credit, savings, and insurance services. The World Bank (Demirgüç-Kunt et al. 2018) reports that, globally, 1.7 billion adults (31%) do not have accounts at financial institutions or through mobile money providers.

Common reasons include not having enough money, physical distance from financial institutions, and documentation requirements. Digital financial services (DFS) can address those constraints, provided that an active mobile phone is available to use as an entry point for financial inclusion. Evidence points to positive DFS impacts on rural households. In Kenya, Kirui et al. (2013) report that use of mobile money in rural areas increased input use by 95%, agricultural commercialization by 37%, and annual household incomes by 71%. Suri and Jack (2016) estimate that the M-PESA mobile money service in Kenya helped 194,000 households escape poverty and diversify income sources. Evidence from India suggests that picture-based insurance, which verifies insurance claims using smartphone images of insured plots, minimizes asymmetric information and claim verification costs while reducing risk compared to index-based insurance (Ceballos et al. 2019).

- **E-commerce.** Unlike traditional agricultural value chains involving multiple intermediaries, e-commerce allows farmers to directly connect with buyers, and so increase income. Agricultural e-commerce is at an early stage in LMICs, yet, although comprehensive impact evidence is unavailable, its potential is undeniable. By shortening supply chains, e-commerce can also reduce food waste and benefit consumers with fresher produce (GSMA 2019). During the COVID-19 pandemic, e-commerce has been pivotal in connecting farmers to markets and consumers to fresh foods (Reardon et al. 2021).

Like bio-innovations, digital technologies in LMICs face important policy challenges related to data ownership and user rights that require well-defined guidelines in terms of IP frameworks and regulations.

2 Agricultural R&D Enabling Investments and Capacities

The rise of biological and digital technologies offers viable options for LMICs, but also raises concerns about their preparedness to take advantage of these opportunities and to foster an appropriate enabling environment to support product development, deployment, and adoption.

Public agricultural R&D investment is a recognized major engine for promoting food system innovations; this investment funds socially valuable research that can potentially lead to private innovation for local benefits. In recent decades, support for public agricultural research in high-income (HI) countries has stagnated, while private agricultural research spending has increased, reshaping the structure of the global agricultural research system (Fuglie and Toole 2014). Global agricultural R&D investments have shifted from HI countries toward large middle-income economies (Brazil, China and India), which have grown in importance as agricultural producers and research leaders. Meanwhile, most low-income countries continue to lag significantly in agricultural R&D investments and human and institutional capacity, having thus experienced limited agricultural productivity growth.

Table 1 Countries grouped by level of development of their agricultural research systems, 2016

Key indicators	Lagging	Average	Advanced	Brazil, China, & India
Number of countries	55	50	15	3
Total R&D investment (million 2011 $)	17,679	83,170	212,256	202,615
Average R&D investment (million 2011 $)	9	46	393	1876
Share of R&D investment among LMICs	3%	16%	41%	39%
Annual agricultural TFP growth, 2000–2016 (%)	0.7%	1.0%	1.3%	2.6%
Published articles per FTE researcher	0.1	0.4	0.7	1.3
H index (quality and influence of publications)	26	72	160	266
Share of total population among LMICs	11%	26%	14%	50%
GDP per capita (2011 $)	5405	5146	11,832	11,419
Number of people living on under $1.9/day (million)	111	238	80	366

Source: ASTI (2021), SCImago (n.d.), USDA-ERS (2021), and World Bank (2021). These are gaps in investment, human capital, and institutional capacity.

To fully benefit from the range of bio-innovations and digital technologies, LMICs require focused efforts to close the gaps in R&D. Only 18 LMICs possess agricultural research systems comparable to HI countries in quality and productivity (Table 1).[6] Overall, countries with *lagging* research systems account for only 3% of total R&D investment in LMICs. Their investments are significantly smaller and less productive than those in countries with *average* or *advanced* systems. Moreover, LMICs with *lagging* research systems also show considerably slower agricultural productivity growth. Similarly, LMICs with *average* research systems trail those with *advanced* research systems in terms of R&D investment and long-term agricultural productivity growth. Given their modest share in global agricultural R&D investments and over-representation in global extreme poverty, evidence suggests these *lagging* and *average* countries could make enormous progress if R&D efforts were to be stepped up. Three main R&D gaps differentiate LMICs with *lagging*, *average*, and *advanced* agricultural research systems.

- **The R&D investment gap.** A country's agricultural R&D investment capacity depends on factors beyond the size of its agricultural GDP. The overall size of the economy, its income level, and the availability of relevant technology spillovers from other countries also play important roles. When comparing R&D investments of a given country with those of countries with similar characteristics, it is

[6] We used the country's H index of agricultural science and biology publications from SCImago (n.d.) to classify countries by quality and productivity of the agricultural research system.

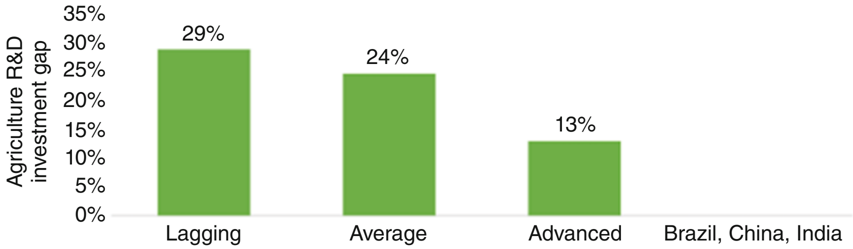


Fig. 2 Agricultural R&D investment gap, as a percentage of R&D investment by country group, 2014–2016. (Sources: ASTI (2021) and World Bank (2021). Note: The Lagging group includes 53 countries; Average 50; Advanced 15. Eastern European and former Soviet countries were excluded)

possible to determine attainable R&D investment based on relative investment differences. The ASTI intensity index (AII) does precisely this by quantifying the gap between a country's agricultural research investment and its potential, based on country comparisons (Nin-Pratt 2016). Use of the index shows that the investment gap is much higher in countries with *lagging* and *average* agricultural research systems than in countries with *advanced* systems (Fig. 2). Economic development, the quality of institutions, and political constraints are major factors determining governments' revenues and spending capacity. Total government spending in the *lagging* group was only \$0.7 per person in 2011, compared to \$1.95 in the *advanced* group. Only 3–6% of total government spending in LMICs is for agriculture, and only a fraction of that is allocated to R&D. These findings underscore the need to reconsider the generalized recommendation to "increase R&D investment in LMICs" and examine the unique development challenges faced by countries with weaker R&D systems.

- **The human capital gap.** Even more significant than the investment gap is the human capital gap affecting the quality, scope, and potential of research systems in LMICs. This gap limits their participation in the emerging opportunities presented by bio-innovations and digital technologies. Despite an increase in the number of PhD-qualified agricultural researchers in developing countries since 2000 (ASTI 2021), the composition of researchers by degree differs significantly—countries in the *lagging* group are clearly disadvantaged, with only 17% of their agricultural researchers holding PhD degrees, compared with 75% in Brazil, China and India, and 27% in countries with *advanced* systems (Fig. 3). Although researchers in the *average* group of countries hold higher qualification levels, a very large portion of their PhD-qualified researchers is set to retire in the coming decade, a situation that is particularly severe in sub-Saharan Africa.
- **The institutional capacity gap.** The suboptimal quality of institutions causes inefficiencies and results in the underperformance of agricultural R&D systems, especially in *lagging* and *average* countries. Some of these inefficiencies may emanate from decisions made within countries (for example, centralized versus

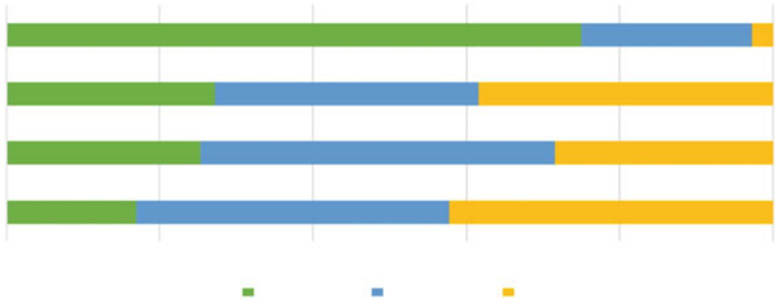


Fig. 3 Researchers with PhD, MSc, and BSc degrees as a share of total full-time equivalent (FTE) researchers. (Source: ASTI 2021)

decentralized systems); others are structural in nature. For countries with relatively small economies and/or agriculture sectors and a limited supply of researchers, overall development of their agricultural research system is constrained by the size of research teams and the capacity to develop a critical mass of diverse and relevant research platforms. The situation for research systems in these countries will likely worsen with the increasing demand for research-oriented responses to address climate change-related challenges.[7]

3 Actions and Solutions for Enabling Food System Innovations

This analysis proposes a way forward to advance agricultural research and accelerate the scaling and adoption of bio- and digital innovations for food systems by closing critical gaps and promoting the necessary investments, policies, and regulations through actions at the global, regional, and national levels. Synergistically, those efforts will help accelerate agricultural productivity growth and food system transformations, as well as the achievement of the Sustainable Development Goals (SDGs).

At the **global level**:

- **Facilitate LMIC engagement with global players in food system innovations to strengthen IP access and management capacity.** Given the role of IP frameworks in determining access to emerging bio- and digital innovations, it will be important to create the conditions for agricultural research entities—such as IARCs, NAROs, and national agricultural research systems—to negotiate IP agreements with global innovators and enhance their IP management capacity so

[7] The average number of researchers per country in the group of *lagging* research systems is below 300 full-time equivalents (FTEs), compared to 900 FTEs in the *average* group, 3700 FTEs in the *advanced* group, and more than 12,000, on average, in China, India, and Brazil.

as to ensure jurisdictional freedom to operate while fostering strategic alliances. On the crop biotechnology side, it will be important to engage with China and the United States to secure and support public good technology flows to developing countries.[8] For digital technologies, appropriate mechanisms need to be established with key global players to enable efficient and cost-effective access to data and digital applications for the relevant stakeholders in LMICs.

- **Promote North–South, South–South, and triangular cooperation to strengthen LMIC regulatory frameworks**. Building on their relatively more advanced regulatory framework development, countries in the global North, as well as emerging players such as China, India and Brazil, should use available mechanisms to support LMICs' efforts to advance their regulatory capabilities, including strengthening institutional and stakeholder capacity at different levels (Arndt et al. 2020).

To complement these global efforts, programmatic and policy actions will be needed at the **national and/or regional levels** to improve the development, delivery, and use of food system and digital innovations.

- **Adapt emerging technologies to local conditions.** Countries will need to invest in science-based participatory approaches to benefit from the range of food system innovations highlighted here that have potential to help address multiple challenges. Given the diversity among countries, adapting these technologies to local conditions—in ways that make them accessible to farmers and retain much of the gain among consumers—is challenging, especially for developing economies, smallholder farmers, and small businesses (Hendriks et al. 2021). Therefore, investments in science-based, participatory processes to map out realistic and equitable options are needed (Basso and Antle 2020).
- **Close the regulatory gaps for enabling innovations.** To minimize opportunity costs associated with regulatory delays, governments must create evidence-based regulatory environments, in a timely manner, that enable the safe use and application of bio-innovations and digital technologies by stakeholders in LMICs. This involves working with a diverse set of actors, including local and international scientists, the private sector, and others, to provide a pathway that ensures timely, secure, and equitable access. While these processes can benefit from global engagement, they should be customized to country-specific circumstances.
- **Close human capital gaps at the country level.** Training for a new generation of scientists and researchers should emphasize the development of skills needed to generate and deliver emerging and fast-changing biotechnology and digital innovations relevant to food systems, including the capacity to integrate local knowledge with modern science. Managerial capacity, business education, and multidisciplinary thinking are also critical. At the same time, work with governments and the private sector should improve the capacity of farmers, farmer organizations, and other value chain actors to adopt transformative food system innovations.

[8] For livestock, other players such as Argentina and Brazil are also critical.

- **Close institutional capacity gaps.** Increasing institutional capacity will require addressing limitations in organizations' capacities and strengthening institutional coordination among food system stakeholders. Efforts by regional institutions and organizations to achieve long-term reforms could provide a more efficient and cost-effective way for groups of countries to work together to target specific goals and escape the trap of lagging research systems. In this context, it will be critical to create policy environments that stimulate cooperation among agricultural R&D agencies so as to maximize synergies and efficiencies, rather than solely relying on individual country efforts. The restructured One CGIAR can play a constructive role in this regard.
- **Develop a deeper understanding of political economy factors.** These factors impact the development and deployment of food system innovations to and within countries. A more nuanced understanding of actors, agendas (both social and economic), and influence relationships may better inform the understanding of technology hesitancy and will better support targeted communications and outreach efforts to build consumer confidence and enable pro-poor technology access. Informed political will is also essential for building local, regional, and global policy platforms in support of safe and timely access to these technologies in emerging economies.
- **Strengthen communications and public acceptance of modern biotechnology innovations.** Early and enhanced communication efforts to inform decision-makers and the public are needed in order to develop a climate of transparency and trust about the safety and socioeconomic benefits of genome editing applications. This will be critical for policy development and public/market acceptance (Gao 2018). Similarly, discussions on the costs of regulatory delays and the results of losing access to important food security, productivity, and environmental solutions must be part of the policy and public dialogues.
- **Close digital infrastructure gaps in rural areas.** Although 50% of the global population has Internet connectivity, significant digital divides exist between rural and urban areas. Only 6% of rural households in Africa have Internet access, compared with 28% in urban areas (ITU 2020). Data costs remain prohibitive, and technology ownership and access are gender-divided (GSMA 2020). Croplands with severe yield gaps, climate-stressed locations, and food-insecure populations have relatively poorer service coverage (Mehrabi et al. 2021). Enabling policies and investments targeting rural households are urgently needed. Connecting all of Africa is estimated to cost $100 billion and would only be feasible with strong private sector involvement (Broadband Commission 2019). Slow progress on electrification in LMICs further limits the affordability and coverage of digital technologies. The number of people without access to electricity in sub-Saharan Africa likely increased in 2020 due to the COVID-19-related economic slowdown (IEA 2020). Research is needed to develop business cases for simultaneous investment in digital infrastructure and electrification and to provide evidence of their synergistic impact for creating value and achieving the SDGs (GeSI 2019).

- **Develop sustainable business models for digital service providers across food systems.** Most digital service providers lack viable business models and revenues. In sub-Saharan Africa, only 26% of agricultural information service providers generate enough revenue to break even (CTA 2019). Achieving profitability, interoperability and scale is essential to reaching a sustainable critical mass. This would facilitate the use of financially viable digital technologies across value chains, thus increasing the adoption of various innovations, including new bio-innovations.

Additionally, as digital information comes to play an increasingly vital role in LMICs, clear policies and secure infrastructure are needed to protect the privacy of farmers and value chain actors while ensuring transparency and inclusivity. Strengthening technology capacity and digital literacy and skills (OECD 2019) will further accelerate the prospects for the democratization of digital technologies as part of game-changing solutions to end hunger.

References

Abate GT, Bernard T, Makhija S, Spielman DJ (2019) Accelerating technical change through video-mediated agricultural extension: evidence from Ethiopia. IFPRI discussion paper 1851. International Food Policy Research Institute, Washington, DC

Ahmed AU, Hoddinott J, Abedin N, Hossain N (2021) The impacts of GM foods: results from a randomized controlled trial of Bt eggplant in Bangladesh. Am J Agric Econ. https://doi.org/10.1111/ajae.12162

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050 [2012 revision]. ESA working paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome

Annan K, Dryden S (2015) Food and the transformation of Africa: getting smallholders connected. Foreign Aff 94(6):18

Antony AP, Leith K, Jolley C, Lu J, Sweeney DJ (2020) A review pf practice and implementation of the internet of things (IoT) for smallholder agriculture. Sustainability 12(9):3750

Arndt C, Chambers JA, Zambrano P, Alahmdi MI, Alatawi A, Benfica R, Edward MG, Gatehouse AMR, Moronta-Barrios F, Ahmed A (2020) Embracing innovation to meet food systems challenges: task force 10 sustainable energy, water, and food systems (policy brief). T20 Saudi Arabia 2020 THINK

ASTI (Agricultural Science and Technology Indicators) (2021) Agricultural research expenditures and human resource capacity database. International Food Policy Research Institute, Washington, DC. http://www.asti.cgiar.org/data

Basso B, Antle J (2020) Digital agriculture to design sustainable agricultural systems. Nat Sustain 3(4):254–256

Beintema N, Stads G, Fuglie K, Heisey P (2012) ASTI global assessment of agricultural R&D spending: developing countries accelerate investment. ASTI, International Food Policy Research Institute/Global Forum on Agricultural Research, Washington, DC/Rome

Belton B, Thomas R, Zilberman D (2020) Sustainable commoditization of seafood. Nat Sustain 3(9):677–684

Benami E, Jin Z, Carter MR, Ghosh A, Hijmans RJ, Hobbs A, Kenduiywo B, Lobell DB (2021) Uniting remote sensing, crop modelling and economics for agricultural risk management. Nat Rev Earth Environ 2(January):140–159

Brinegar, K., A.K. Yetisena, S. Choi, E. Vallillo, G.U. Ruiz-Esparza, A.M. Prabhakar, A. Khademhosseini, and S.H. Yun. 2017. "The commercialization of genome-editing technologies." Crit Rev Biotechnol 37(7): 924–932

Broadband Commission (2019) Connecting Africa through broadband: a strategy for doubling connectivity by 2021 and reaching universal access by 2030

Burke M, Driscoll A, Lobell DB, Ermon S (2021) Using satellite imagery to understand and promote sustainable development. Science 371(6535):eabe8628

Casagli N, Frodella W, Morelli S, Tofani V, Ciampalini A, Intrieri E, Raspini F, Rossi G, Tanteri L, Lu P (2017) Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning. Geoenvironmental Disasters 4(1):1–23

Ceballos F, Kramer B, Robles M (2019) The feasibility of picture-based insurance (PBI): smartphone pictures for affordable crop insurance. Dev Eng 4(May):100042

Chen K, Wang Y, Zhang R, Zhang H, Gao C (2019) CRISPR/Cas genome editing and precision plant breeding in agriculture. Annu Rev Plant Biol 70(April):667–697

CTA (2019) The digitalisation of African agriculture report 2018–2019. CTA/Dalberg Advisers, Wageningen

Davis, K.E., S.C. Babu, and C. Ragasa. 2020. "Conclusions and policy implications." In Agricultural extension: global status and performance in selected countries, eds. K.E. Davis, S.C. Babu, and C. Ragasa. Part 2: performance of extension systems, chapter 9 313–331. Washington, DC: International Food Policy Research Institute

Demirgüç-Kunt A, Klapper L, Singer D, Ansar S, Hess J (2018) The global Findex database 2017: measuring financial inclusion and the fintech revolution. World Bank, Washington, DC

Dzanku FM, Zambrano P, Wood-Sichra U, Falck-Zepeda JB, Chambers JA, Hanson H, Boadu P (2018) Adoption of GM crops in Ghana: Ex ante estimations for insect-resistant cowpea and nitrogen-use efficient rice. IFPRI Discussion Paper 1775. International Food Policy Research Institute, Washington, DC

Eş I, Gavahian M, Marti-Quijal FJ, Lorenzo JM, Khaneghah AM, Tsatsanis C, Kampranis SC, Barba FJ (2019) The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: current status, future perspectives, and associated challenges. Biotechnol Adv 37(3):410–421

Evenson RE, Gollin D (2003) Assessing the impact of the green revolution, 1960 to 2000. Science 300(5620):758–762

Fabregas R, Kremer M, Schilbach F (2019) Realizing the potential of digital development: the case of Agricultural advice. Science 366(6471):eaay3038

Falck-Zepeda JB (2021) Defining an enabling environment for bio-innovation technologies and products: *quo vadis investigationis publicum*? Unpublished paper

Falck-Zepeda JB, Smyth S, Ludlow K (2016) Zen and the art of attaining conceptual and implementation clarity: socio-economic considerations, biosafety and decision-making. Estey J Int Law Trade Policy 17(2):117–136

Fuglie K (2018) R&D capital, R&D Spillovers, and productivity growth in world agriculture. Appl Econ Perspect Policy 40(3):421–444

Fuglie K, Toole A (2014) The evolving institutional structure of public and private agricultural research. Am J Agric Econ 96(3):862–883

Gao C (2018) The future of CRISPR technologies in agriculture. Nat Rev Mol Cell Biol 19(January):275–276

GeSI (2019) Digital with purpose: delivering a SMARTer2030. GeSI and Deloitte. https://digitalwithpurpose.gesi.org

Gouse M, Sengupta D, Zambrano P, Zepeda JF (2016) Genetically modified maize: less drudgery for her, more maize for him? Evidence from smallholder maize farmers in South Africa. World Dev 83(July):27–38

GSMA (2019) E-commerce in agriculture: new business models for Smallholders' inclusion into the formal economy. London

GSMA (2020) Connected women: the Mobile gender gap report 2020. London

Hendriks S, Soussana J, Cole M, Kambugu A, Zilberman D (2021) Ensuring access to safe and nutritious food for all through transformation of food systems. Paper prepared for Action Track 1, Scientific Group of the UN Food Systems Summit

Huawei and Oxford Economics (2017) Digital spillover: measuring the true impact of the digital economy. Shenzhen and Oxford

IEA (International Energy Agency) (2020) World energy outlook 2020. Paris

IPStudies (2019) CRISPR patent analytics. https://www.ipstudies.ch/crispr-patent-analytics/

IPStudies (2020) CRISPR patent analytics. https://www.ipstudies.ch/crispr-patent-analytics

ITU (International Telecommunication Union) (2020) Measuring digital development: facts and figures 2020. Geneva

Jouanjean M (2019) Digital opportunities for trade in the agriculture and food sectors, OECD food, agriculture and fisheries papers, no. 122. OECD Publishing, Paris

Kikulwe EM, Falck-Zepeda JB, Oloka HK, Chambers JA, Komen J, Zambrano P, Wood-Sichra U, Hanson H (2020) Benefits from the adoption of genetically engineered innovations in the Ugandan banana and cassava sectors: an ex ante analysis. IFPRI discussion paper 1927. International Food Policy Research Institute, Washington, DC

Kirui OK, Okello JJ, Nyikal RA, Njiraini GW (2013) Impact of mobile phone-based money transfer services in agriculture: evidence from Kenya. Quart J Int Agric 52(2):141–162

Krishna VV, Lantican MA, Prasanna BM, Pixley K, Abdoulaye T, Menkir A, Bänziger M, Erenstein O (2021) Impacts of CGIAR maize improvement in sub-Saharan Africa, 1995–2015. International Maize and Wheat Improvement Center (CIMMYT), Mexico City

Lantican MA, Braun HJ, Payne TS, Singh RP, Sonder K, Baum M, van Ginkel M, Erenstein O (2015) Impacts of international wheat improvement research, 1994-2014. CIMMYT, Sept, p 15

Liu C, Guo L, Ye L, Zhang S, Zhao Y, Song T (2018) A review of advances in China's flash flood early-warning system. Nat Hazards 92(2):619–634

Martin-Laffon J, Kuntz M, Ricroch AE (2019) Worldwide CRISPR patent landscape shows strong geographical biases. Nat Biotechnol 37(June):601–621

Mehrabi Z, McDowell MJ, Ricciardi V et al (2021) The global divide in data-driven farming. Nat Sustain 4:154–160

Nin-Pratt A (2016) Comparing apples to apples: a new indicator of research and development investment intensity in agriculture. IFPRI discussion paper 1559. International Food Policy Research Institute, Washington, DC

OECD (Organisation for Economic Co-operation and Development) (2019) Digital opportunities for better agricultural policies. Paris

Perisse IV, Fan Z, Singina GN, White KL, Polejaeva IA (2021) Improvements in gene editing technology boost its applications in livestock. Front Genet 11:614688. https://doi.org/10.3389/fgene.2020.614688

Phillip D, Nin-Pratt A, Zambrano P, Wood-Sichra U, Kato E, Komen J, Hanson H, Falck-Zepeda JB, Chambers JA (2019) Insect-resistant Cowpea in Nigeria: an ex ante economic assessment of a crop improvement initiative. IFPRI discussion paper 1896. International Food Policy Research Institute, Washington, DC

Piou C, Gay PE, Benahi AS, Babah Ebbe MAO, Chihrane J, Ghaout S, Cisse S, Diakite F, Lazar M, Cressman K, Merlin O (2019) Soil moisture from remote sensing to forecast desert locust presence. J Appl Ecol 56(4):966–975

Pixley KV, Falck-Zepeda JB, Giller KE, Glenna LL, Gould F, Mallory-Smith CA, Stelly DM, Stewart CN (2019) Genome editing, gene drives, and synthetic biology: will they contribute to disease-resistant crops, and who will benefit? Annu Rev Phytopathol 57(August):165–188

Reardon T, Heiman A, Lu L, Nuthalapati CSR, Vos R, Zilberman D (2021) 'Pivoting' by food industry firms to cope with COVID-19 in developing regions: E-commerce and 'co-pivoting' delivery-intermediaries. Agric Econ (preprint). https://doi.org/10.1111/agec.12631

Ruhinduka RD, Falck-Zepeda JB, Wood-Sichra U, Zambrano P, Semboja H, Chambers JA, Hanson H, Lesseri G (2020) Ex ante economic assessment of impacts of GM maize and cassava on producers and consumers in Tanzania. IFPRI Discussion Paper 1911. International Food Policy Research Institute, Washington, DC

Ruttan V (1982) Agricultural research policy. University of Minnesota Press, Minneapolis

SCImago (n.d.) SJR — SCImago Journal & Country Rank [Portal]. Retrieved in May 2021 from http://www.scimagojr.com
Sheffield J, Wood EF, Pan M, Beck H, Coccia G, Serrat-Capdevila A, Verbist K (2018) Satellite remote sensing for water resources management: potential for supporting sustainable development in data-poor regions. Water Resour Res 54(12):9724–9758
Smyth SJ, Falck-Zepeda J, Ludlow K (2016) The costs of regulatory delays on genetically modified crops. Estey J Int Law Trade Policy 117(2):173–195
Suri T, Jack W (2016) The long-run poverty and gender impacts of mobile money. Science 354(6317):1288–1292
Torero M (2021) Robotics and AI in food security and innovation: why they matter and how to harness their power. In: von Braun J, Archer MS, Reichberg GM, Sorondo MS (eds) Robotics, AI, and humanity: science, ethics, and policy. Springer, Cham, pp 99–107
USDA-ERS (2021) Economic research service. US Department of Agriculture, Washington, DC
Van Eenennaam AL, de Figueiredo Silva F, Trott JF, Zilberman D (2021) Genetic engineering of livestock: the opportunity cost of regulatory delay. Ann Rev Animal Biosci 9(1):453–478
Von Braun J, Gulati A, Kharas H (2017) Key policy actions for sustainable land and water use to serve people. Economics 11(32):1–14
Wesseler J, Zilberman D (2014) The economic power of the golden rice opposition. Environ Dev Econ 19(6):724–742
Wesseler J, Kaplan S, Zilberman D (2014) The cost of delaying approval of golden rice. ARE Update 17(3):1–3. University of California Giannini Foundation of Agricultural Economics, Berkeley
Wesseler J, Smart RD, Thomson J, Zilberman D (2017) Foregone benefits of important food crop improvements in Sub-Saharan Africa. PLoS ONE 12:e0181353
World Bank (2021) World development Indicators. Washington, DC
Yirga C, Nin-Pratt A, Zambrano P, Wood-Sichra U, Habte E, Kato E, Komen J, Falck-Zepeda JB, Chamber JA (2020) GM maize in Ethiopia: an ex ante economic assessment of TELA, a drought tolerant and insect resistant maize. IFPRI Discussion Paper 1926. International Food Policy Research Institute, Washington, DC
Yum SY, Youn KY, Choi WJ, Jang G (2018) Development of genome engineering technologies in cattle: from random to specific. J Animal Sci Biotechnol. https://doi.org/10.1186/s40104-018-0232-6
Zambrano AP, Falck-Zepeda JB, Chambers J (2021, forthcoming) Intellectual property of agriculturally based gene editing technologies: follow the new leaders. IFPRI discussion paper. International Food Policy Research Institute, Washington, DC
Zhao J, Lai L, Ji W, Zhou Q (2019) Genome editing in large animals: current status and future prospects. Natl Sci Rev 6:402–420. https://doi.org/10.1093/nsr/nwz013

Leveraging Data, Models & Farming Innovation to Prevent, Prepare for & Manage Pest Incursions: Delivering a Pest Risk Service for Low-Income Countries

Bryony Taylor, Henri Edouard Zefack Tonnang, Tim Beale, William Holland, MaryLucy Oronje, Elfatih Mohamed Abdel-Rahman, David Onyango, Cambria Finegold, Jessica Zhu, Stefania Pozzi, and Sean T. Murphy

1 Introduction

Globally, pests (invertebrates, vertebrates, pathogens, weeds) remain a major barrier to crop production, with annual losses estimated at between 20–40% (FAO, 2019). The impact of pests is particularly acute in many low-income countries, as agriculture is the mainstay of the majority of the people and also of the national economies (Perrings, 2007; Pratt et al. 2018; Wiggins et al. 2010). Additionally, climate change is predicted to increase the likelihood, frequency, and impact of pests in the future, resulting in increased crop losses, thus causing damage to the economy of low-income countries. For instance, Deutsch et al. (2018) predicted that global yield losses of major grains will increase by 10–25% per degree of global mean surface warming. The vulnerabilities of these countries are further exacerbated because of the small size of farms, which often witness outbreaks of transboundary

B. Taylor (✉) · T. Beale · W. Holland · D. Onyango · C. Finegold
Centre for Agriculture and Bioscience International (CABI), Wallingford, UK
e-mail: b.taylor@cabi.org

H. E. Z. Tonnang · E. M. Abdel-Rahman
Modelling and Geo-Information Unit, International Centre of Insect Physiology and Ecology (icipe), Nairobi, Kenya

M. Oronje
Centre for Agriculture and Bioscience International (CABI), Nairobi, Kenya

J. Zhu · S. Pozzi
Precision Development, Nairobi, Kenya

S. T. Murphy
Centre for Agriculture and Bioscience International (CABI), Egham, UK

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_23

and /or new invasive pests (Early et al. 2016) and multiple indigenous pests (Constantine et al. 2021).

A number of factors, such as weak phytosanitary systems and inadequate human, financial and infrastructure capacity, are exacerbating the problem caused by these pests. There are weak linkages between research and national systems, resulting in gaps in effectively translating research into policy for their management. Significant progress has been made in the last decade in providing means for access to important knowledge about the identification of important pest groups such as arthropods, plant pathogens and weeds and their controls, both at the national and smallholder farmer levels (e.g., the global Plantwise program (www.plantwise.org) and PlantVillage (https://plantvillage.psu.edu/)), but information about pests is generally not accessed by users until a pest has reached a damaging stage; for example, in the case of farmers, this is when pest symptoms become most apparent. Thus, crop yield losses remain high (Pratt et al. 2017). Additionally, existing knowledge on how to manage pest and disease incursions has also become more difficult to apply, given the changing backdrop of weather patterns and the effect this has on the phenology of pest and disease outbreaks (Castex et al. 2018; Chidawanyika 2019) or the range expansion of invasive alien species (Kalnicky et al. 2019). In all, pests pose a major barrier to these countries' ability to meet the aims of the UN Sustainable Development Goals (SDGs), particularly SDG2, "End hunger, achieve food security and improved nutrition and promote sustainable agriculture," but all the SDGs depend to some extent on the delivery of improved food systems. However, solutions, in the form of pest risk alert systems, do exist that address this barrier, and major advances in technology are now providing opportunities to apply these in low-income countries.

It is well established in integrated pest management (IPM) that 'prevention is far more effective than cure' (Barzman et al. 2015; Pretty and Bharucha 2015), and this critical tenet of IPM is key to reducing losses from pests and improving crop yields. Although preventative measures emphasize aspects such as the use of healthy seed or maintaining healthy soil, etc., the colonization by multiple indigenous pests or even the invasion of new pests in smallholder farms within a cropping season is inevitable in most regions. Hence, the provision of timely pest risk prediction information through risk-mapping or early warning systems is of paramount importance. Active communication of real-time information enables the intelligent mobilization of resources by national governments and other actors in the food value chains and/or early action by farmers to prevent pest populations from reaching economically damaging levels.

The development of national pest risk assessment and early warning systems can be complex, though. It requires the combining of expertise of different actors, well beyond those in pest modeling and pest management alone (Magarey and Sutton 2007; FAO 2007). Many advances have been made in pest modeling, and several types of models are now available for pest risk-mapping and early warning (Orlandini et al. 2017; Tonnang et al. 2017). However, equally important is the availability of and access to suitable input data sources (e.g., pest data, weather data) to build or drive such systems, a deep understanding of farmer decision-making, and efficient communication means to deliver risk information to end users; for the last, in the case of farmers, this involves large numbers of people spread over vast areas. As a result, pest risk systems have mostly been developed in high income countries and only applied in low-income countries for a handful of significant pests (e.g., transboundary pests in Africa, see Box 1) and for import and export market access, but this situation is now changing. Recent innovations and advances in data availability (e.g., earth observation (EO) data, meteorological data), data architectures, data management workflows, computing power and communications technology has allowed for increasingly sophisticated risk assessment and decision support systems to be developed and extended to end users. In particular, there has been a developing interest in the use of weather and environmental data derived from EO sources, as such data are available for large areas (Marques da Silva et al. 2015). EO data have already proved to be useful in broad scale alert systems such as Global Forest Watch (GFW), the Famine Early Warning Systems Network (FEWS NET) and the Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM).

These advances in data availability and data management may now be combined with advances made in the field of extension and have the opportunity to make significant improvements in the field of pest prediction and subsequent extension of messages. Increasing access to mobile phone technology (World Bank 2019), along with the emergence of ICT-based advisory extension services, has allowed the extension sector to disseminate advice through multiple complementary communication channels, such as Short Message Services (SMS) and Unstructured Supplementary Service Data (USDD), on broader scales than previously possible (Thakur et al. 2016; Tambo et al. 2019).

Here, we discuss how these advances, in terms of data availability, management and modeling and communication technology, have provided new and novel solutions for the development of agricultural pest and disease early warning and risk-mapping systems in low-income countries. In particular, we explore how this provides opportunities to improve food systems and identify key areas for the UNFSS that will help guide governments in engaging with these developments.

2 Technology Developments and Their Application to Pest Risk

Several pest risk prediction systems are now in place or in development for low-income countries that forewarn of within season pest and disease incursions. These systems provide alerts about near-future potential geographic hotspots of transboundary pests or build-up of local pests that can be used at any scale (national, regional and local) for warning of potential pest outbreaks.

The development of these systems with a wide outreach has been possible thanks to the onset of increasingly accessible high-quality data with high spatial resolution derived from EO and meteorological sources used to drive the models, and the collation and generation of field and laboratory data to build, train and test the models.

2.1 Access to Datasets and Data Management

Through numerous projects, an immense number of datasets on occurrence, abundance, and prevalence of pests has been collected across many countries. However, these data remain scattered, are not widely accessed and used, and no mechanisms exist for bringing these datasets together, enabling sharing for multiple uses. Data are heterogeneous, owing to the diversity of their sources, differences in objectives for collection, and multiple storage and retrieval formats. However, recently, with the advancement in data collection and collation instruments like crowdsourcing, EO and geospatial tools, and cross-cutting analytics like artificial intelligence (AI) and the internet of things (IoT), the development of cloud-based platforms (e.g., 'data hubs') and mobile apps for real-time pest detection and risk profiling is highly possible. This enables the integration of data on historical and ongoing collections of pests and associated natural enemies from disparate sources as its centerpiece and may act as repositories that can be utilized to build and validate pest risk prediction systems.

With the availability of such diverse data sources, several initiatives have been underway to combine and utilize these data for the development of pest risk or other applications. For example, *icipe* through the data management, modeling, and geo-information (DMMG) unit is establishing a state-of-art data management workflow (DMWf) and advancing the use of 'big data' and cloud-based cross-cutting processing technologies that allow for harmonized storage and analysis of petabytes of various data types. This includes observational, experimental, simulation and derived datasets. The observational data are commonly collected through open-ended survey, observation and the use of equipment and devices to monitor and record information. Experimental data are obtained through functional involvement by the data collector that creates and gauges the change to establish causal relationships. Simulation data are obtained through mimicking known processes and applying computer-based methods for reproduction, while derived data are the result of the application of formulae used to transform the information. The DMWf provides a collaborative framework with cooperation between data scientists and information communication technology (ICT) experts.

With relatively more complex datasets, the opportunity for more sophisticated data handling methods has emerged. The AI allows for the exploration and utilization of large datasets and predictors and the expansion of assessments beyond binary outcomes, and considers the costs of different types of forecasting errors to generate improved and accurate knowledge for decision-making with feedback and accountability in the context of IPM. Approaches such as machine learning (ML) and deep learning (DL) enable the characterization, discrimination, classification, prediction, forecast and utilization of existing knowledge in pest management for appropriate interventions.

2.2 Improved Access to Earth Observation and Meteorological Data

EO data are complex and require specialized human and technical capacity to process and manipulate the source data into compatible formats for analysis, which can often be lacking in developing countries and organizations. Space agencies are leaders in the use of EO data and are increasingly driving initiatives to make data more widely accessible and standardized to require less processing (O'Connor et al. 2020). One such initiative is the Group on Earth Observations (GEO), an intergovernmental partnership developed to promote accessibility and the subsequent use of EO. Key goals of GEO are to promote the use of open access and sustainable data sharing to support research, to facilitate improved decision-making, and therefore to benefit agricultural stakeholders.

Increased collaboration between EO and biological pest risk modeling experts and cutting-edge actors in extension of information have allowed these data sources to be utilized at a broad spatial scale to benefit those in receipt of early warning information. Data derived from EO sources can provide a consistent stream of measurements at regular time intervals with global coverage. These data can include various vegetation indices, which may be related to plant biomass or vigor (i.e., Normalized Difference Vegetation Index: NDVI), or used within reanalysis datasets to give a broad range of atmospheric, land and oceanic climate variables (i.e., ERA5 ECMWF dataset https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). The quality, accuracy and availability of these data are increasing with each new space program (ESA 2020).

Well-established vegetation proxies, such as the NDVI, have been used effectively by the FAO since 2010 to measure the amount of 'green area' so as to monitor potential locust habitat recession and growth (see Box 1). These data have helped direct local teams on the ground to survey localities at higher risk of locust population build-up, and thus help direct monitoring and control resources (Renier et al. 2015). Recently, data from the European Space Agency (ESA) have been used to classify different tree species and crop types (Persson et al. 2018; Van Tricht et al. 2018), and now such data are being used to monitor agricultural weed problems such as Striga or 'witchweed' in Kenya (Mudereri et al. 2020) and *Parthenium hysterophorus* or 'famine weed' in Africa and Asia. These weeds can be successfully mapped using EO technology (Kganyago et al. 2017; CABI 2021) and species-level mapping solutions can offer great benefits to policymakers, who, with knowledge of a weed's distribution at a national scale, can implement suitable management programs.

High-quality data feeds of meteorological observations are essential, as broad-scale modeling approaches such as those used in pest risk prediction systems rely on an accurate estimation of localized conditions like temperature, humidity and rainfall (Magarey et al. 2005). Mechanistic or deductive models use detailed knowledge of the pest/disease biology to predict the response of the organism to a specific climatic driver (Venette 2010; Donatelli et al. 2017), therefore access to accurate, high spatial and temporal resolution datasets is essential for the correct estimation of insect and disease outbreaks. In the recent past, weather data feeds for early warning systems have used observations from meteorological stations set up as either regional networks or farmer-owned stations (Gleason et al. 2008; Magarey et al. 2001; Cressman 2016). However, networks require funds for their upkeep and coverage can be either geographically unrepresentative of the needs of a study or altogether limited (Colston et al. 2018). Climate data products derived from EO sources and reanalysis datasets have the potential to overcome these issues by providing complete coverage at good spatial and temporal resolutions and can offer a wider range of variables that may be applicable to modeling needs (Colston et al. 2018). Improved access to sophisticated weather models, such as the Unified Model (a numerical weather prediction model) available from the UK Met office, have also contributed to the development of disease early warning systems. Recent advances in the availability and access to these data have advanced the capabilities of models to deliver near real-time information. This increasing amount and accessibility of data from varied sources offers great opportunities to inform agricultural stakeholders so that they can make better decisions when it comes to plant health challenges, and thus move towards reducing crop losses as outlined in SDG2. Recent projects such as the PRISE (Pest Risk Information Service) project funded by the UK Space Agency (UKSA), and a near real-time early warning system to predict future potential hotspots of two wheat diseases in Ethiopia (Allen-Sader et al. 2019), have utilized access to these improved data sources for the purpose of pest and disease early warning systems. Both systems have extended messages to relevant stakeholders (governments, farmers, extension workers) in order to inform better management decisions with the ultimate aim of reducing crop losses.

2.3 Validation of EO Data and Models

Pest and disease risk prediction models driven using EO data inputs require field data for testing and validating species' presence, incidence and development. Historically, data collection in pest early warning systems has been limited by ground surveys, which may fail as a result of political unrest, border disputes, and inaccessible terrain, or can be limited by funds to generate these data. However, although detailed controlled studies remain vital for testing EO and pest models, there are now opportunities to collect supporting data from a much larger source. Increase in access to digital communication technology (GSMA 2020) enables data to be collected directly from farmers and to enrich early warning systems. This citizen science approach is adapting to new technologies that smartphones provide (GPS, digital cameras, internet connectivity). Many efforts are also ongoing to build AI-based tools (applications and sensors) for pest and disease detection and identification through image processing (www.plantvillage.psu.edu; https://www.inaturalist.org/home), which may be used for in-field diagnostics of pests and diseases or to assess local pest/disease pressure. The collation of accurate, or, in the term of iNaturalist, "research grade" datasets (Ueda 2021) relating to pest presence may contribute to the building, calibration and validation of early warning models. There is a growing societal acceptance of mass participation projects, and advances in statistical approaches allow these data to be analyzed in a less structured way (Pocock et al. 2017). In order to be sustainable, these systems need to consider the incentives and motivations for users to contribute data. This surveillance method contributes vital observations in support of national and international programs, detecting pest incidence outside of formal research studies, extension services, border control checks and the work of plant protection organizations (Brown et al. 2020).

Box 1: Rolling Out a Cost-Effective Surveillance and Early Warning System to Manage the Acute Desert Locust Crisis

The desert locust, *Schistocerca gregaria* (Orthoptera:Acrididae) is an eruptive, transboundary pest, which affects Africa and parts of Asia. Under certain conditions, the locust forms large swarms, which affect large geographies and severely impact food production. Given the relationship between local environmental conditions, abundance of vegetation and locust biology, it is possible to use state-of-the-art approaches to collect data on locust presence, monitor movement, model the potential spatial extent of the locusts and assess crop damage to produce a dynamic and reactive response to locust outbreaks. In addition, schemes such as the FAO Desert Locust Information Service (DLIS) are able to forewarn of potential conditions, which may lead to the formation of swarms, thus preventing future swarms. Below are the ways in which technology and data should be utilized in frontline countries in response to the *S. gregaria* outbreak 2019–2021.

Activity	Example
Monitoring presence of populations	Innovative digital tools like smart phone apps (e.g., e-locust3M), as means of crowdsourcing, for real-time desert locust data collections, tracking and monitoring the spread of the pest. High-resolution remote sensing systems mounted on unmanned aerial vehicles (UAV), i.e., drones, for timely desert locust surveillance and monitoring in remote and/ or inaccessible areas.

(continued)

Box 1 (continued)

Activity	Example
Monitoring of habitats/ potential habitats	Use of newly-launched earth observation (EO) tools (e.g., satellite-based vegetation coverage, wind speed/ direction and soil moisture) of relatively better spatial and temporal resolutions to monitor desert locust habitats.
Monitoring of movement	Ground-based radar systems to track and monitor desert locust breeding sites and hoppers migrations.
Collation of data	Harmonize and standardize the existing national and centralized open-source desert locust data systems/ platforms to receive and store 'big data' transmitted from crowdsourcing tools and drones.
Early warning	Develop desert locust early warning and early action platforms using combinations of above-mentioned tools, machine learning (ML) and artificial intelligence (AI) algorithms.
Future situations/scenarios	Assess vegetation and crop damage due to desert locust using long-term EO data, ML and AI algorithms. Use of historical long-term (e.g., 30 years) satellite-based climate data and AI algorithms to assess the impacts of climate change on desert locust occurrence and forecast future desert locust outbreaks weeks and months in advance to enhance targeted and effective interventions

3 Potential for Improving Plant Health Systems and Livelihoods: The Requirement for Effective Extension

The key aim of pest risk prediction systems should be to communicate risks and mitigation strategies to those who need the information most, with the aim of reducing potential losses, and allow time for sustainable interventions to be made. Such extension messaging should consider the technological capabilities of the end user. Rapid large-scale investment in telecommunication and the subsequent reduced cost of mobile phones and internet connectivity has resulted in the widespread accessibility of mobile phones across Africa and Asia, including their most rural areas (World Bank 2019), with an estimated 34% of the surveyed population owning a smartphone in Kenya, and 53% owning an older device without internet connectivity (Krell et al. 2020).

As a result of the increase in mobile phone ownership, ICT-based advisory extension services have evolved to use communication channels such as SMS and USDD. With the direct-to-farmer and local language adoption capabilities of SMS, it is considered the most impactful single communication method in terms of improving farmers' knowledge and practice changes in Sub-Saharan Africa (Silvestri et al. 2020). A recent example is an initiative set up in 2018 through collaboration between Kenya's Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALFC) and Precision Agriculture and Development (PAD) to disseminate advisory messages relating to the fall armyworm (*Spodoptera frugiperda*) (Bakirdjian 2020). The initiative has grown to provide actionable advice for ten crops, and has demonstrated broadscale uptake by reaching over half a million farmers, and, in an additional pilot study on the fall armyworm, in collaboration with PRISE, 59% of 6,000 farmers who received timely SMS pest alert warnings self-reported changing their management practices with positive outcomes (Mbugua et al. 2021). Similar programs across Africa and India showed that a 4% average yield gain has been associated with digital agriculture programs, demonstrating a positive impact on livelihoods (Fabregas et al. 2019). This can be achieved at significantly lower costs compared with traditional agricultural advisory services. Estimates show the cost per farmer reached by SMS services to be between 28 and 122 times cheaper per year compared to funding in-person farmer field days (Low and Thiele 2020; Quizon et al. 2001; Ricker-Gilbert et al. 2008). An integrated approach that includes in-person farmer visits, farmer field days and digital advisory services can offer more sustainable and effective extension.

4 Conclusions and Future Actions

The bringing together of state-of-the-art advances in data availability, resolution, management and architecture, along with new extension approaches that can deliver rapid and timely information, stands to make real changes in the way in which pest risk can be communicated to end users in a timely way. The resulting synergy in these individual improvements can be combined to result in real gains in terms of yield on the ground and make headway towards the sustainable development goals such as SDG2. To maintain the momentum of the synergy of these approaches, there are several aspects that could be considered in the near future.

The collation and curation of data from disparate sources is key to being able to drive the construction and validation of pest risk models and to exploit opportunities from the 'big data' and ML approaches. Data should be published openly (when possible) following FAIR (findability, accessibility, interoperability, and reusability) principles, so that data are findable, accessible, interoperable and reusable. Openly accessible data can be shared through common interactive web platforms such as the Global Biodiversity Information Facility (GBIF) or institutional repositories such as those hosted by CABI, FAO or IITA. This will bridge the data gap in national, regional and local surveillance and improve data systems, linkage and the sharing of pest data. Overall, the modeling platforms themselves can serve as means of communication and networking. It is important to ensure that these early warning and monitoring systems are truly sustainable (self-managing and self-funding) in the long-term, and public-private partnerships will be key in ensuring this. Moreover, projects should ensure that the data and related materials, both digital and non-digital, should be accompanied by proper metadata and documentation in a way that facilitates the verification, replication and, if possible, reuse and remixing of the data.

The exploitation and interpretation of 'big data' can be used to develop geospatial cloud-based tools and mobile apps that can be operationally utilized for 'real-time' insect and weed surveillance, monitoring and forecasting. To do this, a complete, accurate and reliable DMWf is required, with advanced skills in common data models (CDM), data warehouse and repository, modeling methods and analytics, including ML, AI, design thinking, system thinking, system dynamics and computer vision algorithms. This information can be used to better learn, adapt and transform risk into knowledge to change practice. For instance, applying AI on a CDM extract could uncover hidden patterns, unknown correlations, trends, preferences, and other information that can help stakeholders make better and more informed decisions for the target insect pests and weeds. The AI may be utilized for the optimization of spatial positioning of pest traps that auto-disseminate sustainable interventions such as biopesticides (Guimapi et al. 2019).

Global environmental monitoring platforms provide portals for policy and national and regional decision-makers to view datasets and reports, however, there is now an opportunity to bring early warning to the farmer level. Advances in digital technology have demonstrated great opportunities for disseminating data to local scales and communicating this information so as to aid decisions made in the field. To achieve greater impact, these large datasets must be turned into timely information that can support agricultural decision-making at a local scale, to avoid preventable losses. To be effective, pest early warning system outputs must reach the farmer in the form of actionable advice. In order to effectively manage pests and diseases, farmers need timely warnings on taking preventative actions, advice on when to prepare and stock plant protection products, and alerts on the optimum times to monitor their crops for particular problems in order to act. The combination of this improved extension with the availability of high-quality, high temporal and spatial resolution datasets that can drive models within pest risk prediction systems is opening up opportunities to extend the outputs of models to broader geographical audiences and reach those who need the information most. There is also an opportunity to combine early warning model outputs with models related to management practices. Research projects investigating the estimated time to kill of traditionally slower acting biopesticides, combined with information of pest phenology, can lead to optimization of the timing of application of more sustainable interventions such as entomopathogenic fungi (CABI 2021).

For smallholder farmers and rural communities, the uptake of new digital solutions can often be limited by access to smartphones and other mobile tools, technological literacy, and willingness to change farming practices, many of which can be linked to gender and wealth (World Bank 2019). As such, the diversity of target users needs to be incorporated into the development and rollout of new services, with users taking on different roles that may not require high-level digital literacy. Numerous studies have agreed with the statement that digital extension will not replace face-to-face and more traditional advisory practices, and therefore new services need to take a more user-centered approach to support smallholder decision-making (Steinke et al. 2020).

Looking to the future, for the successful uptake of pest risk prediction systems, there needs to be a sufficient level of multidisciplinary involvement across the plant health sector, from governments and policymakers to extension services and smallholder farmers (Winarto 2018). The adoption of novel technologies into existing plant health services needs to be taken up at a national level, with the ability to be disaggregated across regional and local platforms. National-level uptake or endorsement of early warning pest services could potentially benefit existing pest monitoring and plant health systems, notably, in low-income countries, by supporting the sharing of knowledge across boundaries and improving decision-making, resulting in improved food security and farmer incomes (Rivera and Alex 2004; Chapman and Tripp 2003).

For the long-term sustainability of early warning systems, the technological infrastructure and capabilities that are available in western countries need to be made accessible to low-income countries. Capacity-building for key actors, organizations and services in the plant health system is an integral part of promoting the uptake and success of such innovations that incorporate EO data and the use of models. Sufficient training and support are required to promote the adoption of novel systems into national, regional and local early warning dissemination services.

If digital-based technologies of any theme are to create sustainable lasting impacts on farmers and crop health systems, policymakers need to shift to a more inclusive digital understanding and acceptance (Steinke et al. 2020). Governments, the private sector, development partners and donors can promote successful digital services through increased investment, rather than short-term projects, with more focus on capacity-building and user-centered design processes. For example, governments may seek to partner with private sector and development partners in the provision of digital services, especially when incentives align, including commercial terms, data privacy and ownership rights (Lutz et al. 2021). Innovation at any level will always require investment, but with an extensive portfolio of existing technologies and services in the agricultural advisory sector, it is apparent that novel applications must be applied under collaborative and cross-cutting processes.

References

Allen-Sader C, Thurston W, Meyer M, Nure E, Bacha N, Alemayehu Y, Stutt ROJH et al (2019) An early warning system to predict and mitigate wheat rust diseases in Ethiopia. Environ Res Lett 14(11):115004. https://doi.org/10.1088/1748-9326/ab4034

Bakirdjian E (2020) MoA-INFO is two years old! Available at: https://precisionag.org/moa-info-is-two-years-old. Accessed 22nd Mar 2021

Barzman M, Bàrberi P, Birch ANE, Boonkamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR, Messéan A, Moonen A-C, Ratnadass A, Rissi P, Sarah J-L, Sattin M (2015) Eight principles of integrated Pest management. Agron Sustain Dev 35:1199–1215. https://doi.org/10.1007/s17593-015-0327-9

Brown N, Pérez-Sierra A, Crow P et al (2020) The role of passive surveillance and citizen science in plant health. CABI Agric Biosci 1:17. https://doi.org/10.1186/s43170-020-00016-5

CABI (2021) Enabling safe and climate smart coffee production in Colombia. Centre for Agriculture and Bioscience International, Wallingford. https://www.cabi.org/projects/enabling-safe-and-climate-smart-coffee-production-in-colombia/

Castex V, Beniston M, Calanca P, Fleury D, Moreau J (2018) Pest management under climate change: the importance of understanding Tritrophic relations. Sci Total Environ 616–617:397–407. https://doi.org/10.1016/j.scitotenv.2017.11.027

Chapman R, Tripp R (2003) Changing incentives for agricultural extension- a review of privatized extension in practice. Agricultural Research & Extension Network. Network Paper 132. ISBN 0 85003 679 8

Chidawanyika F (2019) Global climate change as a driver of bottom-up and top-down factors in agricultural landscapes and the fate of host-parasitoid interactions. Front Ecol Evol 7:13

Colston JM, Ahmed T, Mahopo C, Kang G, Kosek M, de Sousa Junior F, Shrestha PS, Svensen E, Turab A, Zaitchik B (2018) Evaluating meteorological data from weather stations, and from satellites and global models for a multi-site epidemiological study. Environ Res 165:91–109. https://doi.org/10.1016/j.envres.2018.02.027

Constantine KL, Murphy ST, Pratt CF (2021) The interaction between pests, mixed-maize crop production and food security: a case study of smallholder farmers in Mwea West, Kenya. Cogent Food Agric 6:1857099. https://doi.org/10.1080/23311932.2020.1857099

Cressman K (2016) Chapter 4.2 – Desert Locust. In: Shroder JF, Sivanpillai R (eds) Biological and environmental hazards, risks, and disasters. Academic, Boston, pp 87–105

Deutsch CA, Tewksbury JJ, Tigchelaar M, Battisti D, Merrill SC et al (2018) Increase in crop losses to insect pests in a warming climate. Science 361:916–919. https://doi.org/10.1126/science.aat3466

Donatelli M, Magarey RD, Bregaglio S, Willocquet L, Whish JPM, Savary S (2017) Modelling the impacts of pests and diseases on agricultural systems. Agric Syst 155:213–224. https://doi.org/10.1016/j.agsy.2017.01.019

Early R, Bradley B, Dukes J et al (2016) Global threats from invasive alien species in the twenty-first century and national response capacities. Nat Commun 7:12485. https://doi.org/10.1038/ncomms12485

ESA (2020) Compendium of Earth Observation contributions to the SDG Targets and Indicators. European Space Agency, Paris. https://eo4society.esa.int/wp-content/uploads/2021/01/EO_Compendium-for-SDGs.pdf

Fabregas R, Kremer M, Schilbach F (2019) Realizing the potential of digital development: the case of agricultural advice. Science 366(6471):eaay3038. https://doi.org/10.1126/science.aay3038

FAO (2007) Pest Risk Analysis Training - Participants Manual. UN Food and Agriculture Organization, Rome. https://assets.ippc.int/static/media/files/publications/1229703410292_PRA_training_course_Participant_manual.pdf

FAO (2019) New standards to curb the global spread of plant pests and diseases. UN Food and Agriculture Organization, Rome. http://www.fao.org/news/story/en/item/1187738/icode/

Gharde Y, Singh PK, Dubey RP, Gupta PK (2018) Assessment of yield and economic losses in agriculture due to weeds in India. Crop Prot 107:12–18. https://doi.org/10.1016/j.cropro.2018.01.007

Gleason ML, Duttweiler KB, Batzer JC, Taylor ES, Sentelhas PC, Boffino JE, Monteiro A, Gillespie TJ (2008) Obtaining weather data for input to crop disease-warning systems: leaf wetness duration as a case study. Sci Agric 65(spe):76–87. https://doi.org/10.1590/S0103-90162008000700013

GMSA (2020) Mobile Economy 2020. GSM Association, London. https://www.gsma.com/mobileeconomy/wp-content/uploads/2020/03/GSMA_MobileEconomy2020_Global.pdf

Guimapi RA, Mohamed SA, Ekesi S, Freudenberger LB, Borgemeister C, Tonnang HEZ (2019) Optimizing spatial positioning of traps in the context of integrated pest management. Ecol Complex. https://doi.org/10.1016/j.ecocom.2019.100808

Kalnicky EA, Brunson MW, Beard KH (2019) Predictors of participation in invasive species control activities depend on prior experience with the species. Environ Manag 63(1):60–68. https://doi.org/10.1007/s00267-018-1126-2

Kganyago M, Odindi J, Adjorlolo C, Mhangara P (2017) Selecting a subset of spectral bands for mapping invasive alien plants: a case of discriminating *Parthenium hysterophorus* using field spectroscopy data. Int J Remote Sens 38(20):5608–5625. https://doi.org/10.1080/01431161.2017.1343510

Krell NT, Giroux SA, Guido Z, Hannah C, Lopus SE, Caylor KK, Evans TP (2020) Smallholder farmers' use of mobile phone services in Central Kenya. Clim Dev:1–13. https://doi.org/10.1080/17565529.2020.1748847

Livingston G, Schonberger S, Delaney S (2011) Sub-Saharan Africa: the state of smallholders in agriculture. IFAD International Fund Agric. Dev. Conference New Dir Smallhold. Agric, pp 1–36

Low JW, Thiele G (2020) Understanding innovation: the development and scaling of orange-fleshed sweet potato in major African food systems. Agric Syst 179:102770. https://doi.org/10.1016/j.agsy.2019.102770

Lutz G, Ryan M, Amandla O, Gillian P (2021) How digital tools can help transform African agri-food systems. McKinsey Insights

Magarey RD, Seem RC, Russo JM, Zack JW, Waight KT, Travis JW, Oudemans PV (2001) Site-specific weather information without on-site sensors. Plant Dis 85(12):1216–1226. https://doi.org/10.1094/PDIS.2001.85.12.1216

Magarey RD, Sutton TB, Thayer CL (2005) A simple generic infection model for foliar fungal plant pathogens. Phytopathology 95:92–100. https://doi.org/10.101094/PHYTO-95-0092

Magarey RD, Sutton TB (2007) How to create and deploy infection models for plant pathogens. In: Ciancio A, Mukerji KG (eds) General concepts in integrated pest and disease management. Springer, pp 3–25

Marques da Silva JR, Damásio CV, Sousa AMO, Bugalho L, Pessanha L, Quaresma P (2015) Agriculture pest and disease risk maps considering MSG satellite data and land surface temperature. Int J Appl Earth Obs Geoinf 38:40–50. https://doi.org/10.1016/j.jag.2014.12.016

Mbugua F, Bundi M, Day C, Beale T, Williams F (2021) PRISE-PAD fall armyworm SMS alert pilot results, CABI study brief 35: learning. https://doi.org/10.1079/CABICOMM-62-8141

Mudereri BT, Dube T, Niassy S, Kimathi E, Landmann T, Khan Z, Abdel-Rahman EM (2020) Is it possible to discern Striga weed (*Striga hermonthica*) infestation levels in maize agro-ecological systems using in-situ spectroscopy? Int J Appl Earth Obs Geoinf 85:102008. https://doi.org/10.1016/j.jag.2019.102008

O'Conner B, Moul K, Pollini B, de Lamo X, Simonson W (2020) Earth observation for SDG: contributions to the SDG compendium of EO contributions to the SDG targets and indicators. UNEP-WCMC. Available at: https://eo4society.esa.int/wp-content/uploads/2021/01/EO_Compendium-for-SDGs.pdf

Orlandini S, Magarey RD, Park EW, Sporleder M, Kroschel J (2017) Methods of agroclimatology: modelling approaches for pests and diseases. Agroclimatology. https://doi.org/10.2134/agromonogr60.2016.0027

Perrings C (2007) Pests, pathogens and poverty: biological invasions and agricultural dependence. Biodivers Econ Princ Methods Appl:133–165. https://doi.org/10.1017/CBO9780511551079.008

Persson M, Lindberg E, Reese H (2018) Tree species classification with multi-temporal Sentinel-2 data. Remote Sens 10:1794. https://doi.org/10.3390/rs10111794

Pocock MJO, Tweddle JC, Savage J, Robinson LD, Roy HE (2017) The diversity and evolution of ecological and environmental citizen science. PLoS One 12(4):e0172579. https://doi.org/10.1371/journal.pone.0172579

Pratt CF, Constantine KL, Murphy ST (2017) Economic impacts of invasive alien species on African smallholder livelihoods. Glob Food Sec 14:31–37. https://doi.org/10.1016/j.gfs.2017.01.011

Pretty J, Bharucha ZP (2015) Integrated pest management for sustainable intensive of agriculture in Asia and Africa. Insects 6:152–182. https://doi.org/10.3390/insects6010152

Quizon J, Feder G, Murgai R (2001) Fiscal sustainability of agricultural extension: the case of the farmer field school approach. J Int Agric Ext Educ 8(1):13–24. https://doi.org/10.5191/jiaee.2001.08102

Rebaudo F, Rabhi V-B (2018) Modeling temperature-dependent development rate and phenology in insects: review of major developments, challenges, and future directions. Entomol Exp Appl 166:607–617. https://doi.org/10.1111/eea.12693

Renier C, Waldner F, Jacques D, Ebbe MB, Cressman K, Defourny P (2015) A dynamic vegetation senescence indicator for Near-Real-Time Desert Locust habitat monitoring with MODIS. Remote Sens 7(6):7545–7570. https://doi.org/10.3390/rs70607545

Ricker-Gilbert J, Norton GW, Alwang J, Miah M, Feder G (2008) Cost-effectiveness of alternative integrated pest management extension methods: an example from Bangladesh. Rev Agric Econ 30(2):252–269. https://doi.org/10.1007/s12571-020-01046-7

Rivera W, Alex G (2004) The continuing role of government in pluralistic extension systems. J Int Agric Ext Educ 11(3). https://doi.org/10.5191/jiaee.2004.11305

Savary S, Willocquet L, Pethybridge SJ et al (2019) The global burden of pathogens and pests on major food crops. Nat Ecol Evol 3:430–439. https://doi.org/10.1038/s41559-018-0793-y

Silvestri S, Musebe R, Baars E, Ganatra D, Romney D (2020) Going digital in agriculture: how radio and SMS can scale-up smallholder participation in legume-based sustainable agricultural intensification practices and technologies in Tanzania. Int J Agric Sustain. https://doi.org/10.1080/14735903.2020.1750796

Steinke J, van Etten J, Müller A, Ortiz-Crespo B, van de Gevel J, Silvestri S, Priebe J (2020) Tapping the full potential of the digital revolution for agricultural extension: an emerging innovation agenda. Int J Agric Sustain:1–17. https://doi.org/10.1080/14735903.2020.1738754

Tambo JA, Aliamo C, Davis T, Mugambi I, Romney D et al (2019) The impact of ICT-enabled extension campaign on farmers' knowledge and management of fall armyworm in Uganda. PLoS One 14(8):e0220844. https://doi.org/10.1371/journal.pone.0220844

Thakur M, Pandit V, Chaudhary M, Rajkumar R (2016) ICT interventions in crop health knowledge management for smallholder farmers. J Global Commun 9(conf):35–46

Tonnang HEZ, Herve BDB, Biber-Freudenberger L, Salifu D, Subramanian S et al (2017) Advances in crop insect modelling methods- towards a whole system approach. Ecol Model 354:88–103. https://doi.org/10.1016/j.ecolmodel.2017.03.015

Ueda K (2021) iNaturalist Research-grade Observations. iNaturalist.org. Occurrence dataset 10.15468/ab3s5x accessed via GBIF.org on 2021-04-13

Van Tricht K, Gobin A, Gilliams S, Piccard I (2018) Synergistic use of radar Sentinel-1 and optical Sentinel-2 imagery for crop mapping: a case study for Belgium. Remote Sens 10:1642. https://doi.org/10.3390/rs10101642

Venette RC, Kriticos DJ, Magarey RD, Koch FH, Baker RHA, Worner SP, Gómez Raboteaux NN, McKenney DW, Dobesberger EJ, Yemshanov D, De Barro PJ, Hutchison WD, Fowler G, Kalaris TM, Pedlar J (2010) Pest risk maps for Invasive Alien Species: a roadmap for improvement. Bioscience 60(5):349–362. https://doi.org/10.1525/bio.2010.60.5.5

Weier J, Herring D (2000) Measuring vegetation (NDVI & EVI). NASA Earth Observatory, Washington, DC

Wiggins S, Kirsten J, Llambi L (2010) The future of small farms. World Dev 38:1341–1348. https://doi.org/10.1016/j.worlddev.2009.06.013

Winarto YT (2018) The role of an interdisciplinary approach to improving farmers' resilience to climate change: its potentials and challenges. IOP Conf Serie Earth Environ Sci 166:012049

World Bank (2019) Information and Communications for Development 2018: Data-Driven Development. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1325-2. License: Creative Commons Attribution CC BY 3.0 IGO

Food Systems Innovation Hubs in Low- and Middle-Income Countries

Kalpana Beesabathuni, Klaus Kraemer, Sufia Askari, Srujith Lingala, Madhavika Bajoria, Martin Bloem, Breda Gavin-Smith, Hamid Hamirani, Priyanka Kumari, Anne Milan, Puja Tshering, Kesso Gabrielle van Zutphen, and Kris Woltering

1 Introduction

Our food systems are under pressure and failing us. This failure includes the inability to (a) produce and deliver high-quality diets to meet nutritional needs, (b) produce equal and equitable benefits, and (c) mitigate negative consequences (Baker 2020).

The **threats and consequences of such failing food systems** are wide-ranging. Diets are a significant predictor for the nutritional status and overall health of vulnerable groups. In 2019, 21.3% (144 million) of children under five were estimated to be stunted, 6.9% (47 million) wasted, and 5.6% (38.3 million) overweight, while at least 340 million children suffer from micronutrient deficiencies (Advisory Board 2020). Although child stunting is declining, global hunger is on the rise again (Advisory Board 2020). Simultaneously, over one-third of the global adult population is overweight or obese. Furthermore, sub-optimal diets serve

K. Beesabathuni (✉) · S. Lingala · M. Bajoria · B. Gavin-Smith · P. Kumari · A. Milan
P. Tshering · K. G. van Zutphen · K. Woltering
Sight and Life Foundation, Sydney, Australia
e-mail: Kalpana.beesabathuni@sightandlife.org

K. Kraemer
Sight and Life Foundation, Sydney, Australia

The Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA

S. Askari
Children's Investment Fund Foundation, London, UK

M. Bloem
The Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA

H. Hamirani
Food Systems for the Future Institute, Chicago, IL, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_24

as a major risk factor for non-communicable diseases, driving up morbidity and mortality risks, especially in low- and middle-income countries (LMICs) (Afshin et al. 2017; Arneth et al. 2019).

Malnutrition results in an unacceptably high economic burden for individuals, communities and entire economies. Direct costs of poor nutrition relate, for instance, to the treatment of overweight-related conditions, underweight-related conditions, and diet-related non-communicable diseases. All of these contribute to significant and rapidly rising health care costs. In fact, government spending on healthcare increased by a factor of 2.5 in the last 20 years (Ball et al. 2018). Such dramatic trends are clearly unsustainable. Indirect costs are also generated in the form of preventable child deaths and impaired cognitive development.

Food systems are, however, driving additional economic losses due to supply chain inefficiencies. Approximately 14% of all food produced globally is lost, or significantly reduced in quality, before reaching the retail stage of the supply chain (Beesabathuni et al. 2018). Moreover, considering that food systems are the major driver of global greenhouse gas (GHG) emissions, contributing 21–37% of total emissions, there is an urgent need to explore opportunities and innovative approaches to accelerate sustainable transformation (Béné et al. 2019; Bora et al. 2020).

Although information on 'how' to transform food systems remains scarce, **innovative approaches and opportunities** exist. These include the innovative use of technology, the reallocation of government expenditure, and the promotion of more nutritious diets. However, scaling these innovations requires capital and a platform to connect stakeholders and facilitate the transfer of technology and know-how.

Food system innovation hubs provide an opportunity to address these challenges. They have the potential to stimulate investments in resilient and responsive food systems with the goal of alleviating malnutrition through corporate partnerships, impact investors and government collaboration. These hubs can encourage food companies to expand into LMICs, facilitate investments in local companies, and stimulate supply chain innovations.

This chapter aims to draw attention to the role that **food system innovation hubs** can play in creating healthy, resilient and inclusive communities in LMICs. First, eight different archetypes of food innovation hubs are described. Future opportunities for these hubs to deliver planet-friendly nutritious and safe foods are then explored. It is argued that the complexity of food systems calls for context-specific transformations, and that innovation hubs have a key role to play here. Three key actions are identified as essential for developing effective food system innovation hubs in LMICs: Inspire! Invest! And Innovate!

2 The Current Landscape

Thus far, most recommended changes in food systems have involved incremental adjustments to existing technologies. Examples include improving egg consumption through backyard farming(Busby and Macpherson 2020), improving yields through new varieties and alternative farming practices (Crippa et al. 2021; Davies and Macpherson 2020; FAO, IFAD, UNICEF, WFP, WHO 2020; Farm Together 2021; Florida and Hathaway 2018; Foley et al. 2011), and reducing micronutrient deficiencies through biofortification (FAO 2019a). Evidence nevertheless suggests that, even with these changes, it will be challenging to nourish ourselves adequately while observing planetary boundaries (Crippa et al. 2021; FAO 2010, 2019b; Frank et al. 2017; Gao and Bryan 2017; World Health Organization 2019; Gursel 2014).

The future of food systems hinges on disruptive new solutions that can help us achieve our collective Sustainable Development Goals (SDGs). We define 'innovation' broadly to include new products, business models, policy practices, technologies, behavioral insights, or ways of delivering products and services that benefit the poor in LMICs — any solution that has the potential to address malnutrition more effectively than existing approaches. However, innovations at a systems level are not easy to implement. While solutions are in the pipeline, they vary in their degree of maturity and require patient capital allocation and robust implementation strategies. Moreover, far too many promising innovations fail to scale their impact due to a lack of ability to manage the lengthy and demanding processes they entail (Havlík et al. 2014).

Food system innovation hubs can provide transformative solutions to food systems by bringing the right innovations to market faster in a cost-effective manner. We mapped different types of innovation hubs based on their coverage, capacity and capabilities. In our mapping (Fig. 1), we identified eight archetypes. The archetype nomenclature is similar to what we see in other peripheral sectors, such as education, housing, water and sanitation (Herrero et al. 2020).

1. Science and technology parks are usually established by governments in transition economies characterized by market imperfections, limited access to knowledge and finance, high transaction costs due to lack of infrastructure, and weak institutions (Ittersum et al. 2016). They are often seen as developing the innovation ecosystem. Further, they subsidize research and development (R&D) costs for companies and eventually foster collaboration and capital between industry and universities (Katz and Wagner 2014). When there is a strong political will to nurture innovation and facilitate ease of doing business, they can attract international investors.
2. Research centers combine infrastructure and talent to unlock the next big scientific breakthrough and take it to market. An example is the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT). ICRISAT adopts integrated genetic and natural resource management as its research strategy, with the aim of combining tested methods of crop commodity research with well-established practices in research in natural resource management.
3. Advanced development spaces are typically asset-heavy institutions that support R&D, commercialization, technology applications, testing, product design and prototyping. With the rise in entrepreneurs in many cities in LMICs, we see an

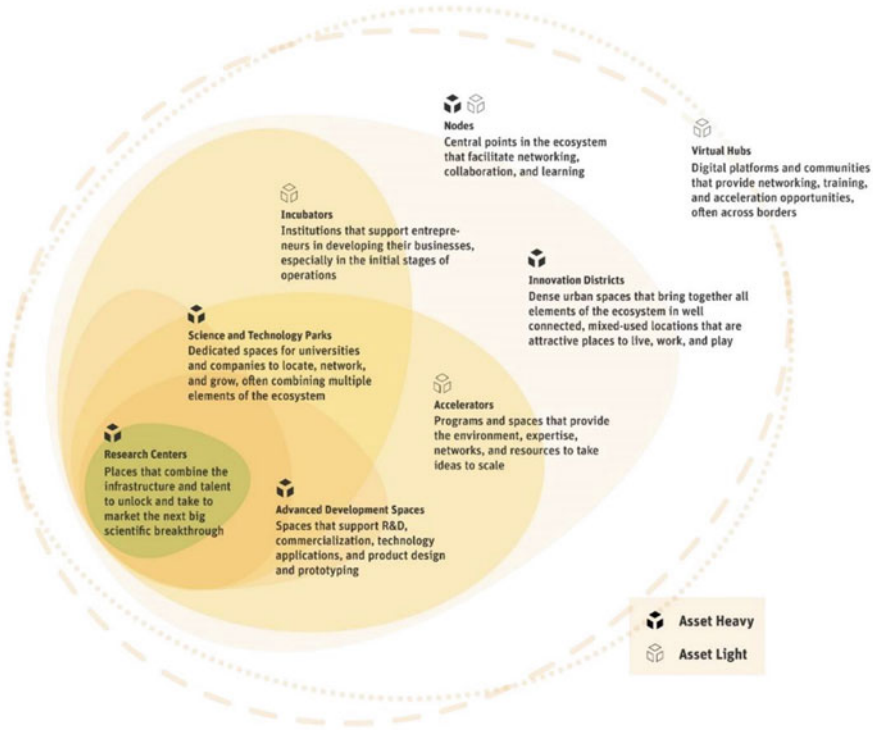


Fig. 1 Schematic representation of the eight archetypes of innovation hubs characterized by their physical infrastructure: asset-light to asset-heavy

emergent variant of advanced development spaces that have less physical infrastructure and provide informal, unscheduled activity with more open-source knowledge. For example, Fabrication Labs is a small-scale workshop equipped with an array of flexible computer-controlled tools.

Incubators and accelerators are the two most common archetypes found in both high-income countries (HICs) and LMICs.

4. Incubators are institutions that support entrepreneurs in developing their businesses, especially in the initial stages. An example of this is the *WeInnovation* Hub in Nigeria (Lane et al. 2019), which focuses on education, agriculture, healthcare and infrastructure. The *WeInnovation* Hub has supported more than 300 start-up teams and more than 6000 youth entrepreneurs.
5. Accelerators are programs and spaces that provide the environment, expertise, networks, and resources to take ideas to scale. They are probably the most common archetype. Here, we describe four noteworthy examples:

Rockefeller's SME Accelerator: The investment thesis of this accelerator covers three areas. Firstly, it brings together actors to finance small and medium enterprises (SMEs). Secondly, it facilitates stand-alone investments in making nutritious foods accessible and affordable. Thirdly, it functions as an accelerator for start-ups that have been in operation for a minimum of two years.

World Economic Forum's Food Innovation Hubs: The World Economic Forum (WEF) plans to launch four food innovation hubs to support food system transformation. These hubs will be locally driven and owned, both multi-stakeholder and inclusive, creating a community of practice to share learnings and build capacity (Lockyer et al. 2018).

World Food Programme's (WFP) Innovation Accelerator: Based in Munich, Germany, this accelerator provides WFP employees, entrepreneurs, and start-ups with funding, hands-on support, and access to WFP's global operations. In just five years, 80 projects worldwide have received support, with fourteen innovations scaling up to reach 3.7 million people (OECD 2021).

LAUNCH was constructed ten years ago in partnership with NASA, Nike, USAID, and the US State Department. The platform sources and accelerates solutions to the challenges faced by rice farmers and the institutions, governments, and companies surrounding them. LAUNCH fosters new models such as network-centered innovation and collaborative equilibrium (Results for Development 2021).

6. Innovation districts are "geographic areas where leading-edge anchor institutions and companies cluster and connect with start-ups, business incubators, and accelerators. They are also physically compact, transit-accessible, and technically wired, and offer mixed-use housing, office, and retail"(Ringel et al. 2020). Found primarily in HICs, the state of Michigan (USA) is a prominent example, in which a state-wide policy encouraged the sourcing of 20% of Michigan's food from Michigan markets. This has stimulated the creation of 13 more food innovation districts throughout the state. Some examples of food design interventions are community gardens or fruit-bearing street trees. A well-planned innovation district can reduce transport and storage requirements and create an enabling environment for the demand and supply of safe and nutritious foods. One such example is *Sight and Life*'s Nutrition Kiosk, which was conceived as a solution to the problem of delivering last-mile nutrition in the urban landscape of India. The Nutrition Kiosk uses a pushcart format that is compact and in line with the strong street-vending culture of India (Rockström et al. 2020).
7. Virtual hubs are digital platforms and communities that provide networking, training, and acceleration opportunities, transcending borders. They are constantly absorbing new information and capacities that can be accessed by other connected 'users' anywhere in the network. Virtual hubs consequently open up the possibility of leaner and more agile local ecosystems. A minor variant of virtual hubs is aggregation on a platform approach for advancing innovations in rural areas. Aggregation is a popular way to achieve the critical mass of consumers or producers needed for any innovation to succeed.

8. Nodes are central points in the ecosystem. Nodes typically have a regional presence, but aim for global collaboration and impact. One example is the Foodvalley in the Netherlands, which has built an active relationship strategy with regions and countries worldwide to collaborate and accelerate innovation in agri-food. The Foodvalley caters to the full range of businesses. Research programs are supported via research and academic partners.

3 The Future Opportunity for Food System Innovation Hubs and Their Impact on Society, Economy and the Environment

In our review, we find that innovation hubs are not a new phenomenon. Most are technology-focused. Some are yet to launch. A thorough assessment of their capacity to deliver planet-friendly, nutritious and safe foods will guide us to coordinate, collaborate and invest in building capacity in LMICs.

Food system innovation hubs are social, private or government-owned enterprises that support local entrepreneurs and practitioners in advancing productivity- and sustainability-enhancing innovations, accessing capital and knowledge through collaborations, training and building their technical and business capacity and creating an enabling ecosystem together with local government. They present a tremendous opportunity to reimagine our food systems by connecting various ecosystem actors to enable co-creation, develop linkages and alignment, and generate innovative and inclusive governance models that enable collaboration and unlock barriers to scale (Rosegrant et al. 2014). In doing so, the hubs aim to unlock investments and leverage innovations to create healthy, inclusive and resilient communities in LMICs (Fig. 2). Most of the local hubs are owned by actors within the country, while those with a multi-country reach or a global reach are often owned by more than one stakeholder. Furthermore, governments have a crucial role to play in creating an enabling environment for food system innovations.

Economic Development

Innovation has profound effects on macro-economic environments. It accelerates economic growth and is the reason why some economies are more robust in the long term than others (Crippa et al. 2021). However, the capacity to innovate rests almost exclusively in HICs and with large companies endowed with capital, expertise, networks and resource-intensive R&D departments (Rubin et al. 2009; Searchinger et al. 2019). Shifting the locus of innovation from internal R&D teams to communities (Fig. 3) could facilitate the rapid transformation of food systems.

Moving the locus of innovation: Stimulating innovation calls for two knowledge-based activities: (i) generating a range of solutions to an innovation problem and (ii) selecting the appropriate solution(s) from the alternatives generated (Fig. 3). Innovation platforms can bring together communities of problem-solvers and

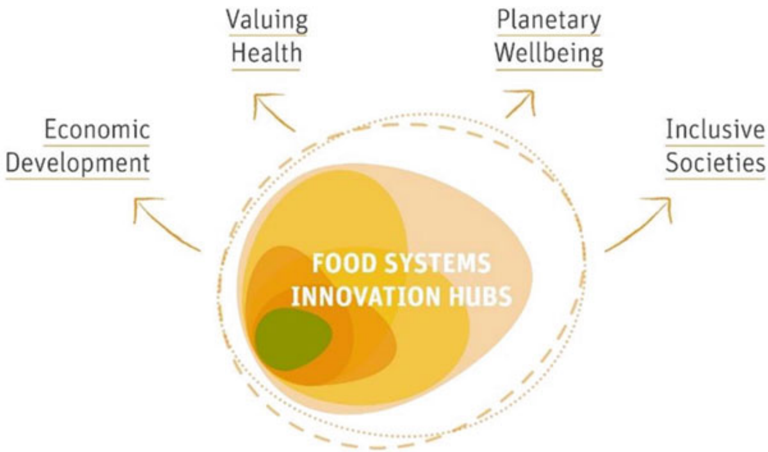


Fig. 2 Food system innovation hubs stimulate economic growth, ensure health benefits for all, protect the environment, and create sustainable societies

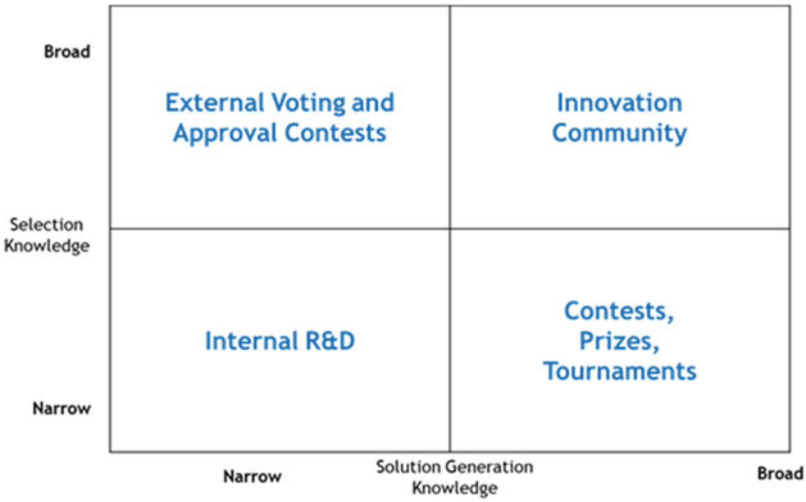


Fig. 3 Engineering serendipity: the future of Innovation Platforms. (Sherrick 2020)

expand the locus of innovation from internal to external. 'Thought for Food' and *Sight and Life*'s 'Elevator Pitch Contest' are creating such innovation platforms. Hubs can intensify such efforts.

Purposive Financing: Hubs must unlock innovative funding mechanisms in order to attract governments and investment funds. A few novel ones are described below.

Governments: Health spending is rapidly increasing, with 60% of the current budget coming from governments. In LMICs, this spending grew by a factor of 2.2 and increased 0.6 percentage points as a share of GDP (Shukla et al. 2019). Such dramatic increases are clearly unsustainable without reforms (Sight and Life 2019). Interventions aimed at disease prevention and health improvement can cut healthcare costs dramatically while improving health outcomes. For example, healthy lifestyles in the USA, including healthy eating, could result in healthcare savings of 2.7 trillion USD per year, reducing healthcare expenditure from 20% to 7% of GDP (Springmann et al. 2018). This makes a compelling case for the US government, other nations and funding agencies to invest in innovative food solutions.

Investment Funds: As private sector investors and sovereign wealth funds look to create sustainable lending portfolios (Startup Scene 2021), financing healthy, resilient and carbon-neutral solutions is a compelling proposition. Moreover, creating asset classes to fund innovations in food systems can help governments to reduce spending on healthcare and help companies to adhere to their carbon commitments.

We present below three examples of investment-worthy cases:

- Vertical farming is a sustainable alternative that uses up to 90% less water and land, and 60% less fertilizer, than traditional agriculture (Swinburn et al. 2019). The farm can be located at the city's edge, reducing transportation costs and time from farm to fork, thus lowering food loss or waste. Vertical farming can also release arable land for the cultivation of cereals and legumes.
- Farmland investment: Compared to conventional asset classes, investing in farmland has generated excess returns (The Grocer 2021), is relatively less volatile (Union of Concerned Scientists 2021), is uncorrelated (United Nations Industrial Development Organization 2021), is resilient to economic cycles (OECD 2021), and represents a good hedge against inflation (van Huis and Oonincx 2017). This is likely to encourage more investment in farmland as a yielding asset and to provide fresh capital for nutritious foods.
- Insect farming is a promising and sustainable alternative to conventional protein sources. It is resource-light and planet-friendly and can recycle nutrients from food loss and waste at improved feed conversion efficiencies (Villa 2017; Wennovation Hub 2018).

Funding and investing in nutritious food is a necessity and no longer a privilege for the few. Developing nutritious foods will reduce health care expenses, provide a sustainable alternative to achieve carbon reduction goals, and provide an asset class that ticks all boxes for institutional investors while generating inclusive economic growth.

Valuing Health

Increased availability and affordability of nutritious foods will not by itself generate change on the scale necessary to meet national and global commitments related to hunger and malnutrition. Moreover, the role of advertising in driving people towards unhealthy foods cannot be underestimated. Nudging consumers to value nutrition is therefore critical. Consumers in LMICs are ready to pay more for nutritious products if they deem these to be valuable. Nutritious foods will need to be positioned as foods that add value to the consumer's life. Creating such demand appears to depend on both tangible and intangible factors. Tangible factors focus on the intervention or product, for instance: (i) availability, affordability; (ii) nutrient content, energy value, serving size; (iii) taste, appearance, aroma, mouthfeel, convenience. Intangible factors consider the consumer context: (i) consumer aspirations, anxieties, expectations; (ii) culture, values, belief systems, social norms; (iii) knowledge, perceptions, behaviors around health/nutrition. Social marketing should ensure that the consumer is at the center of the campaign. Food system innovation hubs can focus on amplifying the values and priorities of the communities they serve, encouraging consumers to choose healthy, nutritious diets.

Planetary Well-Being

Global warming is a formidable challenge. The way we produce, process, and package food contributes to more than one-third of global GHG emissions (Béné et al. 2019). Innovations are needed to rapidly lower GHGs, such as unlocking barriers to scaling the (bio)fortification of staple foods, reducing food loss and waste, effecting better management of marine fisheries, aggregating smallholder livestock farmers to improve productivity, and increasing supply chain efficiencies.

The effects of global warming are most keenly felt in LMICs. These regions have also seen less widespread fortification of their local food staples than HICs. (Bio) fortification could therefore be an effective intervention against both micronutrient deficiencies and the climate change shocks experienced by food systems. Closer to the consumer, solar-energy-based innovative techniques such as solar dryers or solar storage for perishables can preserve food quality and prevent waste (Union of Concerned Scientists 2021). These techniques can alleviate global warming, because solar energy generates up to 90% fewer GHG emissions than natural gas and coal (Willett et al. 2019).

Targeted investment and technology transfer from HICs to LMICs will be crucial in advancing and adapting product innovations such as new food enzymes and insect protein, business model innovations for solar technologies and improved livestock management. To that end, food system innovation hubs in Africa and Asia can accelerate this process. These hubs will share both capital goods and knowledge resources with partners in LMICs, allowing them to access innovations vital to (bio) fortifying local diets and strengthening fragile food systems.

Inclusive Societies

Innovation can help alleviate social exclusion and inequalities in the food system by providing more personal, predictive and preventive nutritious products and services that improve human health. Additionally, inclusive innovations help reduce inequalities by making existing goods and services cheaper and more accessible. A food system transformation would ensure social inclusion for all food system actors, especially women, smallholders and young people. The WEF describes three key actions: link smallholders and SMEs to finance and markets; empower women; and engage youths.

Link smallholders & SMEs to finance and markets: This involves elevating the position of smallholders and SMEs in value chains through access to financial services and market and asset information. We need to see more companies across many sectors developing new business models with the potential to help close the rural and agricultural finance gap affecting smallholder farmers and agri-SMEs.

Empower women: Women make up 43% (World Bank Group 2021) of the agricultural workforce in LMICs, yet less than 20% (World Economic Forum 2021) of the landowners are women. With more equitable agricultural policies towards women, more than 100—150 million (World Bank Group 2021) people could be lifted out of poverty.

For any innovation to truly have an impact on women's empowerment, it needs to have a gender-transformative approach from its very inception. This refers to an approach that explicitly engages women and men to examine, question, and change institutions and norms that reinforce gender inequalities and, through that process, to achieve both economic growth and gender equality (World Food Programme Innovation Accelerator 2020).

Engage youths: The average age of farmers exceeds 60 years in most geographies, and farming is unattractive to most young people (World Health Organization 2021). The younger generation has the potential to combine the introduction of new technologies with learning from traditional methods to solve the food system's biggest challenges. Many organizations, such as the CGIAR, also believe that innovation will help make agriculture more attractive to young people.

To spark social change, hubs can design food systems in a more deliberate manner, with innovations targeted at each of the levers of social change. This can be done through a combination of an inclusive design lens and purposive financing.

4 Concluding Remarks

Not only are food systems complex, each is also unique to the geography and culture it is supposed to nourish. Therefore, a one-size-fits-all solution does not exist, and the approaches used by HICs cannot be expected to work in the same way for LMICs. Our aspiration is that the transformation of underperforming food systems lies in innovation hubs.

As next steps, with country ownership, diverse actors in the food system will collaborate and connect with existing models in a few LMICs, such as India, Rwanda and Nigeria, and then build cohesive food system innovation hubs for scale and sustainability. Operating in a variety of different locations, these hubs will be able to mold themselves to the needs of their specific nations and communities by engaging directly with their people, culture, entrepreneurial talent, and unique climate. This will be achieved by focusing on three key actions: Inspire! Invest! Innovate!

Inspire!
Hubs can encourage outstanding food and technology companies to expand into LMICs, with the goal of growing market interest, aligning with a range of investors, and developing and testing new products.

Invest!
Hubs can facilitate investment in local companies that have the potential to scale, as well as in technology transfer, nutrition, food safety, and consumer studies to prove market viability and identify latent demand for nutritious foods.

Innovate!
Hubs stimulate innovation throughout the value chain in a manner tailored to LMIC markets and draw additional investment into scaling up and innovating new technologies. This will be especially impactful to the SMEs and start-ups that dominate food production in these markets today. These SMEs also face unique constraints compared to their developed-nation peers.

Food system innovation hubs are bold initiatives that will accelerate innovation, streamline processes, support nature-positive, biodiverse agriculture, build sustainable supply chains, and create a consumer pull for healthy foods to better nourish the nations and communities they serve.

References

Advisory Board (2020) CMS: US health care spending will reach $4T in Version Current 03 April 2020. Internet: https://www.advisory.com/daily-briefing/2020/04/03/health-spending. Accessed 02 Mar 2021

Afshin A, Sur PJ, Fay KA, Cornaby L, Ferrara G, Salama JS et al (2017) Health effects of dietary risks in 195 countries, 1990–2017: A systematic analysis for the Global Burden of Disease Study. Lancet 393(10184):1958–1972. Internet: https://www.thelancet.com/article/S0140-6736(19)30041-8/fulltext. Accessed 12 Mar 2021

Arneth A et al (2019) Summary for policymakers. In: Masson-Delmotte V et al (eds) Special Report on Climate Change and Land. IPCC, WMO

Baker S (2020) Global ESG-data driven assets hit $40.5 trillion. Internet: https://www.pionline.com/esg/global-esg-data-driven-assets-hit-405-trillion. Accessed 02 Mar 2021

Ball D et al (2018) Network-centered innovation to fuel food system change. Sight Life Mag 32(1). Internet: https://sightandlife.org/wp-content/uploads/2018/08/SightandLifeMagazine_ProductInnovation_2018_Networked-centeredInnovationtoFuelFood-SystemChange.pdf. Accessed 15 Mar 2021

Beesabathuni K, Lingala S, Kraemer K (2018) Increasing egg availability through smallholder business models in East Africa and India. Matern Child Nutr 14(S3):e12667. https://doi.org/10.1111/mcn.12667. Internet: https://pubmed.ncbi.nlm.nih.gov/30332537/. Accessed 12 Mar 2021

Béné C, Oosterveer P, Lamotte L, Brouwer ID, Haan S, Prager SD et al (2019) When food systems meet sustainability–Current narratives and implications for actions. World Development (113): 116–130. Internet: https://www.sciencedirect.com/science/article/pii/S0305750X18303115. Accessed 12 Mar 2021

Bora S, Kowatsch B, Desai N (2020) How food innovation hubs will scale technology to transform our food system. World Economic Forum, Geneva. Internet: https://www.forbes.com/sites/worldeconomicforum/2020/11/20/how-food-innovation-hubs-will-scale-technology-to-transform-our-food-system/?sh=5c93717b5363. Accessed 18 Mar 2021

Busby G, Macpherson S (2020) Improving Portfolio Diversification with Uncorrelated Market Exposure. Internet: https://www.nuveen.com/en-us/institutional/thinking/alternatives/improving-portfolio-diversification-with-uncorrelated-market-exposure. Accessed 03 Mar 2021

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 2:198–209. Internet: doi:10.1038/s43016-021-00225-9. Accessed 10 Mar 2021

Davies M, Macpherson S (2020) Why farmland now? Amidst unprecedented market volatility, a durable and consistent investment with compelling upside. Internet: https://www.nuveen.com/global/thinking/alternatives/why-farmland-now. Accessed 03 Mar 2021

FAO, IFAD, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world. Transforming food systems for affordable healthy diets. UN Food and Agriculture Organization, Rome. Internet: https://www.fao.org/documents/card/en/c/ca9692en/. Accessed 12 Mar 2021

Farm Together (2021) What sets farmland apart from other investment options. Version current 18 March 2021. Internet: https://farmtogether.com/why-farmland. Accessed 22 Mar 2021

Florida R, Hathaway I. (2018) Rise of the global startup city: the new map of entrepreneurship and venture capital. Internet: https://startupsusa.org/global-startup-cities. Accessed 10 Mar 2021

Foley J, Ramankutty N, Brauman K, Cassidy ES, Gerber JS, Johnston M et al (2011) Solutions for a cultivated planet. Nature 478:337–342. Internet: https://doi.org/10.1038/nature10452. Accessed 02 Mar 2021

FAO (2010) Women in Agriculture: closing the gender gap for development.. UN Food and Agricultural Organization of the United Nations, Rome. Internet: http://www.fao.org/3/i2050e/i2050e02.pdf. Accessed 18 Mar 2021

FAO (2019a) Promoting youth engagement and employment in agriculture and food systems — e-consultation on the Report's scope, proposed by the HLPE Steering Committee. UN Food and Agricultural Organization of the United Nations, Rome. Internet: http://www.fao.org/fsnforum/cfs-hlpe/discussions/youth_engagement_employment. Accessed 18 Mar 2021

FAO (2019b) The State of Food and Agriculture: Moving forward on food loss and waste reduction. Version Current.. UN Food and Agricultural Organization of the United Nations, Rome. Internet: https://www.fao.org/3/ca6030en/ca6030en.pdf. Accessed 12 Mar 2021

Frank S, Halvik P, Soussana JF, Levesque A, Valin H, Wollenberg E et al (2017) Reducing greenhouse gas emissions in agriculture without compromising food security? Environ Res Lett 12:105004. Internet: https://iopscience.iop.org/article/10.1088/1748-9326/aa8c83/meta. Accessed 03 Mar 2021

Gao L, Bryan BA (2017) Finding pathways to national-scale land-sector sustainability. Nature 544(7649):217–222. Internet: https://doi.org/10.1038/nature21694. Accessed 04 Mar 2021

Gursel A (2014) Science and technology parks and university collaborations. Periodicals Eng Natl Sci2:35–40. Internet: https://doi.org/10.21533/pen.v2i2.41. Accessed 18 Mar 2021

Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC et al (2014) Climate change mitigation through livestock system transitions. Proc Natl Acad Sci USA 111:3709–3714. Internet: https://www.pnas.org/content/111/10/3709. Accessed 10 Mar 2021

Herrero M, Thornton PK, Mason-D'Croz D, Palmer J, Benton TG, Bodirsky BL, et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1:266–272. Internet: https://doi.org/10.1038/s43016-020-0074-1. Accessed 04 Mar 2021

Ittersum MK, Bussel LGJ, Wolf J, Grassini P, Wart J, Guilpart N et al (2016) Can sub-Saharan Africa feed itself? Proc Natl Acad Sci U S A 113:14964–14969. Internet: https://www.pnas.org/content/113/52/14964. Accessed 17 Mar 2021

Katz B, Wagner J (2014) The rise of innovation districts: a new geography of innovations in America. Brookings. Internet: https://www.brookings.edu/essay/rise-of-innovation-districts/. Accessed 15 Mar 2021

Lane JN, Ganguli I, Gaule P, Guinan EC, Lakhani KR (2019) Engineering serendipity: when does knowledge sharing lead to knowledge production? Harvard Business School Working Paper, No. 20–058, 2019. (Revised July 2020.) Internet: https://www.hbs.edu/ris/Publication%20Files/20-058_39f454e9-bef0-4bed-bfa8-526e90601ade.pdf. Accessed 18 Mar 2021

Lockyer S, White A, Buttriss JL (2018) Biofortified crops for tackling micronutrient deficiencies – what impact are these having in developing countries and could they be of relevance within Europe? Nutr Bull 43:319–357. Internet: https://onlinelibrary.wiley.com/doi/full/10.1111/nbu.12347. Accessed 03 Mar 2021

OECD (2021) Fiscal sustainability of health systems: bridging health and finance perspectives. Version current 24 September 2015. Organisation for Economic Co-operation and Development, Paris. Internet: https://www.oecd.org/publications/fiscal-sustainability-of-health-systems-9789264233386-en.htm. Accessed 02 Mar 2021

Results for Development (2021) Scaling innovations. Version current 19 March 2021. Internet: https://r4d.org/how-we-work/scaling-innovations/. Accessed 22 Mar 2021

Ringel M, Baeza R, Panandiker R, Johann-Harnoss, Boston (2020) Consulting Group. In Innovation, big is back: the most innovative companies 2020. Internet: https://www.bcg.com/en-in/publications/2020/most-innovative-companies/large-company-innovation-edge. Accessed 18 Mar 2021

Rockström J, Edenhofer O, Gaertner J, De Clerck F (2020) Planet-proofing the global food system. Nat Food 1(1):3–5. Internet: https://doi.org/10.1038/s43016-019-0010-4. Accessed 04 Mar 2021

Rosegrant MW, Koo J, Cenacchi N, Ringler C, Robertson RD, Fishe M, et al (2014) Food security in a world of natural resource scarcity the role of agricultural technologies (International Food Policy Research Institute. Internet: https://www.ifpri.org/publication/food-security-world-natural-resource-scarcity-role-agricultural-technologies. Accessed 02 Mar 2021

Rubin D, Manfre C, Barrett KN (2009) Promoting gender equitable opportunities: Why it matters for agricultural value chains. The United States Agency for International Development (USAID). Internet: https://culturalpractice.com/wp-content/uploads/4-2009-16.pdf. Accessed 18 Mar 2021

Searchinger T, Waite R, Hanson C, Ranganathan J (2019) Creating a sustainable food future: a menu of solutions to feed nearly 10 billion people by 2050. World Resources Report 2019. Internet: https://research.wri.org/sites/default/files/2019-07/WRR_Food_Full_Report_0.pdf. Accessed 04 Mar 2021

Sherrick B (2020) TIAA Center for Farmland Research. The relationship between inflation and farmland returns. Internet: https://farmland.illinois.edu/wp-content/uploads/2020/10/Relationship-between-inflation-and-farmland-returns.pdf. Accessed 03 Mar 2021

Shukla PR, Skea J, Calvo BE, Masson-Delmotte V, Pörtner HO, Roberts DC et al (2019) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC

Sight and Life (2019) Sight and life nutrition kiosk: reaching the last mile in India. Version current. Internet: https://sightandlife.org/blog/sight-and-life-nutrition-kiosk/#:~:text=The%20Nutrition%20Kiosk%2C%20a%20Sight,and%20services%20for%20vulnerable%20populations. Accessed 15 Mar 2021

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L, et al (2018) Options for keeping the food system within environmental limits. Nature 562:519–525. Internet: https://doi.org/10.1038/s41586-018-0594-0. Accessed 16 Mar 2021

Startup Scene (2021) Kuwait inaugurates its first large-scale indoor vertical farm. Version current 27 August 2020. Internet: https://thestartupscene.me/MenaEcosystems/Kuwait-Inaugurates-Its-First-Large-Scale-Indoor-Vertical-Farm. Accessed 02 Mar 2021

Swinburn BA, Kraak VI, Allender S, Atkins VJ, Baker PI, Bogard JR et al (2019) The global syndemic of obesity, undernutrition, and climate change: The lancet commission report. Lancet 393(10173):791–846. No link and accessed date? Internet: https://pubmed.ncbi.nlm.nih.gov/30700377/. Accessed 12 Mar 2021

The Grocer (2021) Insect protein start-up raises $372m to fund world's largest insect farm. Version current 08 October 2020. Internet: https://www.thegrocer.co.uk/fundraising/insect-protein-start-up-raises-372m-to-fund-worlds-largest-insect-farm/649164. Accessed 02 Mar 2021

Union of Concerned Scientists (2021) Environmental impacts of solar power. Internet: https://www.ucsusa.org/resources/environmental-impacts-solar-power. Accessed 23 Mar 2021

United Nations Industrial Development Organization (2021) Government of the Republic of Slovenia. Conference report: fostering inclusive and sustainable local industrial development in Europe and Central Asia — the role of science, industrial and technology parks. Version current 8 April 2014. Internet: https://www.unido.org/sites/default/files/2015-12/SITP_Slovenia_Conference_Report_0.pdf. Accessed 18 Mar 2021

van Huis A, Oonincx DGAB (2017) The environmental sustainability of insects as food and feed. A review. Agron Sustain Dev 37. https://doi.org/10.1007/s13593-017-0452-8

Villa M. (2017) Women own less than 20% of the world's land. It's time to give them equal property rights. World Economic Forum, Geneva. Internet: https://www.weforum.org/agenda/2017/01/women-own-less-than-20-of-the-worlds-land-its-time-to-give-them-equal-property-rights/#:~:text=rights%20to%20land. Accessed 23 Mar 2021

Wennovation Hub (2018) The future of tech hubs in Nigeria. Internet: https://medium.com/@wennovation/the-future-of-tech-hubs-in-nigeria-5fcd76e16a05. Accessed 10 Mar 2021

Willett W, Rickstrom J, Loken B, Springman M, Lang T, Vermeulen S et al (2019) Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393 (10170); 447–429. Internet: https://doi.org/10.1016/S0140-6736(18)31788-4. Accessed 04 Mar 2021

World Bank Group (2021) Open learning campus. Internet: https://olc.worldbank.org/content/supporting-regional-innovation-hubs-nigeria-0. Accessed 1 Mar 2021

World Economic Forum (2021) Innovation with a purpose: food innovation hubs. World Economic Forum, Geneva. Internet: https://www.weforum.org/projects/innovation-with-a-purpose-strengthening-food-systems-through-technology. Accessed 18 Mar 2021

World Food Programme Innovation Accelerator (2020) About us. Version current 2020. Internet: https://innovation.wfp.org/. Accessed 18 Mar 2021

World Health Organization (2019) Global spending on health: a world in transition, WHO/HIS/HGF/HF Working Paper/19.4. World Health Organization, Geneva. License: CC BY-NC-SA 3.0 IGO

World Health Organization (2021) Global spending on health: A world in transition. Version current 12 December 2019. Internet: https://www.who.int/health_financing/documents/health-expenditure-report-2019.pdf. Accessed 12 Mar 2021

A Whole Earth Approach to Nature-Positive Food: Biodiversity and Agriculture

Fabrice A. J. DeClerck, Izabella Koziell, Tim Benton, Lucas A. Garibaldi, Claire Kremen, Martine Maron, Cristina Rumbaitis Del Rio, Aman Sidhu, Jonathan Wirths, Michael Clark, Chris Dickens, Natalia Estrada Carmona, Alexander K. Fremier, Sarah K. Jones, Colin K. Khoury, Rattan Lal, Michael Obersteiner, Roseline Remans, Adrien Rusch, Lisa A. Schulte, Jeremy Simmonds, Lindsay C. Stringer, Christopher Weber, and Leigh Winowiecki

What Evidence Is There?
Healthy diets require dietary diversity, which requires greater crop diversity and agricultural biodiversity supporting production. **Enhancing production of more diverse foods can be a win-win solution for both improved nutrition and biodiversity [*High Agreement, Robust Evidence*]**.

F. A. J. DeClerck (✉) · A. Sidhu · N. E. Carmona · S. K. Jones · C. K. Khoury · R. Remans
Alliance of Bioversity and CIAT, CGIAR, Montpellier, France
e-mail: f.declerck@cgiar.org

I. Koziell
The International Centre for Integrated Mountain Development (ICIMOD), Lalitpur, Nepal

T. Benton
Chatham House, London, UK

L. A. Garibaldi
Universidad National de Rio Negro, Bariloche, Argentina

C. Kremen
University of British Columbia, Vancouver, BC, Canada

M. Maron
University of Queensland, Brisbane, QLD, Australia

C. R. Del Rio
Global Commission on Adaptation, World Resources Institute, Washington, DC, USA

J. Wirths
CGIAR Research Program on Water Land and Ecosystems, Colombo, Sri Lanka

M. Clark
Nuffield Department of Population Health and Department of Zoology, University of Oxford, Oxford, UK

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_25

It is possible to produce healthy diets for 10 billion people and halt the loss of biodiversity, securing its contribution to climate regulation and other planetary boundaries, despite significant challenges and trade-offs in several regions of the world, especially in developing economies [***High Agreement, Medium Evidence***].

Agriculture currently occupies 40% of the global land surface. At ***least*** 10–20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably, pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. **Today, between 18–33% of agricultural lands have insufficient biodiversity to provide those services, an unacceptable risk for food security.**

Agriculture thus needs a multipronged approach. This requires a shift towards regenerative production systems that deliver more diversified diets, coupled with strict conservation of intact habitats. Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems. Regenerative agricultural practices can generate additional critical ecosystem services by maintaining biodiversity in agricultural lands. **At scale, these practices offer the potential to sequester 4.3–6.9 Gt CO2e year^{-1} year [*Medium Agreement, Medium Evidence*], retain $>$ 30% environmental flows in major water to**

C. Dickens
International Water Management Institute, Colombo, Sri Lanka

A. K. Fremier
Washington State University, Pullman, WA, USA

R. Lal
Member of the Scientific Group of the UN Food Systems Summit 2021, Ohio State University, Columbus, OH, USA

M. Obersteiner
Environmental Change Institute, University of Oxford, Oxford, UK

A. Rusch
l'institut national de recherche pour l'agriculture (INRAE), Villenave d'Ornon, France

L. A. Schulte
Natural Resource Ecology and Management, Iowa State University, Ames, IA, USA

J. Simmonds
University of Queensland, Brisbane, QLD, Australia

L. C. Stringer
Department of Environment and Geography, University of York, York, UK

C. Weber
Global Climate and Energy, WWF, Washington, DC, USA

L. Winowiecki
World Agroforestry Center, CGIAR, Nairobi, Kenya

basins [*High Agreement, Limited Evidence*], create 12–17 M km^2 of habitat for biodiversity [*High Agreement, High Evidence*] and increase connectivity for biodiversity [*High Agreement, Limited Evidence*]. There is no evidence that diversified production systems compromise food security – many agricultural diversification practices provide multiple complementary benefits [*High Agreement, High Evidence*].

Halting the expansion of agriculture into intact nature is necessary to achieve zero net loss of biodiversity and secure the critical Earth system functions that nature provides. Ecosystems covering half of the global land surface are currently intact, although these are largely within desert, boreal and tundra biomes. Halting extinction loss will require the retention of most remaining intact ecosystems across ice-free areas. **Regulating regional water cycles and achieving the Paris Climate Agreement (including climate mitigation targets) while halting biodiversity loss requires retaining at least 50% intact nature [*Medium Agreement, Robust Evidence*].**

Global goals, whether the SDGs, the Paris Climate Agreement, or the Convention on Biological Diversity, have repeatedly emphasized the urgent and critical need to halt emissions and accelerate carbon sequestration opportunities. Investing in context-specific research and development (R&D) aligned with global goals while building local capabilities and capacities is critical. While global models remain helpful in setting pathways and understanding the urgency and ambition needed, they need to be complemented with demand-driven R&D for farmer and pastoralist communities that provides them with flexibility and adaptive capacity without compromising their livelihoods.

In light of the vulnerabilities to climate and environmental change in LMICs and increases in all forms of malnutrition, including rapid transitions to unhealthy diets, there is a need for a much greater investment in diversified farming systems that meet societal goals, with increased resilience to climate and environmental change. While society still hopes to achieve climate stability, the impacts of climate change and environmental degradation are manifesting and should be anticipated to persist and worsen for several decades. Farming systems must be designed to be resilient to anticipate change, while simultaneously contributing to building back better: sinking GHGs, producing foods that contribute to the dietary health of local and regional communities, and regenerating environmental goods. Diversified farming systems are a critical strategy for adapting to anticipated change and mitigating impacts while building back better. Investing in nature-positive or circular production systems, which can prevent waste and leakage while supporting reuse, regenerative agroecological systems, complex rotations and mixed farming are “no regrets” investment options.

Investment in food policy is also urgently needed. All too often, the onus of profitability is placed on farmers and farming systems to drive important improvements in efficiency, but at environmental, social and climate costs that are becoming increasingly evident. Investment in a better understanding of how food policy, markets and supply chains enable regenerative and diversified systems to be profitable is urgently needed. This includes greater research on and investment in market systems and value chains, but also agricultural tools and technologies that reduce the drudgery of diversified production and increase labor efficiencies in particular.

In light of the vast environmental footprint of agriculture, the broader food system must be a key part of the solution to the intertwined challenges of biodiversity loss, climate change and human health. Siloed visions of agricultural systems being independent of the natural world and somehow exonerated from environmental responsibilities are no longer compatible with global goals on food and nutritional security, climate security, environmental security and livelihood security. **Thus, the first step is for policymakers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This demands thinking about 'food system productivity,' rather than agricultural productivity,[5] and requires all sectors of government to break out of their own conceptual silos and institutional structures.**

In considering the relationship between agriculture and biodiversity, several key areas for investment emerge: (i) closing the gap between the current composition of crop production and consumption to supply healthy diets at the local, regional and global scales in line with SDG2 and SDG3; (ii) transitioning to managing agricultural systems as ecological systems (agroecosystems); (iii) greater inclusion and recognition of farmers as key actors, with women, youths and indigenous farmers bringing unique knowledge systems and capabilities to bear in food production.

Food security should not be prioritized above other critical goals: nutritional, climate, environmental and livelihood security. Treating these areas solely as inevitable trade-offs fails to recognize important areas of synergy. Making the transition to food production systems that actively take account of and are synergized with biodiversity goals will require significant transitions in the policy landscape. Agriculture needs to be more strongly integrated into global agreements and policies on environment and health. Given that almost 20% of the global dietary energy supply is derived from imported foodstuffs, trade policy also needs to take better account of its impact, creating greater space for diversification of commodities, supporting the conservation of intact ecosystems, and including a consideration of environmental goods and services.

Current agricultural investments and practices often overlook the important potential for increasing ecosystem services that agroecosystems can provide (Wood et al. 2018), with an estimated 7% of innovation spending explicitly targeting environmental outcomes (CoSAI 2021). Farmers and farming communities can produce public goods (e.g., climate mitigation, soil water-holding capacity, water quality improvement), but promoting these public good functions has been consistently underexplored and under-resourced, even though they are also necessary for creating sustainable and resilient production systems. Recognizing that farmers and farmlands can produce these benefits in addition to quality food presents an opportunity for revitalizing rural communities by repurposing public funds for public goods and services. Diversification strategies can be applied in a range of contexts and would benefit from investment in technologies, tools, markets and incentives that increase and improve employment opportunities, reduce the drudgery of food production and provide greater autonomy to producers**.**

During the next decade, priority approaches to diversify production systems should target:

- Urgent investments in undervalued crops and cropping systems, notably, underproduced crops that underpin dietary health and indigenous cropping and knowledge systems;
- Greater investment in tools, technologies and enabling environments that amplify and/or complement biodiversity's contribution to agriculture, rather than seeking to replace it;
- Repurposing policies and public and private agriculture funds to support farmers producing public goods, including the production of healthy foods, carbon capture, clean water and habitat for biodiversity.

A coordinated, transformational adjustment of policies, incentives, regulations and other public sector instruments is needed to make healthy and sustainable food affordable and available for all and enable farmers and farming communities to gain greater recognition, reward and payments for actions that produce healthy foods or environmental benefits.

Achieving food, nutrition, climate and environmental goals can occur if a policy framework is developed that takes a whole system perspective. This means valuing not just the amount of production, but production of healthy foods with low or regenerative environmental impacts. **This perspective necessarily incorporates reducing food waste, encouraging good eating habits low on the food chain, and providing access to a diversity of nutritious foods for low-income communities globally [*High Agreement, Robust Evidence*].**

1 Introduction

It is widely recognized that a major transformation of food systems is urgently needed if we are to achieve food and nutrition security globally, *while also* meeting global climate, biodiversity and health targets. What foods people eat, how and where it is produced, as well as how much is wasted and lost, have a significant impact on human and planetary health, including 11 million premature deaths, over 30% of global greenhouse gas (GHG) emissions, 70% of freshwater use and 80% of land conversion driving biodiversity loss. Paradoxically, while agriculture is currently the largest single source of environmental degradation and biodiversity loss, it is also likely to be the biggest victim of this degradation – the conversion of natural ecosystems into croplands and pastures, coupled with the impacts of agricultural pollution, severely threaten vital ecosystem services that underpin agriculture itself (Rockström et al. 2020).

Agroecology, *as an ecological science, focuses on the contribution of* ***biodiversity*** *to enhancing the generation of ecosystem services to and from agriculture with the aim of* ***regenerating*** *these services. Diversification, agro-ecological, or regenerative agricultural practices are overlapping and include a diversity of management options from fields to landscapes (Source: Report Authors).*

FAO and the HLP Report #14 (FAO-HLPE 2019) *on "Agroecological and other innovative approaches" suggests a concise set of 13 agroecological principles related to: recycling; reducing the use of inputs; soil health; animal health and welfare; biodiversity; synergy (managing interactions); economic diversification; co-creation of knowledge (embracing local knowledge and global science); social values and diets; fairness; connectivity; land and natural resource governance; and participation.*

2021 signals a pivotal year for the agricultural community. Major events such as the United Nations Food Systems Summit (UNFSS), the UNFCCC COP26, the UNCBD COP15, and the launch of the UN Decade of Ecosystem Restoration offer a real chance to make a step change towards the necessary transformation of our food systems – so they can become more sustainable and equitable and deliver affordable, healthy and nutritious food for all. Ensuring that there is a clear pathway for addressing biodiversity in all this, as well as highlighting its inextricable links to agriculture, is essential, given growing evidence that food system interventions have the potential to become the single largest solution space for both human and planetary health (Rockström et al. 2020).

1.1 Biodiversity Is Inextricably Linked to Food and Agriculture

Covering approximately 40% of the global land surface, agricultural ecosystems (including rangelands) comprise the world's largest terrestrial ecosystem, albeit a highly modified and heterogenous one. Biodiversity in agricultural ecosystems, as in natural ecosystems, is highly threatened, and this has very real consequences for the resilience and sustainability of both the production of food and environmental goods and services generated on agricultural lands and in water. The reduction of biodiversity in agriculture diminishes the ecosystem functions that contribute to local, regional and, when scaled, global processes. To ensure environmental and climate security by 2030, a transition is necessary toward treating agricultural lands as ecosystems, or as 'agroecosystems,' and greater investment in research, practices, technologies and incentives that reward the efforts of farmers just as much for the environmental services they produce as for the foods they produce.

Which and how much of the diversity of available foods we eat, and in what quantities, plays a key role in human health. Yet today, nearly half of the world's population struggles to access or afford either enough food or food that is healthy. Global progress against SDG2 – Zero Hunger – has stalled over the last few years, with current estimates showing that nearly 9 percent (690 million) of the world's population go hungry – up by 10 million people in 1 year and by nearly 60 million in 5 years (FAO I, UNICEF, WFP, and WHO 2020). Global food supply also falls alarmingly short of providing a low health-risk diet: nearly 2 billion struggle with hunger and malnutrition; another 2 billion struggle with diseases related to overconsumption (Global Panel on Agriculture and Food Systems for Nutrition 2020).

Producing healthy diets sustainably is dependent on biodiversity. Decades of research demonstrate that 'sharing space' for biodiversity on agricultural lands is logical and cost-effective for many reasons. The most notable example is our increasing dependence on pollinators to produce the foods that underpin healthy diets. Other examples of agriculture's dependence on biodiversity include: its roles in pest and disease regulation, in building resilience to shocks through crop and intra-species diversity, and in protecting the water cycle and maintaining soil health. However, investments in the kinds of agricultural practices that will build on and enhance these kinds of biodiversity benefits are severely lacking, including in modernizing and time-saving technologies that can increase biodiversity's contribution to production.

Tackling the global-scale challenges of stabilizing global climate, regulating regional water cycles and halting the extinction crisis is dependent on sparing sufficient intact nature from conversion across all biomes. Avoiding any further loss of intact nature is vital, particularly by halting ongoing conversion of land to agriculture, as called for by the Convention on Biological Diversity (CBD) Target 1, "ensuring that all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, *retaining existing intact and wilderness areas."* Achieving these goals requires active contributions from agriculture, starting with the recognition that environmental and climate security are equally non-transgressible goals, along with food and nutritional security. Increasing the productivity of agricultural lands, shifting to nature-positive practices, reducing food waste and loss, and fostering more sustainable diets are four ways in which food systems contribute to CBD conservation targets.

1.2 Reconfigure Biodiversity in Agriculture to Meet Food, Nutrition, Climate and Water Security Targets

Over the last decade, multiple global reviews, commissions and academic papers have argued for more sustainable and healthy food, farming and agriculture. Promoting biodiversity in diets, in farms and fields, and in intact nature makes essential contributions to these goals. International policy frameworks that support this change include the Paris Agreement (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD), the CBD and the SDGs.

In response, bold biodiversity targets to halt the loss of area and intactness of nature and securing nature's contributions to people are being set by the CBD in 2021. Achieving these targets is a prerequisite for food, nutrition, climate and water security, in addition to halting the ongoing extinction crisis. According to the Global Biodiversity Outlook 5, we have failed to meet the 2020 Aichi Biodiversity targets (Díaz et al. 2020; Diversity 2020). This failure points to the need for an urgent rethink and transformation of the relationships among food, agriculture and biodiversity (Rockström et al. 2020; Leclère et al. 2020) if we are to succeed in reaching the 2030 targets.

1.3 Shifting from Crop Productivity to Systemic Productivity

While food production has increased over recent decades, this trend masks an underlying decline in ecosystem services that underpin production (Brauman et al. 2020), including pest and disease regulation, pollination and soil fertility. This rise in productivity similarly masks an alarming decline in dietary health across countries with different income statuses. The focus on crop productivity has fueled a false dichotomy between conservation and production that may have critical consequences for environmental and climate stability. This approach will ultimately also have negative effects on future food production and distribution. Transforming the objective outcomes of agriculture to encompass environmental and human health objectives is a first, and necessary, step in realigning food across multiple global goals. This requires refocusing food from yields per unit input to the food system's overall productivity and efficiency, or the number of people that can be fed healthy diets sustainably per unit input (Benton and Bailey 2019; Remans et al. 2014; DeFries et al. 2015).

1.4 Critical Actions for Reconciling Agriculture and Biodiversity

There is considerable evidence available about *what* needs to change in the food and agriculture system to enable nutritional, climate, environmental and livelihood security, and that innovative solutions can emerge when these goals are considered as equally non-transgressible. There is similarly substantial biophysical evidence that food and agriculture can provide healthy diets while contributing to environmental restoration and regeneration. **But there is still insufficient evidence indicating and understanding *how* to make the necessary social, political, economic and agronomic transformations urgently**. Much of the challenge lies in the siloed nature of policy and innovation, as well as entrenched political economies of food. Recognizing the role that agriculture plays within the Earth system, as an ecosystem; considering the dietary health impacts of food; and recognizing and utilizing the dependencies of agriculture on biodiversity for agroecosystem services suggests the need for agricultural systems that are radically different from those we have today.

In this review, we have attempted to provide the best available evidence of agriculture's relationships with biodiversity. This spans many dimensions of agriculture and biodiversity, including:

- The diversity of food in our diets and calls for production systems to increase that diversity as a contribution to public health. Evidence indicates that there is ample scope to increase the diversity of foods produced in order to improve dietary health, with concomitant benefits for agricultural biodiversity.
- The dependency of food production for healthy diets on in-field and on-farm biodiversity, focusing on five core contributions: (i) genetic diversity of seeds and breeds, (ii) soil fertility, (iii) water, (iv) pollination, and (v) pest control and the risks of technologies and practices that replace, rather than amplify, these contributions.
- The role that in-field, on-farm, and around-farm biodiversity plays in securing non-food-related ecosystem services from agriculture, notably, climate mitigation, regulation of local and regional water fluxes and water quality.
- Halting the expansion of agriculture into intact nature to achieve zero net loss of biodiversity and secure the critical Earth system functions that nature provides.

We have not covered livelihood security here, although we find no evidence that better integration of biodiversity in agriculture reduces the opportunities to create more meaningful and remunerative livelihoods in agriculture. There is recent and growing evidence, however, that small and medium fields and farms are better able to integrate biodiversity without compromising yield (Ricciardi et al. 2021).

We present five critical challenges to agriculture in relation to biodiversity that, borrowing from the Science Based Targets Network (SBTN), suggests that this interaction can be conceived as an **AR^{3}T** 'mitigation classification,' with targets aligned to the forthcoming CBD Kunming objectives (Fig. 1):

- **Avoid** continued land expansion into intact nature to secure nature's essential contribution to climate mitigation, aiming for 30% protected and $>$ 50 intact.
- **Restore** intact nature where possible, prioritizing those areas that have been degraded, have high climate mitigation or have biodiversity conservation potential in line with no net loss as of 2020, restoration in 2030, and full recovery by 2050, contributing to biodiversity conservation, climate mitigation, and regional hydrological flow regulation.
- **Reduce** the impacts of agriculture on biodiversity, notably by halting the losses of nutrients, biocides, and other pollutants to air, soil and water.
- **Regenerate** the ecosystem services provided by biodiversity in all agricultural lands everywhere, retaining, at *minimum,* 10% habitat per km^2 within agriculture. We note that 20% is a much lower risk boundary.

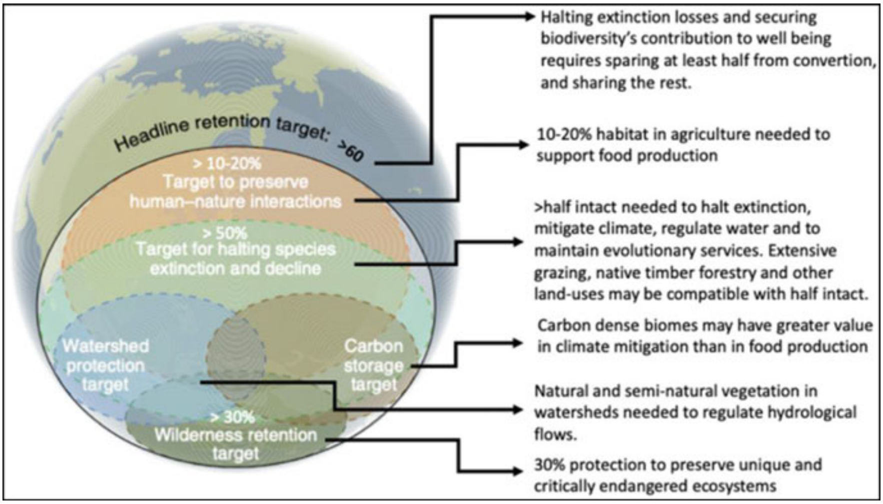


Fig. 1 Bold biodiversity targets are required to halt the loss of biodiversity and to secure biodiversity's contributions to Earth system and ecosystem processes (Maron et al. 2018). Several studies (Willett et al. 2019; Maron et al. 2018; Newbold et al. 2016; Dinerstein et al. 2017; DeClerck et al. In Review), using distinct methodologies, find that approximately half the Earth's land surface remains intact, making 'half intact' the equivalent of a no-net-loss target (CBD Goal A, Target 1). We define intactness here as a measure of biodiversity status measured as the relative abundance of originally present species or level of human pressures. Combined actions to avoid loss, restore intact nature, reduce impacts of human activities on nature, regenerate ecosystem service production through nature-positive production, and transform agricultural policies and actions are needed to maintain a safe environmental space for humanity (Rockström et al. 2020, 2021). (Figure adapted from Maron et al. 2018)

- **Transform** the food system by creating the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional securities (Willett et al. 2019; Rockström et al. 2009; Steffen et al. 2015).

2 Healthy Diets Require Dietary Diversity

Take-Home Messages

- Lack of dietary diversity is a primary cause of diet-related disease and mortality.
- Shifting to increased consumption of fruits, nuts, vegetables and whole grains and healthy consumption of a diversity of meats could avert 11 million premature deaths per year.
- Shifting to healthy, plant-rich diets could avert per capita GHG emissions from crop and livestock production by 32% from 2009 to 2050, and lead to a 20% decrease in the land needed to meet consumption demand, in line with the CBD goal of no net loss of nature by 2050.

- Modern plant breeding threatens traditional crop varieties and crop wild relatives, but is completely dependent on the genetic diversity that they represent.

2.1 The Diversity of Foods Produced and Available Is Insufficient for Healthy Diets

While there is no single solution to the hunger and dietary health challenges afflicting nearly half the global population, low dietary diversity is a common thread. Only around 130 internationally significant food plants – including 20 cereal crops, 7 roots and tubers, 28 fruits, 19 vegetables, 11 pulses, 8 nuts, 16 oils, 15 herbs and spices, 2 sugars and 3 stimulants – make up the bulk of peoples' diets around the world. In addition, just 15–20 major domesticated land animals are used in food and agriculture (Bélanger and Pilling 2019).

Food diversity is as much about choice as it is about health. There is robust evidence showing that, while we produce enough food to meet the caloric needs of today's global population, current production systems fail to provide a healthy diet for all because of underproduction of food diversity. Global analyses of regional trends signal a nearly universal underconsumption of fruits, nuts, vegetables, whole grains and seeds; with regional patterns of over- and underconsumption of red and processed meat; and equally variable consumption of legumes (Afshin et al. 2019). High-sodium, low-diversity diets are the leading cause of mortality attributed to diet, accounting for an estimated 11 million premature deaths per year (Willett et al. 2019).

Global production and the availability of foods are fundamentally mismatched with recommended healthy consumption patterns (Willett et al. 2019; Kc et al. 2018). Ensuring healthy diets for all by 2050 requires an important shift in what foods are produced and consumed, including no significant increase in cereal production coupled with significant increases in vegetables, legumes, fruit, fish, nuts and seeds and a large reduction in red meat production and consumption globally (Afshin et al. 2019) – although, in some regions, meat consumption could be increased to counter nutritional deficiencies such as iron-deficient anemia (Golden et al. 2011) (Table 1). Increasing the diversity of animal-sourced proteins, notably, of healthier and often less energy intensive fish, shellfish, and poultry proteins, is consistently underexplored in discussions on shifts towards healthy and sustainable diets (see the UNFSS Blue Foods and Livestock Reports).

2.2 Healthy Diets Include a Wide Range of Choices

At least five major food groups, and thus, at minimum, 4–5 species, are required in a healthy diet, with whole grains, fruits, vegetables, oils and protein (plant or animal) being essential (Table 1). The absence of one food group drives critical challenges of

Table 1 Summary of food groups, recommended healthy daily consumption

Food Group	Recommended Per Capita Daily Consumption (g)	Estimated Global Production Change (2050)	Diversity of Species/Varieties
Whole grains	232	0	20 major cultivated species with 850,000 varieties; dozens of minor species; many wild species as well
Tubers or starchy vegetables	0–100	+20%	7 major cultivated species with 25,000 varieties; 12 minor species; various wild species as well
Vegetables	200–600	+75%	19 major cultivated species; 40 minor species; hundreds of wild species as well
Seaweeds	–	–	7 commonly cultivated species, unknown diversity, and contribution to health
Fruits	100–300	+50%	28 major cultivated species; 45 minor species; hundreds of wild species as well
Dairy foods	0–500	+5%	3 major domesticated species.
Red meat	0–28	−65%	4 major cultivated species
Poultry	0–58	+2%	6 major cultivated species
Eggs	0–25	−25%	1 major cultivated species
Fish, shell-fish and crustaceans	0–100		>3200 taxa
Legumes	0–100	+75%	11 major cultivated species with 120,000 varieties; 25 minor species; various wild species as well
Nuts	0–75	+150%	8 major cultivated species; 6 minor species; various wild species as well
Unsaturated oils	20–80		16 major cultivated oil crop species; 15 minor species; various wild species as well
Sugars	0–30		2 major cultivated species; various minor species and wild species as well

Willett et al. (2019) required change in production volume compared to current production to secure low risk diets globally, and approximate diversity of cultivable species.

malnutrition, which are stubbornly persistent in several hotspots requiring emergency assistance or fortification as an intermediate remedy. In both high- and low-income countries, however, increasing dietary diversity, within energetic requirements, would have significant impacts on improved health. Thousands more species, breeds and varieties could support human nutrition. Beyond the 130 odd species that dominate global production and consumption, about 120 other food crops that are less well monitored in production, trade and dietary data have regional significance. Practically nonexistent in food system data are well over 1000 wild plants known to be used, at least occasionally, as human food

(Khoury et al. 2019), and the nutritional value of over 3200 aquatic animal species used as food has been documented, not including growing interest in edible aquatic plants (algae) commonly consumed in Asian diets (Rajapakse and Kim 2011). Seaweeds have largely been unexplored as a more important food source, but present an area of innovation for nutritious food production without land, freshwater, or fertilizer requirements (Bernhardt and O'Connor 2021).

Context will determine whether any single food group is over- or under-consumed. Whole-of-plate approaches that ensure that everyone everywhere has access to a diversity of foods, notably, across food groups, are key to SDGs 2 and 3. While a healthy diet with balanced consumption across food groups is a universal goal, the diversity of foods within food groups offers people the possibility to match foods across the year to environmental contexts, individual tastes and cultural preferences.

2.3 The Demand and Supply of Healthy Diets Contributes to Climate and Environmental Outcomes

Diverse production can bring us closer to planetary health goals. A shift towards healthy diets could reduce per capita emissions from food production between 30% and 50%, while also accounting for a 20% reduction in freshwater consumption and a 20% decrease in the land needed to meet consumption demand (Willett et al. 2019; Clark et al. 2019; Tilman and Clark 2014). Globally, this would mean no net increase in agricultural lands, in line with CBD goals of no net loss of nature by 2050, primarily driven by reduced overconsumption of red meat (Tilman and Clark 2014; Clark et al. 2020).

3 Agriculture Must Share Space with Biodiversity to Meet Global Environmental Goals

Take-Home Messages

- Diversification strategies within fields, between fields and across landscapes are often regenerative, synergistic and multipurpose, and can bolster ecosystem functions within resilient agricultural production systems.
- There is no evidence that diversified production systems compromise food security – many agricultural diversification practices provide multiple complementary benefits.
- At least 10–20% of semi-natural habitat per km^2 is needed to ensure ecosystem functions, notably, pollination, biological pest control and climate regulation, and to prevent soil erosion, nutrient loss and water contamination. Today, 18–33% of agricultural lands are below these respective threshold values for biological integrity.

- Regenerative agricultural practices have the potential to mitigate emissions by 4.3–6.9 Gt CO_2e year^{-1} globally, and agricultural lands represent 47% of the soil carbon climate mitigation potential.
- Agricultural, field and farm biodiversity can reduce agriculture's dependence on water capture and water quality through soil carbon sequestration, on-farm practices and appropriate crop selection.
- Crop wild relatives provide critically important traits to cultivated crops through breeding. Many crop wild relatives are also collected for direct dietary, medicinal and other cultural uses, and various species represent attractive candidates for development into new crops.

3.1 Agriculture Depends on Biodiversity

All agricultural systems depend on biodiversity for crop genetic diversity, pest control, animal-mediated pollination and healthy soils that promote nutrient capture and water delivery for crop growth. Diversified agroecological practices offer numerous opportunities at the field, farm and landscape scales, but are not a panacea. Thoughtful application and integration of novel technologies and practices that complement diversification are required, as well as mitigation of trade-offs such as pest species spilling over from natural or semi-natural habitats (Zhang et al. 2007).

3.2 Diversification Strategies Are Often Regenerative, Synergistic and Multipurpose

Agricultural practices that support biodiversity's contribution to soil nutrients, water, pollination and pest reduction, more often than not, are synergistic (Garibaldi et al. 2020; Tamburini et al. 2020; Garbach et al. 2016; Kennedy et al. 2013; Scheper et al. 2015; Landis et al. 2000; Rusch et al. 2017). Taken with genetic diversity, these ecosystem functions represent critical inputs into production systems globally. The aim of agroecology and diversification practices is to secure and make use of ecosystem services both to and from agriculture (DeClerck et al. 2016). Within the AR3T framework, the aim of diversification is to *regenerate* the ecosystem functions and services both from and to agriculture, while *reducing* its negative impacts, notably, habitat loss and pollution of soil and water (DeClerck et al. 2016).

3.2.1 Diversification Within Fields and Pastures

Replacing low diversity annual systems with higher diversity annual or perennial systems has numerous beneficial impacts on ecosystem functions, for example, by reducing soil nutrient loss to aquatic environments, and extending the portion of the year that crops are actively being grown, thus reducing nutrient leaching. Integrating nitrogen-fixing legumes, either as a harvestable or cover crop, is one of the most common forms of diversification (Duchene et al. 2017; Bedoussac et al. 2015; Ghosh et al. 2007). Crop types have variable water needs and can influence demands on available water resources. Management techniques for promoting carbon sequestration and improving drought resilience include organic residue management, mulching and reduced or no-tillage (Amelung et al. 2020). Excessive use of biocides, nutrient inputs and tillage, in turn, favor soil ecosystems with very high carbon loss and little long-term storage potential (Palm et al. 2014). High-diversity cropping systems can also increase natural enemies of pests upwards of 44%, increase pest mortality by 54% and reduce crop damage by 23% (Letourneau et al. 2011; Cook et al. 2007). In-field diversification provides habitat, alternative hosts, pollen and nectar, as well as overwintering or nesting sites essential to diverse communities of pollinators, predators and parasitoids (Landis et al. 2000; Lichtenberg et al. 2017).

3.2.2 Diversification Between Fields and Pastures

Natural elements such as grassed waterways, riparian buffers, prairie strips, hedgerows, live fences and wetlands incorporated around field and pasture margins are highly effective at capturing excess nutrients. To reduce erosion and regulate water, between-field habitat infrastructure can be complemented with engineered features such as terraces, water and sediment control basins, bioreactors and saturated buffers to control nutrient loss. These features also support pollination (Scheper et al. 2015; Nicholson et al. 2020; Kremen et al. 2019; M'Gonigle et al. 2015; Ponisio et al. 2016) and pest regulation (Letourneau et al. 2011; Shelton and Badenes-Perez 2006; Cook et al. 2007; Tschumi et al. 2015) by providing habitat for pollinating and pest-regulating organisms, can serve as barriers to pest movement (Avelino et al. 2012), or can draw pests out of crop fields (Cook et al. 2007; Pickett et al. 2014). A recent synthesis indicated that the planting of annual flower strips on field borders increases pest control by 16% (Albrecht et al. 2020). Between-field habitats can have added value when they comprise multi-use species that provide fodder, fuel or food, and can be designed to reduce wind or evaporative stress in crops while creating corridors for wild biodiversity.

3.2.3 Landscape Diversification

Even where the most extensive monocultures are practiced, landscape diversification, combined with habitat structures between fields, can have significant positive impacts on many services provided by agricultural biodiversity, notably, hydrological, pest regulation (Avelino et al. 2012; Chaplin-Kramer et al. 2011; Veres et al.

2013; Holland et al. 2017) and pollination services (Kennedy et al. 2013; Dainese et al. 2019; Garibaldi et al. 2011). In contrast, landscape simplification often leads to increased risk of pest infestation (Rusch et al. 2016). Diverse mosaics in agricultural land that include multiple farms and integrate natural areas are required to capture and potentially convert, store or sequester nutrients lost to the environment. Policies, or markets that either support increases in field or farm sizes, and/or concentrate the production of a single crop in a landscape, may increase efficiency, but drive loss of between-field cropping diversity and increase risks.

3.2.4 Agricultural Landscapes Need at Least 10–20% of Diversified Habitats to Retain Ecological Integrity

Proposed targets for nature retention within agricultural landscapes (Willett et al. 2019; Garibaldi et al. 2020) are beginning to be reflected in agricultural policy (Díaz et al. 2020). A conservation target for agricultural ecosystems to retain at least 10–20% of habitat per km^2 has been proposed to maintain ecological integrity in production landscapes (Willett et al. 2019; Maron et al. 2018; DeClerck et al., DeClerck et al. In Review; Garibaldi et al. 2020). The rationale for this target is that the services provided by biodiversity to agriculture are locally produced. Nitrogen fixation by legumes impacts soil fertility at the plant scale (0–10 cm), and pollination and pest control are provided by habitats at a wider scale (0–300 m), occasionally further for honeybees (3000 m) (Willett et al. 2019; DeClerck et al., DeClerck et al. In Review; Garibaldi et al. 2020; Fremier et al. 2013; Tscharntke et al. 2005; Tscharntke et al. 2007). Similarly, interception of sediment and nutrients lost from agriculture by buffers is most effective within tens of meters (Fremier et al. 2013). While specific impacts are highly contextual and difficult to predict, the evidence is clear: in the absence of proximate habitat (<500 m), ecosystem services to agriculture are not provided. Alarmingly, 18–33% of global agricultural lands are below this 10–20% km^2 threshold respectively (Fig. 2; DeClerck et al. In Review).

Both the retention of habitat within agriculture and the diversity of cropping systems per unit area have been proposed as indicators to the CBD and to UNFSS[12]. The attraction of these targets is that they allow for alignment and the setting of both global and national goals while leaving ample scope for farming communities to identify the most locally appropriate practices contributing to their achievement. Additional research will be needed to define what qualifies as "semi-natural" habitat in different regions. Pastures are considered to be semi-natural habitats in European analyses. Agroforests, plantations and orchards may be more appropriate in agricultural systems located in forest biomes. In contrast, winter flooding of rice fields in California have provided critical overwintering habitat for migratory waterfowl and other biodiversity without compromising yield. Investments in local research on the relationships between semi-natural habitats and ecological integrity are needed.

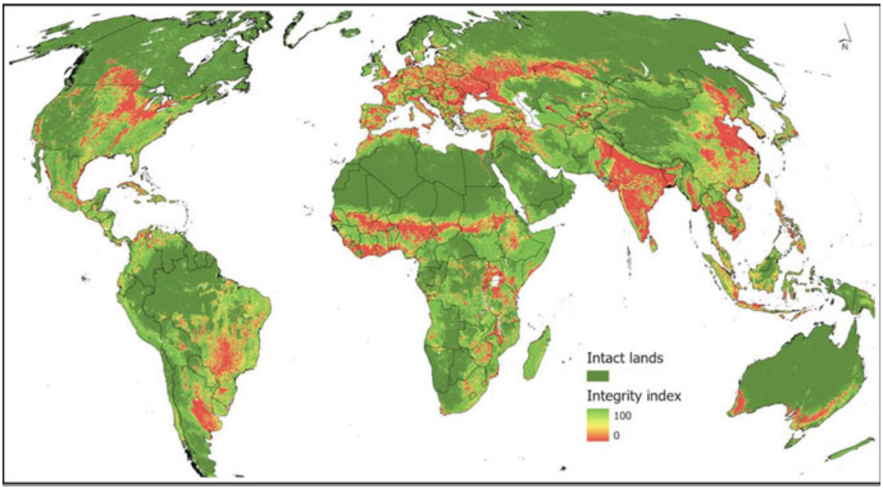


Fig. 2 Global distribution of biodiversity intactness (light green) and ecological integrity. Regions in red are below proposed thresholds for biodiversity in agriculture. (Data from DeClerck et al. In Review. Nearly half the terrestrial landmass is currently classified as "intact." However, many agricultural lands have lost integrity (red), where remaining habitat quantity is insufficient to ensure biodiversity's contributions to food production)

4 Agriculture Must Spare Space for Biodiversity to Meet Global Environmental Goals

Take-Home Messages

- Halting the expansion of agriculture into intact ecosystems is necessary to halt the loss of biodiversity and mitigate climate change, and is likely to contribute significantly to stabilizing hydrological cycles.
- Half of the global land surface is currently intact, with strong biases toward desert, boreal and tundra biomes. Halting extinction loss will require the retention of most remaining intact ecosystems across ice-free areas and is compatible with CBD goals of 'no net loss.'
- Restoring 15% of converted lands in priority areas could avoid 60% of expected extinctions and help provide vital ecosystem services, such as sequestering 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution.

Reducing and reversing the impact of agricultural systems on biodiversity requires a system-wide transformation of agriculture and food production (Tilman et al. 2017; Williams et al. 2020). A sustainable future must therefore be grounded in improving environmental quality and placing strong limits on biodiversity loss. At least 79% of Earth's remaining natural and semi-natural (terrestrial) ecosystems need to be retained simply to meet existing international goals for biodiversity conservation, carbon storage, soil conservation and freshwater regulation (Simmonds et al. 2021).

This equates to keeping half of the planet intact – about the proportion that remains intact today. We can afford to lose very little more: so much land has been converted to agriculture that we are globally either at or nearing land conversion limits (Ceballos et al. 2020). Actions to ensure that intact habitats and their biodiversity can contribute to Earth system processes while also halting the ongoing biodiversity extinction crisis require both *avoiding* further loss of and *restoring* intact nature.

4.1 Halting the Loss of Intact Ecosystems

Preventing the loss or conversion of intact areas, and, where necessary, enhancing their condition, requires setting limits on loss. How much intact land is needed to preserve functioning populations of all species is difficult to quantify precisely. Local contexts are important in determining extinction risk and are important spaces for setting conservation priorities. There is no 'one size fits all' solution (Maron et al. 2018; Allan et al. 2019). However, there is broad consensus that retaining intact habitat, and connectivity between habitats, is necessary to halt loss.

Biological intactness is not incompatible with human use. Relatively intact and ecologically functioning systems can and do support a multitude of human uses, including productive and extractive uses: many such ecosystems rely upon human intervention, and represent the product of millennia of sustainable traditional management. Extensive grazing in grassland and savannah biomes and the sustainable harvest of natural forests are demonstrable activities that retain intactness while supporting livelihoods. Indigenous areas critically overlap with intact nature, with strong evidence that recognizing Indigenous Peoples' rights to land, benefit sharing, and institutions is essential to meeting local and global conservation goals (Garnett et al. 2018). Identifying the range of nature-based benefits that each priority avoidance area supports can provide a guide to the human uses that are compatible with its ongoing provision of those benefits, so long as retaining biodiversity intactness is an explicit priority in these areas.

Interventions should therefore aim *not* to exclude human activities entirely from the areas we need to retain, particularly where local people depend on the natural resource base for their livelihoods. Proposed agricultural expansion can be managed to minimize impacts on biodiversity through the involvement of local people in decision-making. Land use policies, decision-making tools and private sector levers can contribute to nature retention (Garnett et al. 2018).

There is a growing call for the retention of at least half of the global land surface as intact (BII > 90) in order to halt extinction loss at 80% of known biodiversity (Willett et al. 2019; Rockström et al. 2020; Maron et al. 2018; Newbold et al. 2016; Dinerstein et al. 2017). Other estimates, using species-based approaches, find that 44% might be sufficient to protect the most important sites for terrestrial biodiversity (64 million km^2) (Allan et al. 2019). While the specificity of this boundary is vigorously debated, most ecologists agree that, as the intact area of ecosystems dips below 50%, there is growing risk of population decline and extinction risk.

Retaining at least half of the terrestrial realm, in each of the 782 ecoregions, would thus be necessary to halt extinction loss, and has been signaled as a biodiversity boundary for food systems (Willett et al. 2019). Retaining intact regions in ice-free areas (>67 M km^2) and achieving half intactness for all ecoregions would require restoration on 23.9 M km^2. Observing that currently half of the terrestrial realm is considered intact, the CBD has adopted the boundary measure in its ongoing negotiations for a 'no net loss of nature' target. Ensemble models have demonstrated that no net loss is possible to achieve, but requires aligned actions across biodiversity conservation, food production and food consumption (Leclère et al. 2020).

Many parts of the world are currently in intactness deficit, considering a 50% intactness target. Estimates of how much restoration is needed range between 19 and 24 million km^2, with the lower value targeting high conservation value areas (Allan et al. 2019; Strassburg et al. 2020), and the higher value targeting half-intact ecoregions, across all ecoregions (DeClerck et al. In Review). In 552 ecoregions globally (69%), less than 10% of the area remains intact and may be too far gone for meaningful restoration of intactness, or may conflict with food and nutrition security. In these locations, integrating biodiversity into production will be a more viable option.

4.2 Mitigating Climate Change

While reducing fossil fuel burning and halting land conversion are critical strategies to reduce GHG emissions, biodiversity, through photosynthesis, is the only known process to transfer GHG from the atmosphere to the biosphere. The retention and restoration of natural ecosystems, notably, carbon-dense forest and wetland ecosystems, are key in this regard. It has been proposed that 75% of forest biomes be conserved globally because of their specific contribution to climate mitigation (Steffen et al. 2015). Temperate and tropical forest biomes are currently below this threshold, although temperate forest areas are increasing due to agricultural abandonment, whereas tropical forest areas are decreasing due to agricultural expansion. Boreal forest biomes remain above this threshold for the moment (Dinerstein et al. 2017; Ramankutty et al. 2018). The potential of reforestation to contribute to climate mitigation (i.e., 2.7–17.9 Pg $CO_2e\ y^{-1}$) depends on several assumptions (Griscom et al. 2017).

4.3 Regulating Hydrological Cycles

Large tracts of intact nature are key to maintaining regional hydrological patterns (Chapman et al. 2020; McAlpine et al. 2009), including flood pulse flow regulation (Bradshaw et al. 2007) and distribution of rainfall patterns that are critical to agriculture. However, the relationship between water fluxes (storage, evapotranspiration, precipitation and run-off) of extensive intact areas is complex. Intact nature may or may not produce greater volumes of water than converted lands, as losses to storage and evapotranspiration can be greater than in simplified systems such as agricultural ecosystems. However, most evidence does indicate that heavily vegetated ecosystems (e.g., forests, grasslands) provide better flow regulation – while natural ecosystems reduce run-off, they may have greater losses to evapotranspiration. Studies suggest that about 40% of irrigation water currently drawing from surface water bodies is at the expense of environmental flows (Jägermeyr 2020) and roughly 20% of irrigation water depletes groundwater bodies(Döll et al. 2012; Wada et al. 2012; Wada et al. 2016), indicating that 50–60% of current global irrigation practice is unsustainable (Rosa et al. 2019; Rosa et al. 2018).

4.4 Restoring Ecosystems

A growing number of research articles now point toward options for restoration, and evaluate contributions to climate, biodiversity, and food security, but there remains an important research gap on local and regional implementation of such strategies, including the trade-offs over multiple spatial and temporal scales, as well as between different social groups (Leclère et al. 2020; Strassburg et al. 2020; Mehrabi et al. 2018). Restoration, in contrast to regeneration, must include improvements in biodiversity intactness (Newbold et al. 2016; Scholes and Biggs 2005) measured by changes in species richness and population abundance. Defined as such, restoration can be interpreted as driving a net reduction in land available for food production, with the exception of wild harvest systems, and potentially extensive grazing systems. Restoring 15% of converted lands in priority areas could avoid 60% of expected extinctions while sequestering 299 Gt CO_2e – 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution (Strassburg et al. 2020).

5 Conclusions and Recommendations: Food and Agriculture Must Be the Solution to Food, Environmental and Climate Security

While the evidence on when and how biodiversity contributes to global goals is highly context specific, we find that agriculture has the potential to reconcile global goals that have often been considered contradictory: food and nutritional security versus environmental and climate security. There is strong evidence that realizing this potential requires placing biodiversity at the heart of agriculture policy, investment and innovation, with much greater consideration of the role of agriculture as a provider of benefits to biodiversity, rather than just a driver of biodiversity loss. As the lifeline of the entire system, people must be anchored in solutions to upend the system of policies and incentives that are currently stacked against their livelihoods and health.

Understanding that there is a menu of solutions, with related opportunities and trade-offs, will help in progress toward a future that optimizes sustainable agriculture and prioritizes feeding everyone. Biodiversity strategies are among those solutions and can help us move beyond staple crops and commodities when considering policy, investment and research. Three elements, as already detailed in this review, can offer a way to bridge conversations among policymakers engaged in the environment, food, agriculture, finance and social protection sectors, and must be considered in a holistic solution for food and biodiversity: (1) How can we optimize the opportunities and minimize the trade-offs for ensuring diverse diets for all? (2) How can we maintain shared space where agriculture optimizes ecosystem services, and other contributors to regenerative and resilient production systems? And (3) how can we strike the right balance of land sparing, by halting the expansion of agriculture into the intact ecosystems necessary to halt the loss of biodiversity while mitigating climate change and producing enough healthy food?

5.1 Policy Implications: The Transformation Challenge

Biodiversity needs to be part of a sustainable agriculture that will feed a projected population of 10 billion with healthy, culturally appropriate and delicious foods by 2050. The first step is for policymakers to adopt a new conceptual framing that recognizes that all parts of food systems need to work together as a whole if they are to deliver diets that are high quality and sustainable. This leads to thinking about 'food system productivity,' rather than agricultural productivity (Benton and Bailey 2019), and requires all sectors of government to break out of their own conceptual silos and institutional structures. For a true transformation of the food system, there is a need to create the policy instruments, demand and incentives for food production systems that leverage biodiversity's capacity to contribute to climate, environmental, food and nutritional security (Willett et al. 2019; Rockström et al. 2009; Steffen et al. 2015).

5.2 Correcting Distortions Requires Reinvestment

Our food system has been distorted by a framework of subsidies (including for research focused on staples), market incentives (including investment in commodity-based transport infrastructure and marketing/retail incentives for hyper-processed food), and a lack of regulations to curb the externalization of costs onto environmental and healthcare systems. The heavily subsidized agricultural sectors of many countries in the Global North result in trade distortion, or in inequitable trade relationships among many developed and developing countries, adversely affecting the economic prospects of farmers in the Global South (OECD, 2016). These have a strong influence on both the foods that are delivered and their price and accessibility, and in encouraging the supply, demand and consumption of foods that may be less conducive to healthy diets and sustainability in food systems.

In considering the relationship between agriculture and biodiversity, several key areas for investment emerge [*High Agreement, Robust Evidence*]:

- Closing the gap between the current composition of crop production and consumption to supply healthy diets at the local, regional and global scales in line with SDG2 and SDG3.
- Transitioning to managing agricultural systems as ecological systems (agroecosystems).

During the next decade, priority approaches to diversify production systems should target:

- Urgent investments in undervalued crops and cropping systems, notably, underproduced crops that underpin dietary health.
- Greater investment in tools, technologies and enabling environments that amplify and/or complement biodiversity's contribution to agriculture, rather than seeking to replace it.
- Repurposing public funds in agriculture to support farmers producing public goods, including the production of healthy foods, carbon capture, clean water and habitat for biodiversity.

Food security cannot trump other critical goals, notably, nutritional, climate, environmental and livelihood security. Treating these as inevitable trade-offs fails to highlight key areas of synergy. Making the transition to food production systems that achieve synergy with biodiversity will require significant transitions in the policy landscape. Therefore, agriculture must be more strongly:

- Integrated into global environmental policies, both in recognition of its role as a driver of environmental change and to leverage its potential contribution to mitigating climate and biodiversity loss.
- Included in global agreements, recognizing its current impacts on climate, degradation and biodiversity and leveraging its potential contribution to global goals.
- Interwoven into global health policies, as in recent collaborations between the World Health Organization and the Food and Agriculture Organization to define healthy and sustainable diets.

5.3 Developing more Dynamic Investment and Financial Opportunities

There is potential to unlock and unblock investment and facilitate better financial flows to encourage farmers to protect and enhance the environment by rewarding them for the provision of ecosystem services, while mitigating the risks to the adoption of sustainable practices. Current agricultural investments and practices often overlook the important potential for increasing the ecosystem services that agroecosystems can provide (Wood et al. 2018). The CGIAR Commission on the Sustainable Intensification of Agriculture finds "an uplift in finance could come from reorienting current innovation spending to promote environmental, climate change, inclusivity and nutrition outcomes. A recent study commissioned by CoSAI identified that although around USD 50–70 bn per year is spent on agricultural innovation for the Global South, less than 7% explicitly aims to improve environmental and climate outcomes. And only around half of this also addresses social or nutrition outcomes" (CoSAI. 2021).

Farmers and farming communities can produce public goods (e.g., climate mitigation, soil water-holding capacity, water quality improvement), but promoting these public good functions has been consistently underexplored and under-resourced, even though they are also necessary for creating sustainable and resilient production systems. Recognizing that farmers and farmlands can produce these benefits in addition to quality food presents an opportunity for revitalizing rural communities by repurposing public funds for public goods.

5.4 Changing Availability Through Subsidy and Research Reform

Currently, more than US$620 billion is spent globally each year on agricultural subsidies (e.g., commodity support, services) (OECD 2020). Over the past decade, OECD governments have allocated roughly 26% of their subsidy support to cereal grains, and 14% to fruits and vegetables (Freund and Springmann Under review). This value is inverse to the diversity of potential crops within these food categories, inverse to the recommended consumption levels of food groups, and inverse to the projected yield production deficits. While the share of sectoral support to fruit and vegetables was much higher in non-OECD countries, at 37%, the other 63% of subsidy support went to cereals, livestock, oilseeds, sugar, production of fiber (wool) and more (Freund and Springmann Under review).

Even a relatively modest repurposing of subsidies (e.g., 25%) toward promoting production of nutrient-rich perishable foods, and reduced food loss and nutrient waste, would amount to US$150 billion in capital to support the generation of a greater diversity of nutrient-rich foods, while simultaneously lowering the environmental footprint, potentially allowing more nature-positive farming methods.

Only 6% of public sector support to the agricultural sector is dedicated to research (Searchinger et al. 2020). This is a small percentage, but amounts to a big number globally. However, it is typically targeted at productivity improvements in major commodities. A key research need is for a much greater focus on innovation in diverse farming systems, rather than individual crops, for instance, through circular agriculture to prevent waste and leakage while supporting reuse, regenerative, agroecological systems, complex rotations, mixed farming, and so on.

5.5 *Reimagining International Trade*

With almost 20% of the global dietary energy supply derived from imported foodstuffs, trade policy must better integrate its impact by creating greater space for diversification of commodities, supporting the conservation of intact ecosystems, and including trade in environmental goods and services. Trade expansion over recent decades has enabled "higher-income countries to 'off-shore' the adverse impacts of their consumption on ecosystems and biodiversity through trade in commodities, goods and services with lower-income countries" (Dasgupta 2021) International market stability and prices are highly dependent on a few key players (Dasgupta 2021), yet investing well in international trade could bring a range of benefits. It is crucial to find ways to support sustainability via trade (e.g., 'due diligence' requirements for supply chains such as the Global Reporting Initiative (GRI), enhancing traceability through mechanisms such as Trase, or through border tariffs). A key component of the evolution of the food system's focus on large-scale commodity production is the ability to store, transport and process grains with less loss than with fresh produce.

Acknowledgements This paper was funded with support from the CGIAR Collaborative Research Program on Water Land and Ecosystems.

References

Afshin A et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393:1958–1972

Albrecht M et al (2020) The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. Ecol Lett 23:1488–1498

Allan JR et al (2019) Conservation attention necessary across at least 44% of Earth's terrestrial area to safeguard biodiversity. bioRxiv:839977

Amelung W et al (2020) Towards a global-scale soil climate mitigation strategy. Nat Commun 11: 1–10

Avelino J, Romero-Gurdian A, Cruz-Cuellar HF, Declerck FAJ (2012) Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. Ecol Appl 22:584–596

Bedoussac L et al (2015) Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron Sustain Dev 35:911–935

Bélanger J, Pilling D (2019) The state of the world's biodiversity for food and agriculture 2019. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. xli + 529 pp

Benton TG, Bailey R (2019) The paradox of productivity: agricultural productivity promotes food system inefficiency. Global Sustain 2

Bernhardt JR, O'Connor MI (2021) Aquatic biodiversity enhances multiple nutritional benefits to humans. Proc Natl Acad Sci 118

Bradshaw CJ, Sodhi NS, PEH KSH, Brook BW (2007) Global evidence that deforestation amplifies flood risk and severity in the developing world. Glob Chang Biol 13:2379–2395

Brauman KA et al (2020) Global trends in nature's contributions to people. Proc Natl Acad Sci 117: 32799–32805

Ceballos G, Ehrlich PR, Raven PH (2020) Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. Proc Natl Acad Sci 117:13596–13602

Chaplin-Kramer R, O'Rourke ME, Blitzer EJ, Kremen C (2011) A meta-analysis of crop pest and natural enemy response to landscape complexity. Ecol Lett 14:922–932

Chapman S et al (2020) Compounding impact of deforestation on Borneo's climate during El Niño events. Environ Res Lett 15:084006

Clark MA, Springmann M, Hill J, Tilman D (2019) Multiple health and environmental impacts of foods. Proc Natl Acad Sci 116:23357–23362

Clark MA et al (2020) Global food system emissions could preclude achieving the 1.5° and 2° C climate change targets. Science 370:705–708

Cook SM, Khan ZR, Pickett JA (2007) The use of push-pull strategies in integrated pest management. Annu Rev Entomol 52:375–400

CoSAI (2021) What is the innovation investment gap to meet hunger and climate change goals? CGIAR Research Program on Water Land and Ecosystems, Colombo

Dainese M et al (2019) A global synthesis reveals biodiversity-mediated benefits for crop production. Sci Adv 5:eaax0121

Dasgupta P (2021) The economics of biodiversity: the Dasgupta review. H.M. Treasury, London

DeClerck FA et al (2016) Agricultural ecosystems and their services: the vanguard of sustainability? Curr Opin Environ Sustain 23:92–99

DeClerck F, Jones SK, Estrada-Carmona N, Fremier AK (In Review) Spare half, share the rest: A revised planetary boundary for biodiversity intactness and integrity. Nature

DeFries R et al (2015) Metrics for land-scarce agriculture. Science 349:238–240

Díaz S et al (2020) Set ambitious goals for biodiversity and sustainability. Science 370:411–413. https://doi.org/10.1126/science.abe1530

Dinerstein E et al (2017) An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67:534–545

Diversity, C. o. B. Vol. CBD/POST2020/PREP/2/1 (UNEP, 2020)

Döll P et al (2012) Impact of water withdrawals from groundwater and surface water on continental water storage variations. J Geodyn 59:143–156

Duchene O, Vian J-F, Celette F (2017) Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric Ecosyst Environ 240:148–161

FAO I, UNICEF, WFP, and WHO (2020) The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. FAO, Rome

FAO-HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. High level panel of experts on food security and nutrition of the Committee on World Food Security: Rome, Italy

Foley JA et al (2005) Global consequences of land use. Science 309:570–574

Foley JA et al (2011) Solutions for a cultivated planet. Nature 478:337–342

Fremier AK et al (2013) Understanding spatiotemporal lags in ecosystem services to improve incentives. Bioscience 63:472–482

Freund F, Springmann M (Under review) The economic, environmental and health impacts of reforming agricultural subsidies

Garbach K et al (2016) Close yield and nature gaps: multi-functionality in five systems of agroecological intensification. Int J Agric Sustain. https://doi.org/10.1080/14735903.2016.1174810

Garibaldi LA et al (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecol Lett 14:1062–1072

Garibaldi LA et al (2020) Working landscapes need at least 20% native habitat. Conserv Lett e12773

Garnett ST et al (2018) A spatial overview of the global importance of indigenous lands for conservation. Nat Sustain 1:369–374

Ghosh P et al (2007) Legume effect for enhancing productivity and nutrient use-efficiency in major cropping systems–an Indian perspective: a review. J Sustain Agric 30:59–86
Golden CD, Fernald LC, Brashares JS, Rasolofoniaina BR, Kremen C (2011) Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. Proc Natl Acad Sci 108:19653–19656
Griscom BW et al (2017) Natural climate solutions. Proc Natl Acad Sci 114:11645–11650
Holland JM et al (2017) Semi-natural habitats support biological control, pollination and soil conservation in Europe. A review. Agron Sustain Dev 37:1–23
IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn
Jägermeyr J (2020) Agriculture's historic twin-challenge toward sustainable water use and food supply for all. Front Sustain Food Syst 4:35
Kc KB et al (2018) When too much isn't enough: does current food production meet global nutritional needs? PLoS One 13:e0205683
Kennedy CM et al (2013) A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecol Lett 16:584–599
Khoury CK et al (2019) Comprehensiveness of conservation of useful wild plants: an operational indicator for biodiversity and sustainable development targets. Ecol Indic 98:420–429
Kremen C, Albrecht M, Ponisio L (2019) Restoring pollinator communities and pollination services in hedgerows in intensively managed agricultural landscapes. The ecology of hedgerows and field margins, 163–185
Landis DA, Wratten SD, Gurr GM (2000) Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu Rev Entomol 45:175–201
Leclère D et al (2020) Bending the curve of terrestrial biodiversity needs an integrated strategy. Nature 585:551–556
Letourneau DK et al (2011) Does plant diversity benefit agroecosystems? A synthetic review. Ecol Appl 21:9–21
Lichtenberg EM et al (2017) A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. Glob Chang Biol 23:4946–4957
Maron M, Simmonds JS, Watson JE (2018) Bold nature retention targets are essential for the global environment agenda. Nat Ecol Evol 1
McAlpine C et al (2009) A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. Glob Chang Biol 15:2206–2223
Mehrabi Z, Ellis EC, Ramankutty N (2018) The challenge of feeding the world while conserving half the planet. Nat Sustain 1:409
M'Gonigle LK, Ponisio LC, Cutler K, Kremen C (2015) Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. Ecol Appl 25:1557–1565
Newbold T et al (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353:288–291
Nicholson CC et al (2020) Mismatched outcomes for biodiversity and ecosystem services: testing the responses of crop pollinators and wild bee biodiversity to habitat enhancement. Ecol Lett 23: 326–335
Global Panel on Agriculture and Food Systems for Nutrition (2020) Future food systems: for people, our planet, and prosperity. London
OECD (2016) OECD-FAO Agricultural Outlook 2016–2025. Organisation For Economic Co-Operation and Development (OECD), Paris
OECD (2020) Agricultural policy monitoring and evaluation 2020. Organisation for Economic Co-operation and Development, Paris
Palm C, Blanco-Canqui H, DeClerck F, Gatere L, Grace P (2014) Conservation agriculture and ecosystem services: an overview. Agric Ecosyst Environ 187:87–105
Pickett JA, Woodcock CM, Midega CA, Khan ZR (2014) Push-pull farming systems. Curr Opin Biotechnol 26:125–132

Ponisio LC, M'Gonigle LK, Kremen C (2016) On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. Glob Chang Biol 22:704–715
Rajapakse N, Kim S-K (2011) Nutritional and digestive health benefits of seaweed. Adv Food Nutr Res 64:17–28
Ramankutty N et al (2018) Trends in global agricultural land use: implications for environmental health and food security. Annu Rev Plant Biol 69:789–815
Remans R, Wood SA, Saha N, Anderman TL, DeFries RS (2014) Measuring nutritional diversity of national food supplies. Glob Food Sec 3:174–182
Ricciardi V, Mehrabi Z, Wittman H, James D, Ramankutty N (2021) Higher yields and more biodiversity on smaller farms. Nat Sustain:1–7
Rockström J et al (2009) A safe operating space for humanity. Nature 461:472–475. https://doi.org/10.1038/461472a
Rockström J, Edenhofer O, Gaertner J, DeClerck F (2020) Planet-proofing the global food system. Nat Food 1:3–5
Rockström J et al (2021) Identifying a safe and just corridor for people and the planet. Earth's Future e2020EF001866
Rosa L et al (2018) Closing the yield gap while ensuring water sustainability. Environ Res Lett 13: 104002
Rosa L, Chiarelli DD, Tu C, Rulli MC, D'Odorico P (2019) Global unsustainable virtual water flows in agricultural trade. Environ Res Lett 14:114001
Rusch A et al (2016) Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. Agric Ecosyst Environ 221:198–204
Rusch A, Bommarco R, Ekbom B (2017) Conservation biological control in agricultural landscapes. Adv Bot Res 81:333–360
Scheper J et al (2015) Local and landscape-level floral resources explain effects of wildflower strips on wild bees across four European countries. J Appl Ecol 52:1165–1175
Scholes RJ, Biggs R (2005) A biodiversity intactness index. Nature 434:45–49
Searchinger, T. D. et al. Revising public agricultural support to mitigate climate change (2020)
Shelton A, Badenes-Perez F (2006) Concepts and applications of trap cropping in pest management. Annu Rev Entomol 51:285–308
Simmonds JS et al (2021) Limiting the loss of terrestrial ecosystems to safeguard nature for biodiversity and humanity. (in review) Nat Commun
Steffen W et al (2015) Planetary boundaries: guiding human development on a changing planet. Science 347
Strassburg BB et al (2020) Global priority areas for ecosystem restoration. Nature 586:724–729
Tamburini G et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6:eaba1715
Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515:518–522
Tilman D et al (2017) Future threats to biodiversity and pathways to their prevention. Nature 546: 73–81
Tscharntke T et al (2007) Conservation biological control and enemy diversity on a landscape scale [Erratum: 2008 May, v. 45, issue 2, p. 238–253.]. Biological control: theory and application in pest management
Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol Lett 8:857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x
Tschumi M, Albrecht M, Entling MH, Jacot K (2015) High effectiveness of tailored flower strips in reducing pests and crop plant damage. Proc R Soc B Biol Sci 282:20151369
Veres A, Petit S, Conord C, Lavigne C (2013) Does landscape composition affect pest abundance and their control by natural enemies? A review. Agric Ecosyst Environ 166:110–117
Wada Y, Van Beek L, Bierkens MF (2012) Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour Res 48

Wada Y et al (2016) Modeling global water use for the 21st century: the Water Futures and Solutions (WFaS) initiative and its approaches. Geosci Model Dev 9:175–222
Willett W et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492
Williams DR, Balmford A, Wilcove DS (2020) The past and future role of conservation science in saving biodiversity. Conserv Lett 13:e12720
Wood SL et al (2018) Distilling the role of ecosystem services in the sustainable development goals. Ecosyst Serv 29:70–82
Zhang W, Ricketts TH, Kremen C, Carney K, Swinton SM (2007) Ecosystem services and dis-services to agriculture. Ecol Econ 64:253–260

Water for Food Systems and Nutrition

Claudia Ringler, Mure Agbonlahor, Kaleab Baye, Jennie Barron, Mohsin Hafeez, Jan Lundqvist, J. V. Meenakshi, Lyla Mehta, Dawit Mekonnen, Franz Rojas-Ortuste, Aliya Tankibayeva, and Stefan Uhlenbrook

1 Introduction

Water is essential for all life and is integral to the function and productivity of the Earth's ecosystems, which depend on a complex cycle of continuous movement of water between the Earth and the atmosphere. Water is also fundamental for food systems, and a food systems transformation will be essential to meeting SDG 6 on water and sanitation. As described by the High-Level Panel of Experts on Food

C. Ringler (✉)
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: c.ringler@cgiar.org

M. Agbonlahor
African Union Commission, Ouagadougou, Burkina Faso

K. Baye
Addis Ababa University, Addis Ababa, Ethiopia

J. Barron
Swedish University of Agricultural Sciences, Uppsala, Sweden

M. Hafeez
International Water Management Institute, Lahore, Pakistan

J. Lundqvist
Stockholm International Water Institute, Stockholm, Sweden

J. V. Meenakshi
University of Delhi, New Delhi, India

L. Mehta
Institute of Development Studies, Falmer, UK

Norwegian University of Life Sciences, Ås, Norway

D. Mekonnen
International Food Policy Research Institute, Addis Ababa, Ethiopia

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_26

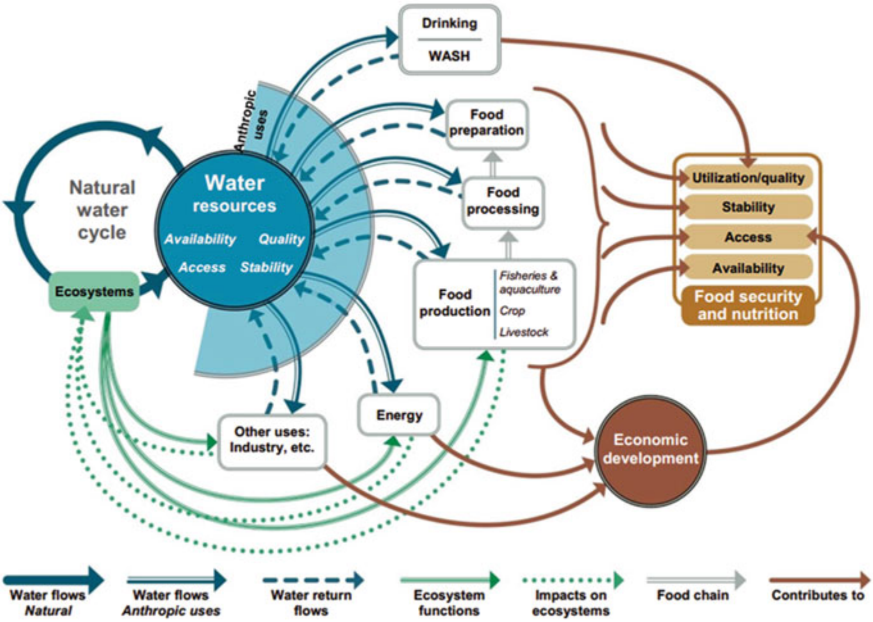


Fig. 1 The linkages between water and food systems (Source: HLPE 2015)

Security and Nutrition (HLPE) (HLPE 2015) and illustrated in Fig. 1, the key dimensions of water that are of importance for humanity are its availability, access, stability, and quality. These have multiple, close linkages and feedback loops with food systems, which can be defined as the activities involved in the production, processing, distribution, preparation, and consumption of food within wider socio-economic, political, and environmental contexts (HLPE 2017). For example, waste streams from food processing often re-enter water bodies, affecting other components of food systems, such as drinking water supplies (water is itself essential for all bodily functions and processes, and is an important source of nutrients) (UNSCN 2020), as well as water-based and water-related ecosystems.

More than 70% of all freshwater withdrawals are currently used for agriculture, and about 85% of withdrawn resources are consumed in irrigated agricultural production. With these resources, irrigated crop areas generate 40% of global food production on less than one-third of the globally harvested area (Ringler 2017). Another key water-food system linkage is water supply for WASH (water, sanitation

F. Rojas-Ortuste
Development Bank of Latin America, Montevideo, Uruguay

A. Tankibayeva
Al-Farabi Kazakh National University, Almaty, Kazakhstan

S. Uhlenbrook
International Water Management Institute (IWMI), Battaramulla, Sri Lanka

and hygiene), which is important for human health, can support nutrition outcomes, particularly if combined with other interventions (Cumming et al. 2019), and is a basic human right, as is the right to food. Water is also essential for agricultural processing and food preparation.

Climate change and other environmental and societal changes (e.g., land use changes, biodiversity loss, urbanisation, and changing lifestyles and diets) are impacting the dynamics of natural water cycles and water resource availability, with further, subsequent impacts on food systems. More than half of all natural wetland areas have been lost due to human activity since 1900 and forest degradation affects streamflow regulation (Sun et al. 2017). At the same time, the growing frequency and severity of floods and droughts in many regions of the world (IPCC 2021) increase competition over water resources. This calls for changes in water management, including increased water productivity, integrated storage solutions, accelerated land restoration and smarter water distribution to support food systems, as well as a reduction in impacts on domestic, industrial, energy-related, and environmental water uses.

2 SDG 2 and SDG 6 Can Only Be Achieved If the Water and Food System Communities Work Together

2.1 Water Scarcity and Pollution Are Growing, Affecting Poorer Populations, Particularly Food Producers

Freshwater-related ecosystems include wetlands, rivers, aquifers, and lakes that sustain biodiversity and life (UN Environment 2018). Although they cover less than 1% of the Earth's surface, these habitats host approximately one-third of vertebrate species and 10% of all species (Stayer and Dudgeon 2010), including mammals, birds (IUCN 2019), and fish (Fricke et al. 2020). Water-related ecosystems are also vital for the function of all terrestrial ecosystems, providing regulating, provisioning, and cultural services (Martin-Ortega et al. 2015). Furthermore, hydropower is an essential energy source, accounting for 85% of global renewable electricity generation in 2015, but has since declined to around 60% (IEA 2016, 2020), and is also key for commerce and industry (Willet et al. 2019). Notably, de-carbonising the energy system can also adversely impact the water system, particularly in the case of increasing hydropower and biofuel production.

Progress on achieving the water and sanitation targets of SDG 6 has been unsatisfactory and uneven. More than 2 billion people live in places with high water stress (FAO SOFA 2020; UN 2018): by 2050, every second person, half of the world's grain production, and close to half of the globe's Gross Domestic Product might well be at risk from water insecurity (Ringler et al. 2016). In 2020, approximately 2.0 billion people lacked access to safely managed drinking water, and 3.6 billion people lacked access to safely managed sanitation services.

One in ten people lacked basic services, including the 122 million people who depend on untreated surface water, mostly in sub-Saharan Africa (UNICEF, WHO 2021). Poor women and girls, who are responsible for more than 70% of all water collection, spend about 200 million hours a day on this task, undermining their health and livelihood opportunities (UNICEF n.d.; Geere and Cortobius 2017).

In terms of agricultural water use, farmers across the world, but particularly in sub-Saharan Africa, continue to rely heavily on rainfall for food production. More than 62 million hectares of crop and pastureland experience high to very high water stress and drought, affecting about 300 million farm households (FAO 2020). With climate change, temperatures and crop evaporation levels are increasing, and there is growing uncertainty about the timing, duration and quantity of rainfall, increasing the risks related to producing food and undermining the livelihood security of the majority of rural people (AUC 2020). Fertiliser use on crop land and livestock excreta are key sources of agricultural water pollution, affecting aquatic life and threatening human health. Projections suggest that nitrogen and phosphorous deposition in water bodies will grow rapidly, particularly in low- and middle-income countries (Xie and Ringler 2017).

With respect to the other SDG 6 targets, such as water use efficiency, water-dependent ecosystems, and integrated water management, progress has been slow and is often not well understood, due to the lack of effective monitoring mechanisms and insufficient data. New, integrated approaches and reinforced efforts to measure and manage water are urgently needed (Sadoff et al. 2020).

While water availability differs dramatically around the globe, differences in access are most often due to politics, public policy, lack of capacity and investment, and flawed water management strategies, as well as exclusions due to geography (i.e., remote rural areas), gender, ethnicity, caste, race, and class. In many cases, water does 'flow uphill' to power and money (Mehta et al. 2019). Furthermore, increasing urbanisation and changing diets are affecting the demand and supply of water resources for food systems and aggravating water stress in many parts of the world, particularly in water-scarce areas of low/middle-income countries where coping capacity is often insufficient.

2.2 *Malnutrition Levels Are on the Rise and Are Closely Linked to Water Scarcity*

An estimated 690 million people, or 8.9% of the global population, were undernourished in 2019, prior to the COVID-19 pandemic (Headey et al. 2020). The number has since grown to between 720 and 811 million people (2020 values). Moreover, 149 million children below the age of five were stunted, 45 million were wasted, and another 39 million were overweight (FAO, IFAD, UNICEF, WFP and WHO 2021). Climate change, associated conflict, and a lack of sufficient water for food production, including irrigation for fruit and vegetable production, are key contributors to unaffordable diets and overall levels of undernutrition. At the same time, overweight continues to dramatically increase around the globe, including in children. Latin America, in particular, suffers from the associated public health burden. Overall, rural areas are currently experiencing the most rapid rate of increase in overweight (NCD Risk Factor Collaboration et al. 2019). Given these trends, neither the 2025 World Health Assembly nutrition targets nor the 2030 SDG nutrition targets will be met. As with inequities in access to water, inequities in access to food and nutrition are highest in rural areas (Perez-Escamilla et al. 2018).

2.3 SDG 2 and SDG 6 Targets Are Co-Dependent

Ending hunger and malnutrition requires access to safe drinking water (SDG 6.1), as well as equitable sanitation and hygiene (SDG 6.2). The underlying productivity (SDG 2.3) and sustainability (SDG 2.4) of agricultural systems are also dependent on adequate availability (SDG 6.4 and 6.6) of good quality (SDG 6.3) water. Moreover, water and related ecosystems (e.g., wetlands, river or lakes in SDG 6.6), which are embedded in sustainable landscapes, are important contributors to sustainable agriculture through regulating and providing water for food production (SDG 2.4) (Ringler et al. 2018).

A key contributor to poor nutritional outcomes in subsistence farming households in low-income countries is the seasonality of production, leading to a seasonality in diets, which can affect pregnancy outcomes and child growth (Baye and Hirvonen 2020; Madan et al. 2018). Well-managed irrigation systems can buffer seasonal gaps in diets, contributing to improved food security and nutritional outcomes, for example, through homestead gardening (Baye et al. n.d.; Hirvonen and Headey 2018).

It is equally important to stress the need for changes in food systems in meeting SDG 6 targets: reducing food loss and waste in food value chains (SDG 12.3), lowering pollution from slaughterhouses, food processing, and food preparation, and considering environmental sustainability in food-based dietary guidelines. All of these actions will be essential to meet the SDG 6 targets (UNSCN 2020).

3 Solutions for Improving Food System Outcomes and Water Security

Based on the above assessment, as well as recent water-food system reviews (Ringler et al. 2018; UNSCN 2020; Mehta et al. 2019; Young et al. 2021), the following actions are proposed for uptake by governments, the private sector, and civil society.

3.1 Strengthen Efforts to Retain Water-Based Ecosystems and Their Functions

The ecological processes underlying the movement, storage, and transformation of water are under severe threat from deforestation, erosion, and pollution, with impacts on local, regional, and global water cycles (WWAP 2018). In addition to a direct halt of deforestation and the destruction of water-based ecosystems, nature-based solutions that use or mimic natural processes to enhance water availability (e.g., groundwater recharge), improve water quality (e.g., riparian buffer strips, wetlands), and reduce risks associated with water-related disasters and climate change (e.g., floodplain restoration, wetlands) should be strengthened (WWAP 2018). Limiting overconsumption of water, particularly in water-stressed regions, will be necessary to stay within sustainable water use limits (Yu et al. 2021).

3.2 Improve Agricultural Water Management for Better Diets for All

Around 3 billion people on this planet cannot afford a healthy diet, particularly dairy, fruits, vegetables, and protein-rich foods (FAO, IFAD, UNICEF, WFP, WHO 2021). Both rainfed and irrigated systems play essential roles in lowering the prices of nutrient-dense foods, growing incomes to be able to afford these foods, and strengthening the diversity of foods available in local markets (Hirvonen et al. 2017).

3.2.1 Strengthen the Climate Resilience of Rainfed Food Systems

Rainfed systems produce the bulk of food, fodder, and fibre, and most animal feed is produced under rainfed conditions (Heinke et al. 2020). These systems are under severe and growing stress from climate change, including extreme weather (FAO 2020). This can be addressed, to some extent, through structural measures (e.g., terracing, soil bunds, drainage), investment in breeding, improved agronomic practices, effective incentives (e.g., payments for watershed conservation), and strong institutions for water, soil and land management (e.g., watershed committees) (Jägermeyr et al. 2016; World Bank 2010).

3.2.2 Strengthen the Nutrient Density of Irrigated Agriculture

As irrigation accounts for the largest share of freshwater withdrawals by humans (more than 90% in some agrarian economies), the potential for water conservation is also largest in this sector. Irrigation development needs keep environmental limits – which are increasingly affected by climate change – in mind. This includes addressing groundwater depletion. The potential for increasing water and nutrition productivity in irrigation remains large. It includes crop breeding for transpiration efficiency, salinity tolerance, climate resilience and increased micronutrients, integrated storage solutions – such as joint use of grey and green infrastructure – advanced irrigation technology, and soil moisture monitoring (Rosegrant et al. 2009). There are clear trade-offs between the nutrient density of foods and irrigation water use. Fruit and vegetable yields depend on frequent water applications in many parts of the world (although the water content of the end product also tends to be high) and need precision applications of agrochemicals to maximise water inputs and avoid water pollution (Meenakshi and Webb 2019). Many livestock products are highly water-intensive due to animal feeds, although the majority of the feed comes from rainfed agriculture. Awareness-raising and social learning interventions can help internalise the water externality of water-intensive diets. Improved coordination of water with other agricultural inputs can also enhance yield per drop of water. This requires access to technology packages, as well as to better agricultural information (Lundqvist et al. 2021), which is increasingly supported by ICTs (Asenso-Okyere and Mekonnen 2012). Moreover, subsidies for water-intensive crops, such as rice, milk and sugar, should be revisited and eventually removed. For water-scarce countries, importing virtual water via food and other commodities will remain essential (Allan 1997).

3.2.3 Address Water Pollution to Improve Food Production, Food Safety, and Water-Based Ecosystems

Globally, 80% of municipal sewage and industrial wastewater with heavy metals, solvents, toxic sludge, pharmaceuticals, and other waste are directly discharged into water bodies, affecting the safety of food, particularly vegetable production, and also, directly, human health (WWAP 2018). Agriculture also directly pollutes aquatic ecosystems and risks food production with pesticides, organic matter, fertilisers, sediments, pathogens, and saline drainage (UNEP 2016). Key measures to address agricultural and overall water pollution include the breeding of crops with higher crop nutrient use efficiency, better agronomic practices, the expansion of nature-based solutions for pollution management, low-cost pollution monitoring systems, improved incentive structures for pollution abatement, and continued investment and innovation in wastewater treatment, including approaches such as implementing the 3Rs (reduce, reuse, and recycle) of the circular economy across the entire food system (Mateo-Sagasta et al. 2018).

3.3 Reduce Water and Food Losses Beyond the Farmgate

Irrigated agriculture is often focused on high-value crops with a higher share of marketed surplus, compared to rainfed agriculture (Nkonya et al. 2011). At the same time, many irrigated crops, such as fruits and vegetables, are time-sensitive, perishable products that require efficient market linkages to consumption centres. Strengthening market linkages includes investment in physical infrastructure that supports on-farm production (irrigation, energy, transportation, pre- and post-harvest storage), efficient trading and exchange (telecommunications, covered markets), value addition (agro-processing and packaging facilities), and improved transportation and bulk storage (Warner et al. 2008). Investments are also needed in ICTs that facilitate farmers' access to localised and tailored information about weather, water consumption, diseases, yield, and input and output prices (Elsabber 2020).

3.4 Coordinate Water with Nutrition and Health Interventions

3.4.1 Strengthen Institutional Coordination and Develop Joint Programmes

Governance and management of water for various uses and functions, as shown in Fig. 1, follow different institutional arrangements. Similarly, professionals engaged in various roles within water-related institutions have different kinds of training and experiences. Few irrigation engineers have a professional background or skills related to WASH, and few WASH professionals have the technical skills needed to design water infrastructure for multiple uses, for example. The notion of integrated water resource management (SDG 6.5) has been promoted as a principle to overcome problems due to sectoral division. Coordination at the lowest appropriate levels is urgently needed between WASH and irrigation for improved food security, nutrition, and health outcomes, as well as to strengthen women's agency over water decisions. Multiple-use water systems can increase food security and WASH outcomes (van Koppen et al. 2014). An example is the MiAgua programme in Bolivia supported by CAF, the development bank of Latin America, which included rural water supply, climate change adaptation measures such as watershed protection, and micro-irrigation projects for small-scale agriculture. MiAgua benefited 2.25 million people with improved or new access to water and contributed to increasing rural water coverage from 59 percent in 2011 to 69% in 2020. At a larger scale, improved coordination across riparian countries is essential for improving water securities linked to competing uses. A key example is the Aral Sea Basin, where lack of coordination between upstream and downstream countries affect both energy and food security (Bekchanov et al. 2015).

3.4.2 Implement Nutrition-Sensitive Agricultural Water Management

Nutrition and health experts need to join forces with water managers at the farm household level, at the community level, and at the government level to strengthen positive transmission pathways between both rainfed and irrigated agriculture and food and nutrition security. A recent guidance (Bryan et al. 2019) describes eight actions for increasing the nutrition sensitivity of water resource management and irrigation, as well as indicators for monitoring progress.

3.5 Increase the Environmental Sustainability of Food Systems

The water footprint of diets varies dramatically between rich and poor countries, but also by socioeconomic group within countries (Lundqvist et al. 2021). More work is urgently needed on the impact of current dietary trends on environmental resources, including water. Food-based dietary guidelines should consider the environmental footprint of proposed diets, whereby government regulations and consumer awareness should be strengthened to reduce the over-consumption of food, and further efforts are needed to reduce post-harvest waste and losses (UNSCN 2020).

3.6 Explicitly Address Social Inequities in Water-Nutrition Linkages

Vulnerable groups need to be proactively included in the development of water services, including incorporating their needs and constraints into initial infrastructure design. For rural smallholders who most lack water and food security, irrigation design should consider multiple uses of water, such as drinking, irrigation, and livestock watering, to meet women's and men's needs. While women make up a large part of the agricultural workforce, they often lack recognition and formal rights, and farmers are often considered to be 'male' in many parts of the world. Women's productive roles should be promoted, and they should be trained in irrigation and water management. Their involvement has important implications for water and food security (Meinzen-Dick et al. 2021; Balasubramanya 2019). It is also important to ensure that women and disadvantaged social groups (e.g., lower castes, stigmatised social groups) have equal access to credit, irrigable land, labour, and markets to be able to buy agricultural inputs and sell their produce (Mehta et al. 2019; UNSCN 2020).

3.7 Improve Data Quality and Monitoring for Water-Food System Linkages, Drawing on Innovations in ICT

Better data are needed if we are to truly understand the water footprint of diets and devise policies that co-maximise water and food security and nutrition goals. Challenges include poor water and poor food intake data and a lack of indicators connecting the two, but improvements are emerging (Bryan et al. 2019; HWISE network (https://hwise-rcn.org/); Lundqvist et al. 2021). More and better data will support better water management and food systems and increase transparency in decision-making. This requires sustained investments in the monitoring of a wide range of hydrological and food-related parameters worldwide. Modern Earth observation methods can support larger-scale assessment, but need to be complemented by dedicated field measurements.

Acknowledgement The support of the CGIAR Research Initiative 'NEXUS Gains – Realising benefits across on water, energy, food and ecosystems' and conceptual support from the WASAG Working Group on Water and Nutrition are gratefully acknowledged.

References

Allan JA (1997) 'Virtual water': a long term solution for water short middle eastern economies? Paper presented at the 1997 British association festival of science, Roger Stevens lecture theatre, University of Leeds, Water and Development Session, TUE.51, 14.45. https://www.soas.ac.uk/water/publications/papers/file38347.pdf

Asenso-Okyere K, Mekonnen DA (2012) The importance of ICTs in the provision of information for improving agricultural productivity and rural incomes in Africa, UNDP working papers 2012–015. United Nations Development Programme, Regional Bureau for Africa

AUC (2020) Framework for irrigation development and agricultural water Management in Africa. https://au.int/en/documents/20200601/framework-irrigation-development-and-agricultural-water-management-africa

Balasubramanya S (2019) Effects of training duration and the role of gender on farm participation in water user associations in southern Tajikistan: implications for irrigation management. Agric Water Manag 216:1–11. https://doi.org/10.1016/j.agwat.2019.01.019

Baye K, Hirvonen K (2020) Seasonality: a missing link in preventing undernutrition. Lancet Child Adolesc Health 4(1):e3

Baye K, Mekonnen D, Choufani J, Yimam S, Bryan E, Griffith JK, Ringler C (n.d.) Seasonal variation in maternal dietary diversity is reduced by small-scale irrigation practices: a longitudinal study. Matern Child Nutr. https://onlinelibrary.wiley.com/doi/10.1111/mcn.13297

Bekchanov M, Ringler C, Bhaduri A, Jeuland M (2015) How does the Rogun dam affect water and energy scarcity in Central Asia? Water Int 40(5–6):856–876. https://www.tandfonline.com/doi/full/10.1080/02508060.2015.1051788

Bryan E, Chase C, Schulte M (2019) Nutrition-sensitive irrigation and water management. World Bank, Washington, DC. http://hdl.handle.net/10986/32309

Cumming O, Arnold BF, Ban R, Clasen T, Esteves Mills J, Freeman MC, Gordon B et al (2019) The implications of three major new trials for the effect of water, sanitation and hygiene on childhood diarrhea and stunting: a consensus statement. BMC Med 17(1):173. https://doi.org/10.1186/s12916-019-1410-x

Elsabber R (2020) ICT for small-scale irrigation: a market study. GIZ GmbH, Bonn/Eschborn

FAO, IFAD, UNICEF, WFP and WHO (2021) The state of food security and nutrition in the world. 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. FAO, Rome. https://www.fao.org/documents/card/en/c/cb4474en

FAO SOFA (2020) Overcoming water challenges in agriculture. http://www.fao.org/state-of-food-agriculture/en

Fricke R, Eschmeyer W, van der Laan R (2020) Catalog of fishes: genera, species, references. California Academy of Sciences. https://researcharchive.calacademy.org/research/ichthyology/catalog/SpeciesByFamily.asp
Geere JA, Cortobius M (2017) Who carries the weight of water? Fetching water in rural and urban areas and the implications for water security. Water Altern 10(2):513–540
Headey D, Heidkamp R, Osendarp S, Ruel M, Scott N, Black R, Bouis H (2020) Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. Lancet 396(10250): 519–521. https://doi.org/10.1016/S0140-6736(20)31647-0
Heinke J, Lannerstad M, Gerten D, Havlík P, Herrero M, Notenbaert AMO, Hoff H (2020) Water use in global livestock production –opportunities and constraints for increasing water productivity. Water Resour Res. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019WR026995
Hirvonen K, Headey D (2018) Can governments promote homestead gardening at scale? Evidence from Ethiopia. Glob Food Sec 19:40–47
Hirvonen K, Hoddinott J, Minten B, Stifel D (2017) Children's diets, nutrition knowledge, and access to markets. World Dev 95:303–315
HLPE (2015) Water for food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome. http://www.fao.org/3/av045e/av045e.pdf
HLPE (2017) Nutrition and food systems. A report by the high level panel of experts on food security and nutrition of the committee on world food security, Rome. http://www.fao.org/3/i7846e/i7846e.pdf
IEA (2016). www.eia.gov/electricity/data/browser
IEA (2020) Global energy review 2020. IEA, Paris. https://www.iea.org/reports/global-energy-review-2020
IPCC (2021) Climate change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani a, Connors SL, Péan C, Berger S, Chaud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press. (in press)
IUCN (2019) The IUCN red list of threatened species, version 2019–1. http://iucnredlist.org
Jägermeyr J et al (2016) Integrated crop water management might sustainably halve the global food gap. Environ Res Lett 11:025002. https://iopscience.iop.org/article/10.1088/1748-9326/11/2/025002
Lundqvist J, Malmquist L, Dias P, Barron J, Wakeyo MB (2021) Water productivity, the yield gap, and nutrition. The case of Ethiopia. FAO land and water discussion paper No. 17. FAO, Rome. http://www.fao.org/documents/card/en/c/CB3866EN
Madan EM, Haas JD, Menon P, Gillespie S (2018) Seasonal variation in the proximal determinants of undernutrition during the first 1000 days of life in rural South Asia: a comprehensive review. Glob Food Sec 19:11–23
Martin-Ortega J, Ferrier R, Gordon I, Khan S (eds) (2015) Water ecosystem services: a global perspective (international hydrology series). Cambridge University Press, Cambridge
Mateo-Sagasta J, Zadeh SM, Turral H (eds) (2018) More people, more food, worse water? A global review of water pollution from agriculture. FAO/IWMI. CGIAR Research Program on Water, Land and Ecosystems (WLE), Rome/Colombo. http://hdl.handle.net/10568/93452
Meenakshi JV, Webb P (2019) Food systems, diets, and nutrition: global trends, challenges and opportunities. Agric Food Syst 2050:215–242. https://doi.org/10.1142/9789813278356_0007
Mehta L, Oweis T, Ringler C, Schreiner B, Varghese S (2019) Water for food security, nutrition and social justice. Routledge, London
Meinzen-Dick RS, Pradhan P, Zhang W (2021) Migration and gender dynamics of irrigation governance in Nepal. IFPRI discussion paper 2061. IFPRI, Washington, DC. https://doi.org/10.2499/p15738coll2.134815

NCD Risk Factor Collaboration, Bixby H, Bentham J et al (2019) Rising rural body-mass index is the main driver of the global obesity epidemic in adults. Nature 569:260–264. https://doi.org/10.1038/s41586-019-1171-x

Nkonya E, Iannotti L, Sakwa B, Wielgosz B (2011) Baseline study of KickStart treadle pumps in East Africa. IFPRI, Washington, DC

Perez-Escamilla R, Bermudez O, Buccini GS, Kumanyika S, Lutter CK, Monsivais P, Victora C (2018) Nutrition disparities and the global burden of malnutrition. BMJ 13:361:k2252. https://doi.org/10.1136/bmj.k2252

Ringler C (2017) Investment in irrigation for global food security. IFPRI policy note. IFPRI, Washington DC. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/131045/filename/131256.pdf

Ringler C, Zhu T, Gruber S, Treguer R, Auguste L, Addams L, Cenacchi N et al (2016) Role of water security for agricultural and economic development – concepts and global scenarios. In: Pahl-Wostl C, Bhaduri A, Gupta J (eds) Handbook on water security. Edward Elgar Publishing Ltd, Aldershot

Ringler C, Choufani J, Chase C, McCartney M, Mateo-Sagasta J, Mekonnen D, Dickens C (2018) Meeting the nutrition and water targets of the sustainable development goals: achieving progress through linked interventions. IWM. CGIAR WLE, World Bank, Colombo. https://doi.org/10.5337/2018.221

Rosegrant MW, Ringler C, Zhu T (2009) Water for agriculture: maintaining food security under growing scarcity. Annu Rev Environ Resour 34:205–223. https://doi.org/10.1146/annurev.environ.030308.090351

Sadoff CW, Borgomeo E, Uhlenbrook S (2020) Rethinking water for SDG 6. Nat Sustain 3(5): 346–347

Stayer DL, Dudgeon D (2010) Freshwater biodiversity conservation: recent progress and future challenges. J N Am Benthol Soc 29(1):344–358. https://bioone.org/journals/journal-of-the-north-american-benthological-society/volume-29/issue-1/08-171.1/Freshwater-biodiversity-conservation-recent-progress-and-future-challenges/10.1899/08-171.1.full

Sun G, Hallema D, Asbjornsen H (2017) Ecohydrological processes and ecosystem services in the Anthropocene: a review. Ecol Process 6(35). https://doi.org/10.1186/s13717-017-0104-6

UN (2018) Sustainable development goal 6 synthesis report 2018 on water and sanitation, New York

UN Environment (2018) Progress on water-related ecosystems. Piloting the monitoring methodology and initial findings for SDG indicator 6.6.1. https://reliefweb.int/sites/reliefweb.int/files/resources/661-progress-on-water-related-ecosystems-2018.pdf

UNICEF (n.d.) Collecting water is often a colossal waste of time for women and girls. Press release. https://www.unicef.org/press-releases/unicef-collecting-water-often-colossal-waste-time-women-and-girls

UNICEF, WHO (2021) Progress on household drinking water, sanitation and hygiene, 2000–2020: five years into the SDGs. UNICEF, WHO, New York. https://washdata.org/sites/default/files/2022-01/jmp-2021-wash-households_3.pdf

UNSCN (2020) Water and nutrition. Harmonizing actions for the United Nations decade of action on nutrition and the United Nations water action decade. UNSCN, Rome. https://www.unscn.org/uploads/web/news/document/Water-Paper-EN-WEB-2mar.pdf

van Koppen B, Smits S, del Rio CR, Thomas J (2014) Scaling up multiple use water services: accountability in the water sector. IWMI Books, Reports H046385

Warner M, Kahan D, Lehel S (2008) Market-oriented agricultural infrastructure: appraisal of public-private partnerships. FAO, Rome

Willet J, Wetser K, Vreeburg J, Rijnaarts HHM (2019) Review of methods to assess sustainability of industrial water use. Water Resour Ind 21:2212–3717. https://doi.org/10.1016/j.wri.2019.100110

World Bank (2010) Improving water Management in Rainfed Agriculture: issues and options in water-constrained production systems. World Bank other operational studies 13028. The World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/13028/696130ESW0P1100gement0Rainfed0Final.pdf
WWAP (2018) The United Nations world water development report 2018: nature-based solutions. UNESCO, Paris
Xie H, Ringler C (2017) Agricultural nutrient loadings to the freshwater environment: the role of climate change and socioeconomic change. Environ Res Lett 12:104008
Young SE, Frongillo E, Melgar-Quinoñez H, Perez-Escamilla R, Rosinger R, Ringler C, Jamaluddine Z (2021) Perspective: the importance of water security for ensuring food security, good nutrition, and well-being. Adv Nutr. nmab00. https://academic.oup.com/advances/advance-article/doi/10.1093/advances/nmab003/6144691
Yu W, Uhlenbrook S, Von Gnechten R, Van der Bliek J (2021) Can water productivity improvements save us from global water scarcity? A white paper. FAO, Rome

Climate Change and Food Systems

Alisher Mirzabaev, Lennart Olsson, Rachel Bezner Kerr, Prajal Pradhan, Marta Guadalupe Rivera Ferre, and Hermann Lotze-Campen

1 Introduction

Climate change affects the functioning of all of the components of food systems (IPCC 2019) that embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and recycling of food products that originate from agriculture (including livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded (von Braun et al. 2021). At the same time, food systems are a major cause of climate change, contributing about a third (21–37%) of the total GHG emissions through agriculture

A. Mirzabaev (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: almir@uni-bonn.de

L. Olsson
Centre for Sustainability Studies (LUCSUS), Lund University, Lund, Sweden

R. B. Kerr
Department of Global Development, Cornell University, Ithaca, NY, USA

P. Pradhan
Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

M. G. R. Ferre
INGENIO (CSIC-Universitat Politècnica de València), Valencia, Spain

H. Lotze-Campen
Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany

The Agricultural Model Intercomparison and Improvement Project (AgMIP), New York, NY, USA

Food System Economics Commission (FSEC), Potsdam, Germany

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_27

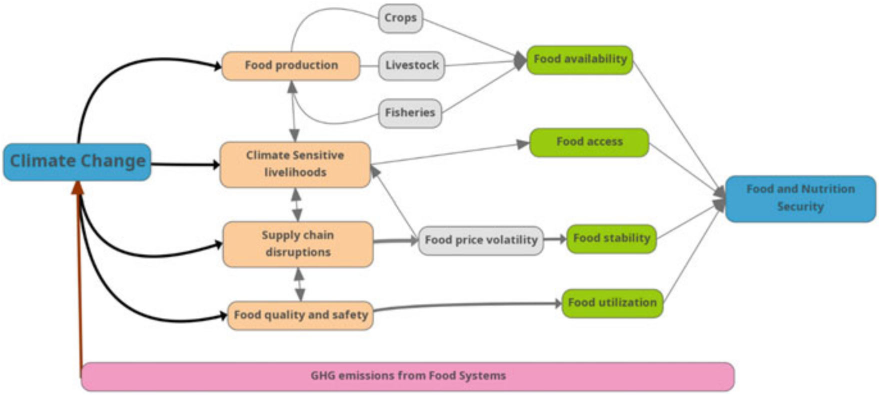


Fig. 1 Linkages between climate change and food systems

and land use, storage, transport, packaging, processing, retail, and consumption (Mbow et al. 2019) (Fig. 1).

Climate change will affect food systems differentially across world regions. While some areas, such as northern temperate regions, may even experience some beneficial changes in the short term, tropical and sub-tropical regions worldwide are expected to face changes that are detrimental to food systems. Such changes will have effects on food and nutrition security through a complex web of mechanisms (Fig. 1). Critical climate variabilities that affect food and nutrition security include increasing temperatures, changing precipitation patterns and greater frequency or intensity of extreme weather events such as heatwaves, droughts and floods (Mbow et al. 2019). They impact the productivity of crops, livestock and fisheries by modulating water availability and quality, causing heat stress, and altering the pests and disease environment, including through the faster spread of mycotoxins and pathogens. Increased frequency and intensity of floods and droughts can lead to considerable disruptions in food supply chains through harvest failures and infrastructure damage. The exposure of people to heatwaves, droughts and floods can harm their health and lower their productivity, affecting their livelihoods and incomes, especially for those engaged in climate-sensitive sectors or working outdoors. This exposure can strongly affect more vulnerable groups in many lower-income countries, e.g., smallholder farmers, low-income households, women and children. Other factors related to climate change that affect food systems are the rise in atmospheric concentrations of CO_2, and, indirectly, land degradation, and a reduction in pollination services. Changes in CO_2 levels in the atmosphere affect both crop yields and their nutrient content. Climate change will exacerbate land degradation through increased soil erosion, especially in sloping and coastal areas, increased soil salinity in irrigated lands, and climates that are more arid and more prone to desertification in some dryland areas (Olsson et al. 2019; Mirzabaev et al. 2019). The potential reduction or loss of pollination services also leads to lower crop yields. Conservative estimates, which consider these climate change impacts only partially, show that the number of people at risk of hunger may increase by 183 million by 2050 under high emission and low adaptation scenario [i.e., under Shared Socioeconomic Pathway (SSP) 3], compared to low emission and high adaptation scenarios (SSP1). An additional 150–600 million people are projected to experience various forms of micronutrient deficiency by 2050 in the higher emission scenario (Myers et al. 2017; Zhu et al. 2018; Medek et al. 2017).

The interactions between climate change and food systems have considerable repercussions across all of the dimensions of sustainable development. In fact, in six of the 17 sustainable development goals (SDGs), climate change-food system interactions increasingly play a major role. These relate to the social goals of zero hunger (SDG 2) and gender equality (SDG5), and the four environmental goals of water resources (SDG 6), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15). Solutions addressing the challenges posed by climate change-food system interactions can serve as a critical entry point for promoting the 2030 Agenda for sustainable development well beyond the timeline of the current SDGs (Pradhan et al. 2017). Since these interactions vary according to the country's income, region, and population groups (i.e., gender, age, and location of its population), solutions prioritising women, youths, and rural people, i.e., "leaving no one behind," can better leverage the achievements of the SDGs (Warchold et al. 2021).

2 How Climate Change Interacts with Food Systems and Food Security

2.1 Food Availability

Considerable evidence has by now emerged indicating that climate change is already negatively affecting crop production in many areas across the world (Kim et al. 2019; FAO 2018). Reductions of 21% in total factor productivity of global agriculture since 1961 have been estimated (Ortiz-Bobea et al. 2021). It has been found that climate change over the last four-five decades has reduced the yields of cereals by about 2–5% on average globally, compared to the situation if there had been no climate change (Iizumi et al. 2018). This range of about 5% lower cereal yields due to climate change was also found in regional studies, for example, for wheat and barley in Europe (Moore and Lobell 2015), for wheat in India (Gupta et al. 2017), and for maize in Africa, Central and Eastern Asia (Ray et al. 2019), and Central and South America (Verón et al. 2015). Higher losses equalling about 5–20% were found for millet and sorghum yields in West Africa (Sultan et al. 2019), and maize yields in Eastern and Southern Europe were estimated to be lower by about 5–25% (Agnolucci and De Lipsis 2020). There is growing literature documenting the negative impacts of climate change on the yields of legumes, vegetables, and fruits in drylands, tropical and sub-tropical areas (Mbow et al. 2019; Scheelbeek et al.

2018). These losses in yields have occurred after the taking of coping and adaptive actions (Mbow et al. 2019).

In temperate climatic zones, such as northern China, parts of Russia, northern Europe, and parts of Canada, observed climatic changes are increasing the agricultural potentials, leading to higher crop production (Moore and Lobell 2015; Ray et al. 2019; Potopová et al. 2017; Meng et al. 2014; Wang and Hijmans 2019; Bisbis et al. 2018). However, in many areas, this increased production is coming at the expense of lower yield stability due to higher weather variability between seasons. Climate change accounts for about half of food production variability globally. Presently, adaptive strategies for increasing crop yields (crop breeding, improved agronomic management, adaptations based on indigenous and local knowledge, etc.) can withstand, at a global average, any impacts of climate change on said yields. However, the acceleration of climate change can overwhelm this trend in the future; and the impacts are already being experienced in many regions. Climate change increased drought-induced food production losses in southern Africa, leading to 26 million people in the region requiring humanitarian assistance in 2015–2016 (Funk et al. 2018). Climate change is also increasing ocean acidification and temperatures, reducing farmed fish and shellfish production, as well as wild fish catches, with some regions experiencing losses of 15%–35% (Mbow et al. 2019).

The impacts of climate change on food production are projected to worsen after the 2050s, particularly under higher emission scenarios (Mbow et al. 2019). In agriculture, the biggest crop yield declines due to climate change are expected to occur in those areas that are already hot and dry, especially in the tropics and sub-tropics, as well as in the global drylands where water scarcity is projected to become more acute (Mirzabaev et al. 2019). More recent modelling shows that previous projections of climate change impacts on future crop yields underestimated the extent of potential yield declines. For example, many crop modelling studies do not consider the effect of short-term extreme weather events. Although extreme weather events have always posed the threat of disruptions in food systems, climate change is increasing the likelihood of simultaneous crop failures in major crop-producing areas in the world (Anderson et al. 2019; Heino et al. 2020). Disruptions in storage and distribution infrastructures and on food provisioning due to extreme event systems will also impact food availability, as well as bringing about a reduction in food exchanges due to lower productivity (Rivera Ferre 2014).

New twenty-first century projections by the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al. 2021a), using ensembles of latest-generation crop and climate models, suggest markedly more pessimistic yield responses for maize, soybean, and rice, compared to the original ensemble. End-of-century maize productivity is shifted from +5 to −5% (SSP126) and from +1 to −23% (SSP585), explained by warmer climate projections and a revised crop model ensemble (Jägermeyr et al. 2021). In contrast, wheat shows stronger high-latitude gains, related to higher CO_2 responses. The 'emergence' of the climate impact signal—when mean changes leave the historical variability—consistently occurs earlier in the new projections, as early as 2030 in several of the main producing regions. While future yield estimates remain uncertain, these results suggest that major breadbasket regions may contend with a changing profile of climatic risks within the next few decades (Jägermeyr et al. 2021). While many fruit, vegetable and perennial crops are understudied, higher temperatures are projected to negatively impact their production, with one study estimating a 4% reduction in fruit and vegetable production as the result of climate change (Springmann et al. 2016).

The impacts of climate change on livestock systems and fisheries have been studied much less than those on the major crops. Nonetheless, considerable evidence indicates that increased frequency of heatwaves and droughts under climate change can lower livestock productivity and reproduction through heat stress, reduced availability of forage, increased water scarcity and the spread of livestock diseases (Mbow et al. 2019; Rojas-Downing et al. 2017). Increased levels of CO_2 can favour the growth of pasture grasses, especially during rainier seasons and in more humid locations (Mirzabaev et al. 2019; Herrero et al. 2016). In contrast, in many arid and semi-arid locations, the projected effects are mostly negative (Rojas-Downing et al. 2017; FAO 2015; Boone et al. 2018). Climate change was found to reduce the maximum sustainable yield of several marine fish populations by about 4% (Free et al. 2019). Every 1 °C increase in global warming was projected to decrease mean global animal biomass in the oceans by 5% (Lotze et al. 2019), as well as redistributing fish populations away from sub-tropical and tropical seas towards poleward areas (Oremus et al. 2020). It is clear that the association between climate change and human nutrition goes beyond issues of caloric availability, and a growing challenge by 2050 will be providing nutritious and affordable diets (Springmann et al. 2016).

2.2 Food Access

The impacts of climate change on agricultural production, supply chains and labour productivity in climate-sensitive sectors will influence both food prices and incomes, strongly affecting people's ability to purchase food through these price and income changes (Baarsch et al. 2020). Climate change is projected to increase global cereal prices by between 1% to 29%, depending on the Shared Socioeconomic Pathway considered (Mbow et al. 2019). The reductions in the yields of legumes, fruits and vegetables will also lead to higher prices for them. The impacts of these price increases on food access are not straightforward. Net food-selling agricultural producers can benefit from higher food prices (Hertel et al. 2010). Those same higher food prices will primarily hurt the urban poor and net food-buying agricultural producers (Mbow et al. 2019). Increased temperatures and more frequent heatwaves will reduce labour productivity for outdoor work and work in closed areas without air conditioning. Lower labour productivity will result in lower incomes and lower purchasing power.

2.3 Food Stability

Climate change will increase the frequency of extreme water events, such as droughts, floods, hurricanes, and sea storms. Resulting inter-annual variability in food production, the destruction of transportation infrastructures, and greater food price instability can ultimately lead to more volatile global and regional food trade, undermining people's ability to access food in a stable way (Mbow et al. 2019). These disruptions could have a particularly negative impact on land-locked countries with less infrastructural access to the global food trade, as well as vulnerable social groups, especially in those locations without functioning or sufficient social protection schemes (FAO 2018).

2.4 Food Utilisation and Safety

Climate change is projected to adversely impact childhood undernutrition, stunting, and undernutrition-related childhood mortality and increase the number of disability-adjusted life years lost, with the largest risks being in Africa and Asia (Hasegawa et al. 2018a). Moreover, climate-related changes in food availability and diet quality are estimated to result in 529,000 excess climate-related deaths with about 2 °C warming by 2050 (Springmann et al. 2016). Most of these deaths are projected to occur in South and East Asia. Extreme climate events will even increase risks of undernutrition on a regional scale, via spikes in food prices and reduced income. Exposure to one pathway of food insecurity risk (e.g., lower yields) does not exclude exposure to other pathways (e.g., income reduction). Higher concentrations of atmospheric CO_2 reduces the protein and mineral content of cereals, degrading the quality of food and, subsequently, food utilisation (Mbow et al. 2019). Rising temperatures are improving the conditions for the spread of pathogens and mycotoxins, posing risks to human health and increasing food waste and loss (Battilani 2016). Climate change is projected to increase the area of spread of mycotoxins from tropical and sub-tropical areas to temperate zones (Mbow et al. 2019). Reduction in water quality due to climate change will also negatively affect food utilisation.

2.5 Impacts of Food Systems on Climate Systems

GHG emissions from food systems are a major contributor to climate change. Food systems are responsible for about one-quarter of global GHG emissions, or even up to one-third if indirect effects on deforestation are included (21%–37%) (Mbow et al. 2019). Specifically, new estimates by the Food Climate Partnership (Rosenzweig et al. 2021b) show that total GHG emissions from the food system were about 16 CO_2 eq year^{-1} in 2018, or one-third of the total global anthropogenic

GHG emissions. Three-quarters of these emissions, 13 Gt CO_2 eq year^{-1}, were generated either during on-farm production or in pre- and post-production activities, such as manufacturing, transport, processing, and waste disposal. The remainder was generated through land use change of natural ecosystems to agricultural land. Results further indicate that pre- and post-production emissions were proportionally more important in high-income than in low-income countries, and that, during the period 1990–2018, land use change emissions decreased while pre- and post-production emissions increased (Tubiello et al. 2021).

Even if fossil fuel-related emissions were stopped immediately, continuation of the current food system emissions could make the below 2 °C climate target unachievable (Clark et al. 2020). There are significant opportunities for reducing these emissions (Smith et al. 2019),, but at the same time, it is important to bear the food security implications in mind when implementing climate mitigation efforts (Frank et al. 2019; Hasegawa et al. 2018b). Without compensatory policies in place, stringent, abrupt and large-scale application of mitigation options, particularly those that are land-based, can have a negative impact on global hunger and food consumption, with the detrimental impacts being especially acute for vulnerable, low-income regions that already face food security challenges (Hasegawa et al. 2018a). However, many climate solutions can have mitigation and adaptation synergies together with other co-benefits, including for health, livelihood, and biodiversity (Smith et al. 2019; Rosenzweig et al. 2020).

3 Solutions for Climate Change Adaptation and Mitigation in Food Systems

Based on the above assessment, as well as the recent IPCC special report on Climate Change and Land (IPCC 2019), the following actions are proposed for uptake by governments, the private sector and civil society. These actions are of two types. Firstly, there are a wide range of both well-tested, ready-to-go solutions, and potential solutions for climate change adaptation and mitigation within food systems (Herrero et al. 2020) (Actions 1 to 7). Many of these already available solutions are well known and are being applied at local scales around the world, even if not at sufficient levels. Hence, the major effort to unleash their potential would involve overcoming various technical and structural barriers for their much wider application. The second type of action (8 and 9) focuses on key promising solutions that can help us meet the longer-term challenges of climate change within the context of food systems in the second half of this century, when most food production practices will face unprecedented challenges.

1. Amplify efforts for sustainable land management

Sustainable management of land (SLM), which includes water, supports and maintains ecosystem health, increases agricultural productivity, and contributes to climate change adaptation and mitigation (Olsson et al. 2019; Mirzabaev et al. 2019). SLM is defined as the use of land resources, including soils, water, animals and plants, to produce goods that meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions (UN 1992 Rio Earth Summit).

There are many practical examples of SLM. Application of water-efficient irrigation methods such as sprinkler and drip irrigation can help increase resilience to increasing aridity under climate change (Mirzabaev et al. 2019). Adoption of drought-resistant crop cultivars under diversified cropping systems is an essential adaptive strategy in many dryland areas (Mirzabaev et al. 2019). Where suitable, agroforestry is a powerful practice for reducing soil erosion and increasing carbon sequestration, while diversifying livelihoods (Smith et al. 2019). Rangeland management systems based on sustainable grazing and re-vegetation can increase rangeland resilience and long-term productivity while supporting a wide range of ecosystem services. Agroforestry practices, shelterbelts and silvio-pasture systems help reduce soil erosion and sequester carbon, while increasing biodiversity that supports pollination and other ecosystem services (Kuyah et al. 2019). SLM also includes agroecological practices, such as use of organic soil amendments, crop diversification, cover crops, intercropping, conservation agriculture practices, etc., that can have positive impacts on ecosystem services, food security and nutrition (Bezner Kerr et al. 2021; Beillouin et al. 2019; Muller et al. 2017; Tamburini et al. 2020; Kremen and Merenlender 2018). Indigenous knowledge and local knowledge hold a great array of practices for SLM (Rivera Ferre et al. 2021). Protection, restoration and climate-friendly management of peatlands are key elements for ambitious emission reduction strategies (Humpenöder et al. 2020).

Although SLM has been proven to provide positive social and economic returns, the adoption is currently insufficient. Important barriers for adoption are access to the resources for changing practices and the time required for the new practices to become productive. Introduction of payments for ecosystem services and subsidies for SLM can help. Enabling policy frameworks that include both incentives and disincentives are needed for promoting the adoption of SLM. Land tenure considerations are a major factor contributing to the adoption of SLM (Olsson et al. 2019), particularly for women. Various forms of collective action are crucial for implementing SLM in both privately and communally managed lands (Pretty 2003), although such efforts need to be strengthened and supported by policy (Isgren 2018). A greater emphasis on understanding gender-specific differences over land use and land management practices can promote SLM practices more effectively. Improved access to markets, including physical (e.g., transportation), economic (e.g., fair prices), and political (e.g., fair competition) support, raises agricultural profitability and motivates investment into climate change adaptation and SLM. Developing, enabling and promoting access to clean energy sources and technologies can contribute to reducing land degradation and mitigating climate change through decreasing the use of fuelwood and crop residues for energy, while significantly improving health for women and children (Sana et al. 2019). Finally, looking at co-benefits between addressing climate change (adaptation and mitigation) and other urgent problems, like land degradation and biodiversity conservation, much can be gained by promoting SLM in agriculture.

2. Promote open and equitable food trade

The very heterogeneous effects of climate change on food production worldwide and the increase in extreme weather events that disrupt local food production activities highlight the importance of international food trade as a key adaptation option to this volatile environment (Van Meijl et al. 2018; Stevanović et al. 2016). At the same time, strengthening regional and local food systems, through policies and programmes that support sustainable local production, can help build a resilient food system. Such policies can include support for urban and peri-urban production, public procurement, and subsidies that encourage the application of sustainable production approaches.

Adapting to changing climate will require a combination of enhanced regional and local food trade, as well as international food trade, that can act as safety nets in the context of climate crises. To this aim, reducing transaction costs of food trade and maintaining transparent and well-enforced international food trade governance can strengthen food systems' resilience. This will particularly include avoiding imposing export bans. Food trade and food sovereignty are complementary elements of food security, and should not be regarded as mutually exclusive; rather, transparent and fair norms need to be agreed upon.

Fiscal instruments (e.g., carbon taxes) need to be given high priority in order to reduce fossil fuel use in agriculture. Agricultural subsidies need to be adjusted to encourage the application of sustainable production approaches and make sure that any negative effects that arise from them will be reduced through trade, and they need to take power differences into account, e.g., the impacts of subsidised food exports by high-income countries that make it harder for farmers in low-income countries to use sustainable methods or sell their products. Trade agreement mechanisms that allow low-income countries to have an equal say in trade governance are needed.

3. Include food systems in climate financing at scale

Food systems represent a range of actors and their interlinked value-adding activities that are most impacted by climate change. Food systems are also a major source of GHG emissions. This makes food systems a high priority target for adaptation and mitigation investments. However, investments into climate change adaptation and mitigation in food systems to date have only accounted for a tiny fraction of the total amounts of climate finance. Investments into climate change mitigation in food systems need to be commensurate with the share of GHG emissions coming from those systems, i.e., about a third of all mitigation funding, which is presently dominated by the energy sector and infrastructure. To illustrate, there are considerable opportunities for climate change adaptation and mitigation through investments into land restoration (e.g., reforestation, sustainable land management, re-seeding degraded rangelands) that allow for sequestering carbon in soils, increasing crop and livestock productivity and providing a wide range of other ecosystem services.

Estimates show that every dollar invested in land restoration yields anywhere from 3 to 6 dollars of return, depending on the location across the world (Nkonya et al. 2015). Investments in food value chains for reducing food waste and loss is another area with substantial mitigation and adaptation benefits. A wide range of public and private sources could be harnessed for these investments, such as increasing substantially the annual development aid dedicated to agricultural and rural development, food and nutrition security, increased investments by international and regional development banks in food systems, and more active involvement of the private sector (e.g., green bonds) and philanthropies.

4. Strengthen social protection and empowerment of the vulnerable

It is now practically impossible to fully adapt to climate change impacts. Even without climate change, extreme weather events periodically inflict significant disruptions on food systems at the local, regional and even global levels. Climate change will make these disruptions more frequent and more extensive. Therefore, it is essential to strengthen the social protection for vulnerable populations in terms of accessing food during the times of such disruptions. Social protection can involve many forms, such as access to subsidised food banks, cash transfers, insurance products, pension and employment guarantee schemes, weather index insurance, and universal income.

The impacts of climate change on food systems are not suffered equally by all social groups. Age, class, gender, race, ethnicity, and disability, among others, are social factors that make some people more vulnerable than others. Actions to address such inequality and differential impacts imply, on the one hand, strengthening social protection and, on the other hand, empowering marginalised social groups through collective action. Empowering women in societies increases their capacity to improve food security under climate change, making substantial contributions to their own well-being, that of their families and that of their communities. Women's empowerment is crucial to creating effective synergies among adaptation, mitigation, and food security, including targeted agriculture programmes to change socially-constructed gender biases (Kerr et al. 2016). Empowerment through collective action and groups-based approaches in the near-term has the potential to equalise relationships on the local, national and global scales (Ringler et al. 2014).

5. Encourage healthy and sustainable diets

Transitioning to more healthy and sustainable diets and minimising food waste could reduce global mortality from 6% to 19% and food-related GHG emissions by 29%–70% by 2050 (Springmann et al. 2016; Willett et al. 2019). According to the WHO, healthy diets are essential to end all forms of malnutrition and protect people from non-communicable diseases, including diabetes, heart disease, stroke and cancer. Currently, food consumption deviates from healthy diets with either too much (e.g., red meat and calories) or too little (e.g., fruits and vegetables) food and nutrition supply (Pradhan and Kropp 2020). Healthy diets have an appropriate calorie intake, according to gender, age and physical activity level. They are mainly composed of a diversity of plant-based foods, including coarse grains, pulses, fruits and vegetables, nuts, and seeds, with low amounts of animal source foods (Willett et al. 2019). The current diets of many high-income countries comprise a large share of animal source foods that are emission-intensive, with red meat consumption higher than the recommended value. Simultaneously, consumption of fresh fruits and vegetables is below the recommended value in most countries (Bodirsky et al. 2020).. Changes towards healthier diets have a mitigation potential of 0.7–8.0 $GtCO_2$-eq year^{-1} by 2050, but social, cultural, environmental, and traditional factors need to be considered to achieve this potential at broad scales (Mbow et al. 2019; Rosenzweig et al. 2020). One critical problem is that, currently, healthy diets are unaffordable to broad sections of societies, even in high-income countries. Sustainable and healthy diets based on diversified intake are often linked to diversified production systems, highlighting the linkages between production and consumption (Chepkoech et al. 2020).

To encourage dietary transitions towards healthy and sustainable diets, a full range of policy instruments, from hard to soft measures, is needed (Willett et al. 2019). For example, unhealthy consumption of emission-intensive animal source foods can be disincentivised by applying taxes and charges, whereas adequate consumption of healthy foods such as fruits and vegetables can be incentivised by providing subsidies and raising consumer awareness. Importantly, policies promoting healthy diets need to pay due consideration to the differential roles of animal source foods in different parts of the world and the important role livestock can play in sustainable agriculture. For example, a recent study from Nepal, Bangladesh and Uganda showed a reduction in stunting in young children due to adequate intake of animal source foods (Zaharia et al. 2021).

6. Reduce GHG emissions from the food systems

Before promoting particular changes to the food systems, it is important to have an overview of where the most important potentials for reducing GHG emissions are. Agriculture is responsible for about 60% (or even 80%, if the indirect land use change is included) of total GHG emissions from the global food system (Mbow et al. 2019). One important message from a systematic meta-analysis of 38,700 farms and 1,600 food processors is the wide range of emissions – about a 50-fold difference between the best and worst practices (Poore and Nemecek 2018). This means that political and economic measures can achieve major reductions in GHG emissions from existing food systems by more broadly applying current best practices and without waiting for new technologies or behaviour changes.

Reducing GHG emissions requires integrated interventions both at the production and consumption sides. On the production side, all of those practices that increase soil organic matter contribute to both adaptation and mitigation, while also decreasing soil degradation and erosion. Globally, cropland soils have lost an estimated 37 GtC (136 Gt CO_2) since the Neolithic revolution (Sanderman et al. 2017); recapturing that lost carbon through SLM would not only contribute to climate change mitigation, it would also increase the ecological resilience of agro-ecosystems and provide opportunities for income and employment in rural societies. A wide range of practices exist, e.g., conservation agriculture practices, lower GHG emissions from fertilisers, agroecology-based approaches, agroforestry or the integration of agriculture and livestock systems that have an estimated potential to sequester 3–6.5 $GtCO_2$-eq/year (Arneth et al. 2021). In rangelands as well, extensive and mixed farming systems, through improved management practices, have the capacity to reduce emissions. Presently, there are between 200 and 500 million pastoralists in the world who act as stewards for 25% of the world's land (Niamir-Fuller 2016).

Meat and dairy consumption is often considered a major culprit of high GHG emissions from food systems, but the discussion often lacks nuance. It is clear that the overall emissions from consumption of animal protein (mainly meat and dairy products) must be reduced to achieve mitigation targets compatible with the Paris Agreement. However, in some regions of the world, an increased consumption of animal protein would be desirable from a health perspective. It is also clear that livestock plays an important role in sustainable food systems – in particular, extensive livestock can help to reduce the need for mineral fertilisers, and they can produce food from areas unsuitable for growing crops (notably, drylands, cold regions and mountainous regions). Finally, expansion of post-harvest processing, refrigeration, subsidy shifts and behavioural changes are needed to reduce food loss and waste and lower the consumption of animal products in those places where intake is too high. Incentives for emission reductions should also be given to agricultural producers by applying GHG emission taxes in agriculture, or including agriculture in existing emission trading schemes.

7. Support urban and peri-urban agriculture

Promoting urban and peri-urban agriculture (PUA) can help increase the resilience of local and regional food systems, create jobs, and, under certain conditions, help reduce GHG emissions from food transportation (Pradhan et al. 2020) and decrease uncertainties that may be associated with disruptions in food systems. PUA includes crop production, livestock rearing, aquaculture, agroforestry, beekeeping, and horticulture within and around urban areas (Clinton et al. 2018). Around 1 billion urban inhabitants (i.e., 30% of the global urban population) can be nourished by producing food through PUA (Kriewald et al. 2019). Simultaneously, PUA can support the regionalisation of food systems, reducing emissions from food transportation (Pradhan et al. 2020). Moreover, PUA is multi-functional and is practised to follow various purposes: it helps to improve food security, generate income, provide employment (Poulsen et al. 2015; Warren et al. 2015), especially for women and youths, and reconnect urban habitants with nature cycles. Subsequently, PUA not only has great potential to reduce poverty and improve nutrition, but also provides a series of ecosystem services such as reduced urban heat island effects (Li et al. 2014) or the fixation of atmospheric nitrogen and carbon when using the appropriate vegetation (Beniston and Lal 2012), thus contributing to climate change mitigation and adaptation. PUA also comprises elements of a circular economy, in which household organic waste can be used as livestock and poultry feed, rather than treated as waste (Ibrahim and Elariane 2018), subsequently reducing environmental pollution and GHG emissions. PUA contributes to increasing the resilience of urban poor households to food price shocks. Previous research on PUA showed that it was the main and only economic activity of poor urban households in many low-income countries. And even when PUA is not the main economic activity of poor urban households, it made a significant contribution to smoothening seasonal food consumption shocks among the urban poor (Poulsen et al. 2015).

8. Invest in research

There have been tremendous advances in better understanding of the interactions between climate change and food systems in recent decades (IPCC 2019; Wheeler and Von Braun 2013). These investments in research and science need to be expanded into the future, not least to ensure viable agricultural systems in the long term when climate change will expose current staple food crops to unprecedented stress. Areas for investment include agroecological approaches to food production, which have so far received far lower investment (HLPE 2019), the breeding of drought-resistant crop cultivars and cultivars with improved nitrogen use to avoid emission of N_2O (Coskun et al. 2017), improved understanding of climate change impacts on both staple and non-staple foods, including impacts on the nutrition values of crops (Soares et al. 2019), particularly vegetables and fruits, and the subsequent implications for healthy diets and the full costs of said diets. Along with these environmental dimensions, increased investment in research on the social and economic impacts of climate change are needed, for example, in such areas as understanding the impacts of climate change and mitigation and adaptation options on vulnerable groups, research on participatory and transdisciplinary approaches to facilitating dialogue between indigenous and scientific knowledge, research on collective action, social innovation and mechanisms to increase food security.

9. Support perennial crop development and cultivation

About 87% of the world's harvested area is cultivated with annual crops, mainly grains (cereals, oilseeds, and pulses) that are germinated [?] and re-sown every year/season (Monfreda et al. 2008). A shift to perennial grain crops would drastically cut GHG emissions from agriculture, and even turn cropping into a carbon sink, while significantly reducing erosion and nutrient leakage. Continued climate change is rendering our existing cultivars increasingly vulnerable to stress, and will ultimately make them unfit for many regions of the world (Altieri et al. 2015). New perennial cultivars have the potential to create cropping systems that are genuinely adapted for the climatic conditions towards the second half of this century. Perennial crops have the potential to drastically reduce the costs of farming by cutting the need for external inputs (seeds, fertilisers, pesticides, machinery, energy, and labour), and hence generate social and economic advantages, particularly or farmers and rural societies (Crews et al. 2018).

Development of new perennial grain crops through *de novo* domestication and wide hybridisation have advanced tremendously in the last decade, thanks to scientific and technological advancements such as genomic selection technology (Crain et al. 2021). The key benefits of perennial crops are that their widespread root systems can help sequester carbon in the soils for extended periods of time, water and minerals are used more efficiently by perennial plants, and weeds are more effectively managed (Crews et al. 2018; DeHaan et al. 2020). They are also exceptionally drought-resistant and can bring soil erosion and nutrient-leaching to a practical minimum (Crews et al. 2016). There are already commercial cultivars of perennial rice (Zhang et al. 2021) and successful semi-commercial experiments with perennial Kernza, a wheat relative (Lanker et al. 2020). The yields of Kernza are still low compared to conventional wheat, but continued breeding can result in a competitive perennial alternative to wheat in 20–25 years (Bajgain et al. 2020). A range of other crops is in the pipeline for domestication and breeding as perennial crops, such as barley, oilseeds and pulses. Equally important is the development of perennial polycultures, such as the intercropping of perennial grains and legumes, making the system more or less self-sufficient in nitrogen. These results are proof of concept that high yielding perennial cultivars can be developed within the timeframe of a few decades, but research on all aspects of such a "perennial revolution" is urgently needed.

4 Conclusion

This chapter has two central messages. The bad news is that climate change is projected to affect food systems around the world significantly, often in ways that exacerbate existing frailties/weaknesses and inequalities among regions of the world and groups in society. The good news is that many practices, technologies, and wells of knowledge and social capital already exist to address climate change constructively, in terms of both mitigation and adaptation, as well as synergies between them and co-benefits with other important goals such as the conservation of biodiversity and other ecosystem services. Therefore, food systems can and should play a much bigger role in climate policies. In the short term, pro-poor policy changes and support systems can unleash a range of positive changes well beyond food systems without delay. In the long term, there is an urgent need to invest in research to ensure food security and ecosystem integrity for coming generations.

References

Agnolucci P, De Lipsis V (2020) Long-run trend in agricultural yield and climatic factors in Europe. Clim Change 159:385–405

Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. Agron Sustain Dev 35:869–890

Anderson WB, Seager R, Baethgen W, Cane M, You L (2019) Synchronous crop failures and climate-forced production variability. Sci Adv 5:eaaw1976

Arneth A et al (2021) Restoring degraded lands. Annu Rev Env Resour 46

Baarsch F et al (2020) The impact of climate change on incomes and convergence in Africa. World Dev 126:104699

Bajgain P et al (2020) 'MN-Clearwater', the first food-grade intermediate wheatgrass (Kernza perennial grain) cultivar. J Plant Regist 14:288–297
Battilani P (2016) Recent advances in modeling the risk of mycotoxin contamination in crops. Curr Opin Food Sci 11:10–15
Beillouin D, Ben-Ari T, Makowski D (2019) Evidence map of crop diversification strategies at the global scale. Environ Res Lett 14:123001
Beniston J, Lal R (2012) Improving soil quality for urban agriculture in the north central U.S. In: Carbon Sequestration in Urban Ecosystems. Springer, pp 279–313. https://doi.org/10.1007/978-94-007-2366-5_15
Bezner Kerr R et al (2021) Can agroecology improve food security and nutrition? A review. Glob Food Sec 29:100540
Bisbis MB, Gruda N, Blanke M (2018) Potential impacts of climate change on vegetable production and product quality – a review. J Clean Prod 170:1602–1620
Bodirsky BL, Dietrich JP, Martinelli E, Stenstad A, Pradhan P, Gabrysch S, Mishra A, Weindl I, Le Mouël C, Rolinski S, Baumstark L, Wang X, Waid JL, Lotze-Campen H, Popp A (2020) The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. Sci Rep 10
Boone RB, Conant RT, Sircely J, Thornton PK, Herrero M (2018) Climate change impacts on selected global rangeland ecosystem services. Glob Chang Biol 24:1382–1393
Chepkoech W, Mungai NW, Stöber S, Lotze-Campen H (2020) Understanding adaptive capacity of smallholder African indigenous vegetable farmers to climate change in Kenya. Clim Risk Manag 27:100204
Clark MA et al (2020) Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science (80) 370:705 LP–705708
Clinton N et al (2018) A global geospatial ecosystem services estimate of urban agriculture. Earth's Futur 6:40–60
Coskun D, Britto DT, Shi W, Kronzucker HJ (2017) Nitrogen transformations in modern agriculture and the role of biological nitrification inhibition. Nature Plants 3:1–10
Crain J, DeHaan L, Poland J (2021) Genomic prediction enables rapid selection of high-performing genets in an intermediate wheatgrass breeding program. Plant Genome 14:e20080. https://doi.org/10.1002/tpg2.20080
Crews TE et al (2016) Going where no grains have gone before: from early to mid-succession. Agric Ecosyst Environ 223:223–238
Crews TE, Carton W, Olsson L (2018) Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. Glob Sustain 1
DeHaan L et al (2020) Roadmap for accelerated domestication of an emerging perennial grain crop. Trends Plant Sci 25:525–537
FAO (2015) Climate change and food systems: Global assessments and implications for food security and trade
FAO (2018) The future of food and agriculture – Alternative pathways to 2050
Frank S et al (2019) Agricultural non-CO_2 emission reduction potential in the context of the 1.5 °C target. Nat Clim Chang 9:66–72
Free CM et al (2019) Impacts of historical warming on marine fisheries production. Science (80) 363:979 LP–979983
Funk C et al (2018) Anthropogenic enhancement of moderate-to-strong El Niño events likely contributed to drought and poor harvests in southern Africa during 2016. Bull Am Meteorol Soc 99:S91–S96
Gupta R, Somanathan E, Dey S (2017) Global warming and local air pollution have reduced wheat yields in India. Clim Change 140:593–604
Hasegawa T et al (2018a) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang 8:699–703

Hasegawa T et al (2018b) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang 8:698
Heino M, Guillaume JHA, Müller C, Iizumi T, Kummu M (2020) A multi-model analysis of teleconnected crop yield variability in a range of cropping systems. Earth Syst Dynam 11:113–128
Herrero M et al (2016) Climate change and pastoralism: impacts, consequences and adaptation. OIE Rev Sci Tech 35:417–433
Herrero M et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1:266–272
Hertel TW, Burke MB, Lobell DB (2010) The poverty implications of climate-induced crop yield changes by 2030. Glob Environ Chang 20:577–585
HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. FAO, Rome, pp 1–162
Humpenöder F et al (2020) Peatland protection and restoration are key for climate change mitigation. Environ Res Lett 15:104093
Ibrahim AAM, Elariane SA (2018) Feasibility tools for urban animal husbandry in cities: case of greater Cairo. Urban Res Pract 11:111–138
Iizumi T, Shin Y, Kim W, Kim M, Choi J (2018) Global crop yield forecasting using seasonal climate information from a multi-model ensemble. Clim Serv 11:13–23
IPCC (2019) Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
Isgren E (2018) If the change is going to happen it's not by us: exploring the role of NGOs in the politicization of Ugandan agriculture. J Rural Stud 63:180–189
Jägermeyr J et al (2021) Climate change signal in global agriculture emerges earlier in new generation of climate and crop models. Nat Food 2(11):873
Kerr RB, Chilanga E, Nyantakyi-Frimpong H, Luginaah I, Lupafya E (2016) Integrated agriculture programs to address malnutrition in northern Malawi. BMC Public Health 16:1–14
Kim W, Iizumi T, Nishimori M (2019) Global patterns of crop production losses associated with droughts from 1983 to 2009. J Appl Meteorol Climatol 58:1233–1244
Kremen C, Merenlender AM (2018) Landscapes that work for biodiversity and people. Science 362
Kriewald S, Pradhan P, Costa L, Ros AGC, Kropp JP (2019) Hungry cities: how local food self-sufficiency relates to climate change, diets, and urbanisation. Environ Res Lett 14:094007
Kuyah S et al (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron Sustain Dev 39:1–18
Lanker M, Bell M, Picasso VD (2020) Farmer perspectives and experiences introducing the novel perennial grain Kernza intermediate wheatgrass in the US Midwest. Renew Agric Food Syst 35: 653–662
Li D, Bou-Zeid E, Oppenheimer M (2014) The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ Res Lett 9:055002
Lotze HK et al (2019) Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proc Natl Acad Sci U S A 116:12907–12912
Mbow C et al (2019) In: Shukla PR, Skea J, Buendia EC, Masson-Delmotte V, Pörtner H-O, Roberts DC, Slade PZR, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold JPP, Vyas P, Huntley E, Kissick K, Belkacemi M, JM (eds) Food security. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
Medek DE, Schwartz J, Myers SS (2017) Estimated effects of future atmospheric co2 concentrations on protein intake and the risk of protein deficiency by country and region. Environ Health Perspect 125
Meng Q et al (2014) The benefits of recent warming for maize production in high latitude China. Clim Change 122:341–349

Mirzabaev A et al (2019) In: Shukla PR, Skea J, Buendia EC, Masson-Delmotte V, Pörtner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Pereira JP, Vyas P, Huntley E, Kissick K, Belkacemi JM (eds) Desertification. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem Cycles 22

Moore FC, Lobell DB (2015) The fingerprint of climate trends on European crop yields. Proc Natl Acad Sci U S A 112:2970–2975

Muller A et al (2017) Strategies for feeding the world more sustainably with organic agriculture. Nat Commun 8:1–13

Myers SS et al (2017) Climate change and global food systems: potential impacts on food security and undernutrition. Annu Rev Public Health 38:259–277

Niamir-Fuller M (2016) Towards sustainability in the extensive and intensive livestock sectors. OIE Rev Sci Tech 35:371–387

Nkonya, E. et al. (2015) Global cost of land degradation. Economics of Land Degradation and Improvement – a Global Assessment for Sustainable Development. https://doi.org/10.1007/978-3-319-19168-3_6

Olsson L et al (2019) Land degradation. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Oremus KL et al (2020) Governance challenges for tropical nations losing fish species due to climate change. Nat Sustain 3:277–280

Ortiz-Bobea A, Ault TR, Carrillo CM, Chambers RG, Lobell DB (2021) Anthropogenic climate change has slowed global agricultural productivity growth. Nat Clim Chang 11:306–312

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science (80) 360:987–992

Potopová V et al (2017) The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014. Int J Climatol 37:1648–1664

Poulsen MN, McNab PR, Clayton ML, Neff RA (2015) A systematic review of urban agriculture and food security impacts in low-income countries. Food Policy 55:131–146

Pradhan P, Kropp JP (2020) Interplay between diets, health, and climate change. Sustain 12:3878

Pradhan P, Costa L, Rybski D, Lucht W, Kropp JP (2017) A systematic study of sustainable development goal (SDG) interactions. Earth's Futur 5:1169–1179

Pradhan P et al (2020) Urban food systems: how regionalization can contribute to climate change mitigation. Environ Sci Technol 54:10551–10560

Pretty J (2003) Social capital and the collective management of resources. Science 302:1912–1914

Ray DK et al (2019) Climate change has likely already affected global food production. PLoS One 14:e0217148

Ringler C, Quisumbing AR, Bryan E, Meinzen-Dick R (2014) Enhancing women's assets to manage risk under climate change: potential for group-based approaches. International Food Policy Research Institute, Washington, DC, p 65

Rivera Ferre MG (2014) In: Freedman B (ed) Impacts of Climate Change on Food Availability: Distribution and Exchange of Food BT – Global Environmental Change. Springer, pp 701–707. https://doi.org/10.1007/978-94-007-5784-4_119

Rivera Ferre MG et al (2021) Traditional agricultural knowledge in land management: the potential contributions of ethnographic research to climate change adaptation in India, Bangladesh, Nepal, and Pakistan. Clim Dev. https://doi.org/10.1080/17565529.2020.1848780

Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA (2017) Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag 16:145–163

Rosenzweig C et al (2020) Climate change responses benefit from a global food system approach. Nat Food 1:94–97
Rosenzweig C, Mutter CZ, Contreras EM (2021a) Handbook of Climate Change and Agroecosystems – Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research (In 2 Parts). Series on Climate Change Impacts, Adaptation, and Mitigation (Vol. 5). World Scientific Publishing
Rosenzweig CF, Tubiello D, Sandalow, Benoit P, Hayek M (2021b) Finding and fixing food system emissions: the double Helix of science and policy. Environ Res Lett 16
Sana A, Meda N, Badoum G, Kafando B, Bouland C (2019) Primary cooking fuel choice and respiratory health outcomes among women in charge of household cooking in Ouagadougou, Burkina faso: Cross-sectional study. Int J Environ Res Public Health 16
Sanderman J, Hengl T, Fiske GJ (2017) Soil carbon debt of 12,000 years of human land use. Proc Natl Acad Sci 114:9575 LP–9579580
Scheelbeek PFD et al (2018) Effect of environmental changes on vegetable and legume yields and nutritional quality. Proc Natl Acad Sci U S A 115:6804–6809
Smith PJ et al (2019) In: Shukla PR, Skea J, Masson-Delmotte ECBV, Portner H-O, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Luz EHS, Neogi S, Pathak M, Petzold J, Pereira JP, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J, Press I (eds) Interlinkages between desertification, land degradation food security and greenhouse gas fluxes: synergies, trade-offs and integrated response options. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
Soares JC, Santos CS, Carvalho SMP, Pintado MM, Vasconcelos MW (2019) Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. Plant and Soil 443:1–26
Springmann M et al (2016) Global and regional health effects of future food production under climate change: a modelling study. Lancet 387:1937–1946
Stevanović M et al (2016) The impact of high-end climate change on agricultural welfare. Sci Adv 2:e1501452
Sultan B, Defrance D, Iizumi T (2019) Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci Rep 9:1–15
Tamburini G et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6:eaba1715
Tubiello FN et al (2021) Greenhouse gas emissions from food systems: building the evidence base. Environ Res Lett
Van Meijl H et al (2018) Comparing impacts of climate change and mitigation on global agriculture by 2050. Environ Res Lett 13:064021
Verón SR, de Abelleyra D, Lobell DB (2015) Impacts of precipitation and temperature on crop yields in the pampas. Clim Change 130:235–245
von Braun J, Afsana K, Fresco LO, Hassan M, Torero M (2021) Food Systems – Definition, Concept and Application for the UN Food Systems Summit. A paper from the Scientific Group of the UN Food Systems Summit
Wang H, Hijmans RJ (2019) Climate change and geographic shifts in rice production in China. Environ Res Commun 1:011008
Warchold A, Pradhan P, Kropp JP (2021) Variations in sustainable development goal interactions: population, regional, and income disaggregation. Sustain Dev 29:285–299
Warren E, Hawkesworth S, Knai C (2015) Investigating the association between urban agriculture and food security, dietary diversity, and nutritional status: a systematic literature review. Food Policy 53:54–66
Wheeler T, Von Braun J (2013) Climate change impacts on global food security. Science 341:508–513

Willett W et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492

Zaharia S et al (2021) Sustained intake of animal-sourced foods is associated with less stunting in young children. Nat Food 2:246–254

Zhang Y et al (2021) An innovated crop management scheme for perennial rice cropping system and its impacts on sustainable rice production. Eur J Agron 122:126186

Zhu C et al (2018) Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. Sci Adv 4

Delivering Climate Change Outcomes with Agroecology in Low- and Middle-Income Countries: Evidence and Actions Needed

Sieglinde Snapp, Yodit Kebede, Eva Wollenberg, Kyle M. Dittmer, Sarah Brickman, Cecelia Egler, and Sadie Shelton

1 Introduction

1.1 Does Agroecology Lead to Better Climate Change Outcomes?

Food systems need to meet food security, nutrition and environmental goals, especially in a world with growing demand and a changing climate. There is now broad consensus on the need to transform current food systems towards more sustainable models. Agroecology is increasingly seen as a framework for transforming food systems (HLPE 2019). A key question is: how far can agroecology meet the needs for climate change adaptation and mitigation in food systems, especially in low- and middle-income countries (LMICs) and at large scales?

S. Snapp (✉)
Department of Plant, Soil and Microbial Sciences, Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI, USA
e-mail: snapp@msu.edu

Y. Kebede
French National Research Institute for Sustainable Development (IRD), Montpellier, France

E. Wollenberg · C. Egler · S. Shelton
CGIAR Research Program of the CGIAR on Climate Change, Agriculture and Food Security (CCAFS), University of Vermont, Burlington, VT, USA

K. M. Dittmer
The Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), University of Vermont, Burlington, VT, USA

S. Brickman
University of Vermont, Burlington, VT, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_28

Box 1: Contemporary Approaches to Defining Agroecology

Ten elements of agroecology: Diversity, the co-creation and sharing of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and food traditions, responsible governance, circular and solidarity economy

Thirteen principles of agroecology (HLPE 2019, also summarised here): recycling, input reduction, soil health, animal health, biodiversity, synergy, economic diversification, the co-creation of knowledge, social values and diets, fairness, connectivity, land and natural resource governance, participation.

Gliessman (2018): "Agroecology is the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic, and social." It is transdisciplinary, participatory, action-oriented and "grounded in ecological thinking where a holistic, systems-level understanding of food system sustainability is required."

To address this question, we conducted a rapid, evidence-based review to assess the quality and strength of evidence regarding (i) the impact of agroecological approaches on climate change mitigation and adaptation in LMICs, and (ii) the programming approaches and conditions supporting large-scale transitions to agroecology.

Defining agroecology with precision is a challenge. The interpretation of agro-ecology in development has been divergent and contested, viewed variously as a set of practices, a social movement or the science of sustainable agriculture (Wezel et al. 2009, 2020). Moreover, differentiating agroecology from other forms of alternative agriculture for sustainability can be challenging due to vague or diverse definitions (Newton et al. 2020; Giller et al. 2021; Petersen and Snapp 2015). Box 1 provides examples of approaches to defining agroecology. Box 2 summarises major schemes for sustainable agriculture related to agroecology and climate change. All share the aim to reduce the negative impacts of agriculture, but approaches vary in their reliance on ecological processes, external inputs, whole system design, or emphasis on specific outcomes.

For this analysis, we considered approaches to be more agroecological to the extent that they made use of ecological processes, supported increasing autonomy from external inputs, or enabled whole system change, rather than focusing on changing single practices (Sinclair et al. 2019; Leippert et al. 2020). We focused on the biophysical science and practice aspects of agroecology to assess impacts on climate change adaptation and mitigation, and on drivers and enabling conditions of farmer behaviour for the analysis of scaling.

We identified agroecology practices and systems guided by the United Nations' Food and Agriculture Organisation (FAO) 10 Elements of Agroecology and Gliessman's (2016) transitions framework. To distinguish agricultural approaches aligned with agroecology, we considered field, farm and landscape-level approaches

Box 2: Schemes for Sustainable Agriculture Related to Agroecology and Climate Change (*Adapted from* Petersen and Snapp 2015)

- **Regenerative agriculture** seeks "to improve the health of soil or to restore highly degraded soil, which symbiotically enhances the quality of water, vegetation and land-productivity" (Rhodes 2017). The potential to enhance soil carbon has recently made these practices more prominent in climate discussions.
- **Sustainable intensification** is the production of more food on a sustainable basis with minimal use of additional land (Baulcombe et al. 2009). It creates "synergistic opportunities for the co-production of agricultural and natural capital outcomes" (Pretty et al. 2020). Often associated with increased energy or fertiliser inputs and viewed as a means for sparing land, e.g., to avoid the conversion of forests.
- **Ecological intensification** "harness(es) biological understanding to improve agricultural system performance, both in terms of productivity and environmental services" (Petersen and Snapp 2015).
- **Biodynamic farming** involves "organic farming techniques that improve soil health" in ways that "influence biological as well as metaphysical aspects of the farm" (Ponzio et al. 2013). Developed by Rudolf Steiner.
- **Organic agriculture is** a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than inputs with adverse effects. Organic agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved.
- **Climate-smart agriculture** is "agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes GHGs (mitigation) where possible, and enhances achievement of national food security and development goals" (Lipper et al. 2014).

that relied on enhanced ecological processes and services, compared to business-as-usual agricultural development. Examples of the agroecology approaches reviewed included diversifying crop production through cover crops, green manure and hosts for beneficial insects; managing organic nutrient sources; biopesticides; crop-livestock integration; agroforestry and organic farming.

The evidence for the review was based on the published scientific literature and semi-structured interviews with representatives from agricultural development programmes. For the literature review, we identified eighteen synthesis papers relevant to the impacts of agroecology on climate change adaptation and mitigation or to the scaling of agroecology, representing over 10,212 studies. Only four of the eighteen synthesis papers focused on LMICs, and only five others included at least 50% of the studies reviewed on LMICs, indicating the poor representation of LMICs for available syntheses in English. In addition, we conducted a systematic literature review of the primary evidence from LMICs for agroecological approaches and climate change outcomes related to nutrient management (15,674 articles) and pests and diseases (5,498 articles), resulting in a final selection of 138 papers representing about 20 agroecological practices. Of these papers, 71% represented data from Africa, 21% from Asia and 7% from Latin America, the latter suggesting the need for a similar review of the Spanish-language literature. One percent of the papers covered multiple regions. Seventy-eight percent of the papers addressed small farms, 9% addressed medium farms and 2% large farms. The full report is available online.

2 What Does the Evidence Tell Us?

2.1 Climate Change Adaptation

Substantial evidence[1] exists in favour of climate change adaptation in LMICs that is associated with practices and systems aligned with agroecology, e.g., farm diversification,[2] agroforestry and organic agriculture (Fig. 1). The agroecological approach with the strongest body of evidence for its impacts on climate change adaptation was farm diversification (strong evidence and high agreement). This included positive impacts of diversification on crop yield, pollination, pest control, nutrient cycling, water regulation and soil fertility. This is consistent with a recent global systematic review of similar practices within smallholder agriculture (Reich et al. 2021).

We found profound evidence concerning the impacts of agroforestry and organic agriculture on adaptation. Agroforestry had a positive impact on biodiversity, water regulation, soil carbon, nitrogen and soil fertility and the buffering of temperature extremes (Beillouin et al. 2019; Niether et al. 2020; Kuyah et al. 2019). Organic agriculture improved regulating (pest, water, nutrient) and supporting services (soils, biodiversity) (Smith et al. 2019).

Very little information was found about how agroecological approaches can improve resilience to extreme weather, which may be partly due to the challenges

[1]The number of articles with primary evidence from LMICs for adaptation was 120 out of 138, based on indicators of productivity (100), diversity (58), water and nutrient regulation (41), soil health (52), and pollination services and pest regulation (59). The quality and relevance of the eight synthesis papers found were mostly medium to high.

Two synthesis papers were found for diversification (covering crop diversification, organic farming, intercropping, accessory crops, and agroforestry) with 98 and 99 high-quality meta-analysis articles, respectively.

[2]"Agricultural diversification is the intentional addition of functional biodiversity to cropping [and livestock] systems at multiple spatial and/or temporal scales, and it aims at regenerating biotic interactions underpinning provisioning [regulating and supporting] …ecosystem services. It embraces a variety of practices encompassing the management of crops, noncrop habitats, soil, and landscapes." Tamburini et al. 2020. *Brackets added by brief authors.*

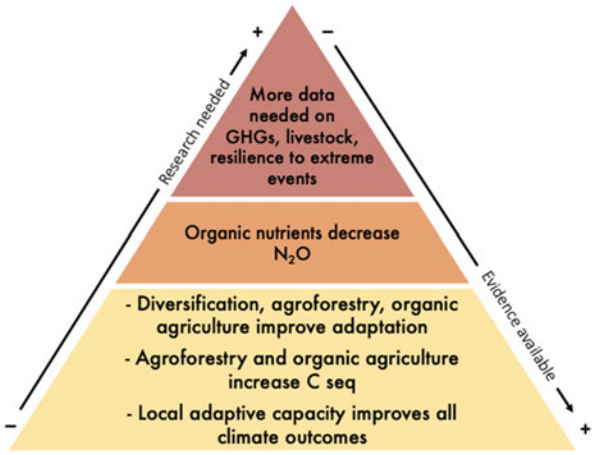


Fig. 1 Evidence base for climate change adaptation and mitigation outcomes

of studying responses to erratic, rare events and the need for modelling and global analytical approaches that were outside the scope of the studies reviewed.

2.2 Climate Change Mitigation

Evidence regarding impacts on mitigation is modest,[3] except for enhanced carbon sequestration in soil and biomass (Fig. 1). The agroecological approach with the strongest body of evidence concerning its impacts on climate change mitigation was tropical agroforestry, which was associated with the sequestration of carbon in biomass and soil (medium evidence, high agreement) (Corbeels et al. 2019; Feliciano et al. 2018). Also, there is a moderate and growing body of evidence in favour of organic agriculture and associated gains in soil carbon, predominantly from temperate regions and high income countries (Gattinger et al. 2012; Smith et al. 2019).

For example, Gattinger et al. (2012) reported that soil carbon stocks were higher by 3.50 ± 1.08 Mg C ha^{-1}, and soil carbon sequestration rates were higher by 0.45 ± 0.21 Mg C for pairwise comparisons of organic compared to non-organic farming, based on datasets from 74 studies. Nitrous oxide mitigation evidence was modest for tropical agriculture overall, and data on methane mitigation was very limited. Evidence from the global North suggests that reliance on organic nutrient sources and organic farming would likely avoid increased nitrous oxide emissions

[3] The number of articles with primary evidence from LMICs was limited: greenhouse gas emissions (6 articles), biomass carbon (4), and soil carbon (12), from a total of 138 articles. The quality and relevance of the six synthesis papers found were low to medium. Two synthesis papers were found for agroforestry, with 66 and 86 articles, respectively.

compared to the use of synthetic nitrogen fertiliser (medium evidence, medium agreement).

As the greenhouse gas (GHG) footprint of outcomes depends on where system boundaries are drawn, multi-scalar analysis is needed to capture flows of inputs and GHG impacts beyond the farm scale; for example, emissions associated with nutrient sources (e.g., industrial fertiliser production), land-use change or feed production (Connor 2018). The almost complete lack of data on tropical agriculture GHG emissions in agroecology exacerbates this research gap (Box 3).

Box 3: Evidence Used for the Assessment

To assess the evidence concerning the impact of agroecology on climate change outcomes, we compiled information from two sources and triangulated findings. We selected:

1. high-quality, peer-reviewed review papers relevant to agroecology and climate change adaptation and mitigation impacts or the scaling of agroecology; and
2. primary evidence in scientific papers on approaches aligned with agroecology for (a) nutrient management and (b) integrated pest and disease management.

For the primary evidence papers, studies were only selected for analysis if they also indicated an aspect of scaling up agroecology. Scaling was defined broadly, and included adoption, farmer innovation, scaling mechanisms or enabling conditions, learning, market or policy incentives and participatory research methods. For these papers, we documented the presence of indicators as evidence in favour of adaptation and mitigation impacts. This did not include whether impacts were positive or negative relative to a control.

We also conducted semi-structured interviews with twelve organisations involved in agricultural development in LMICs, including several organisations implementing agroecology at large scales. These interviews aimed to explore the conditions and constraints for scaling up agroecology, as experience with agroecology is still novel, and thus this information was not widely available in the scientific literature.

Evidence was evaluated based on its quality and the level of agreement based on Intergovernmental Panel on Climate Change (IPCC) guidance for conducting syntheses (Mastrandrea et al. 2010). The evaluation was qualitative and relative. The strength of evidence was based on the degree of scientific robustness (statistical significance, sample size, use of systematic comparison, pairwise comparison, number of articles), relevance to agroecology, extent of geographic representativeness, relevance to LMICs, and overall quality or credibility of an article. The level of agreement was generally "high" if there were more than 100 articles with strong evidence, "medium" if there were 50–99 articles with strong evidence, or "low" if there were less than 50 articles with strong evidence, or, in the case of interviews, where the majority of the respondents agreed.

2.3 Adaptive Capacity

Evidence suggests that agroecology provides more climate change adaptation and mitigation than conventional, higher-input agricultural development in LMICs by emphasising locally relevant solutions, participatory processes and the co-creation of knowledge as core values. Specifically, the co-creation and sharing of knowledge supported farmers' capacity to adapt practices more successfully to local conditions (strong evidence, medium agreement). In addition, multiple lines of evidence have shown that engaging with local knowledge through participatory and educational approaches effectively adapts technologies to local contexts, and thereby delivers improved climate change adaptation and mitigation.

Most interview respondents agreed that system approaches that prioritised local adaptation provided substantial benefits for climate change outcomes, often more than single practices. One respondent explained that "farmers are inherently system-based, and adjusting to their reality has made the work effective and created more opportunities."

2.4 Yields

Evidence concerning trade-offs between yields and climate change adaptation and mitigation exists, but was not systematically reported. There were win-win outcomes for yields and climate change mitigation associated with crop diversity and organic nutrient management. There was some evidence for modest trade-offs between yields and climate outcomes for organic farming and agroforestry. Diversification was associated with increased or maintained yields (although variable) compared to conventional agriculture (high evidence, high agreement). Conversely, variable and sometimes modestly lower yields were reported for organic agriculture (Skinner et al. 2014). Agroforestry systems had variable impacts on yield depending on the main crop, agroecological zone and soil type. For example, cocoa agroforestry produced lower cocoa yields, but higher overall yields from other crops in the system and improved climate change mitigation and adaptation (Niether et al. 2020). A review of agroforestry in sub-Saharan Africa found that agroforestry significantly increased yields and soil carbon (Kuyah et al. 2019).

2.5 Agroecological Transitions for Large-Scale Impacts

Evidence in the scientific literature relevant to scaling and enabling conditions of agroecology was poor, with only four relevant systematic reviews identified. The scientific robustness of the evidence was also mixed. Most reviews did not address agroecology at scale explicitly or compare the scaling conditions of agroecology and conventional agriculture. The literature review of primary evidence in favour of agroecology approaches to nutrient and pest management reported many of the same interventions and enabling conditions as those observed for scaling conventional agriculture interventions. These included the need for farmer capacity-building, use of markets, the necessity of involving government, the lack of cooperation between government offices of agriculture and offices of the environment, and poor implementation of policies (low evidence, medium agreement).

Based on interviews with field programmes, common components of these programmes' efforts to bring agroecology to scale included the co-creation and exchange of knowledge with farmers, community-based, participatory methods, localised solutions and social organising. According to the literature, scaling agroecology systems, as opposed to practices, made more use of participatory and farmer-to-farmer processes and policy. Scaling also relied on market and policy measures that privileged local production. Agroecology's inherent complexity and knowledge intensity sometimes incurred higher costs and more time than conventional agriculture, but this also enabled effectiveness and sustained benefits over multiple years.

Modest evidence was also found regarding disadvantages and challenges that impede agroecological transitions. Of the eighteen synthesis papers addressing agroecology and climate change impacts, only one explicitly addressed scaling (Cacho et al. 2018). Our review of the primary literature on nutrient and pest management yielded only 58 out of 138 articles on scaling-out processes, enabling conditions or barriers.

Critiques of agroecology have raised the issue of how to transition and reach large numbers of people. Compared to high-input sustainable intensification, agroecology can require more land to enable the use of ecosystem-based inputs and nutrient cycles (Connor 2018; Schreinemachers et al. 2011). The co-design of options with farmers can be slower and more costly for facilitating organisations, compared to top-down technical solutions, but farmers are also more likely to benefit. The attention to local knowledge around adaptation is, in this regard, both a strength and a challenge. Supporting local knowledge also requires a change in mindset of local and international actors involved in agricultural research and development and additional investment. Using conventional economic analysis, agroecological approaches can be more expensive, and some require more labour inputs compared to high-input agriculture optimised for yields; however, long-term and ecosystem benefits can be higher. The yield trade-offs associated with some agroecology approaches are a disadvantage and may pose a substantial challenge to adoption, particularly for farmers with limited resources in LMICs. Because of these constraints, the private sector has lacked incentives to facilitate agroecological practices.

2.6 Gaps

There is a need for research, especially in LMICs, that compares agroecology against alternatives, including current practices and expected trajectories in particular localities. More research is also needed for long-term studies on farms and at landscape scales in LMICs. A large data gap was found regarding agricultural GHG emissions and mitigation, with almost no evidence from LMICs. There were also evidence gaps regarding agroecology approaches involving livestock integration, landscape-scale redesign and multi-scalar analysis.

Critiques of agroecology question the extent to which scaling agroecology may restrict farmers' options and become a poverty trap through a lack of access to growth opportunities (Mugwanya 2019). Similarly, to what extent does agroecology empower and enable farmer organisation? There is generally a lack of data or scenarios showing the impacts of agroecological transitions on economic development. A better understanding of the political economy of development, including who wins and who loses, and evaluation of the short-term and long-term social and ecological benefits and trade-offs of agroecology compared with other agricultural development approaches could help inform development investment. The Transformative Partnership Platform on agroecological approaches aims to contribute to this area by evaluating the socioeconomic viability of agroecological practices across Africa.

2.7 Donor Investment

Recent reviews of funding for agroecology found that most investments at least partly support agroecological principles (Biovision and IPES-Food 2020; CIDSE 2020). However, these analyses do not examine investments related to climate change adaptation or mitigation. The majority of agricultural investment (63%) is targeted at reinforcing or making minor adjustments to existing systems (sustainable intensification, separate funding mechanisms for agriculture and environment, performance measured mostly via yields) (Biovision and IPES-Food 2020), despite calls for food system transformation (Steiner et al. 2020). Funding for agroecology remains a small proportion of major global agricultural development investment.

To improve investment in agroecology for the sake of climate change, long-term funding modalities, the setting of targets for outcomes that include environmental services and climate change outcomes – in addition to nutritional and livelihood and social outcomes – and a search for systemic change to building farmer capacities and incentives are needed (Biovision and IPES-Food 2020). Rather than treating climate change adaptation and mitigation as co-benefits, which risks limiting progress to incremental change, there is a need to actively manage for climate change benefits. Key programme elements to increase support for agroecology and climate change outcomes include (Fig. 2):

- Processes for the co-design of practices by farmers, with research to generate relevance, fit the local context, and enable ongoing adaptation to climate risks, rather than pre-determined technical packages.

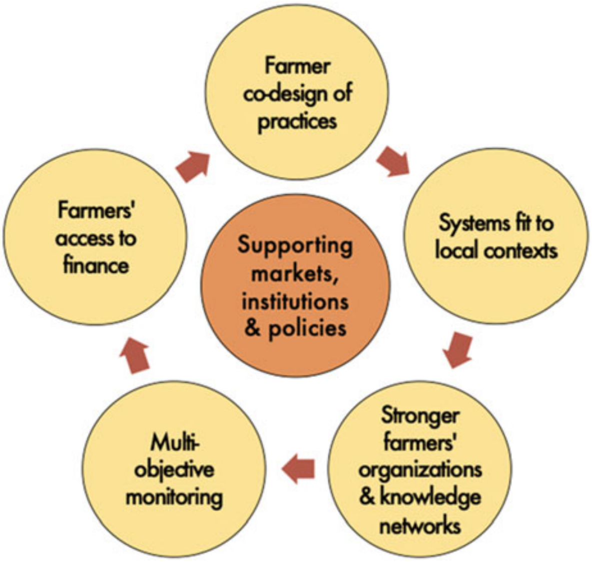


Fig. 2 Programme elements for scaling up agroecology and climate change objectives

- Designing system approaches, including agroforestry, organic farming, diversification, integrated pest and soil management, and landscape management designed for flexibility so as to be contextually specific and effective for climate change mitigation and adaptation.
- Strengthening extension-farmer networks and farmer-based organisations to support finance, training, farmer-to-farmer knowledge exchange, local education, monitoring and decision-making.
- Market, institutional and policy arrangements that promote these approaches and overcome the tendency for environmental and climate change objectives to be treated as separate from agricultural development, and that address trade-offs between environment or social outcomes and productivity or profitability to support more rapid and large-scale impacts, including nationally determined contributions (NDCs) to the Paris Agreement.
- Providing institutional support for monitoring environmental services, in order to assess performance that considers more than productivity or profitability, using climate change mitigation and adaptation indicators. This is needed to inform policy across multiple dimensions and support annual reporting to the UN Framework Convention on Climate Change (UNFCCC).

2.8 What Actions Need to Be Taken?

Tackling climate change will require broad cooperation and diverse approaches. Implementing agroecology across organisations with different political visions for development will require transcending the many labels around sustainable agriculture and climate change (e.g., climate-smart agriculture, regenerative agriculture), including agroecology. Labels like agroecology can still be expedient for communication; the point is to spend less time debating what agroecology is.

We thus **recommend an outcome-based approach to guide donor investment and national policy, using an assessment of the performance of agricultural development that integrates agroecological principles and climate change adaptation and mitigation indicators**. This is to avoid contestation around what is encompassed by a specific label for an agricultural alternative and instead assess performance in terms of environmental services and climate change response. Attention to outcomes relevant to the Sustainable Development Goals (SDGs) such as climate change resilience, environmental health, gender equity and social inclusion, soil health, biodiversity conservation, healthy diets and resource efficiency can provide common points of reference (Leippert et al. 2020).

A number of frameworks can be used to systematise the monitoring of agroecology performance (Wezel et al. 2020; Kapgen and Roudart 2020), including FAO's Tools for Agroecological Performance Evaluation (TAPE) (Barrios et al. 2020). The USAID-supported Sustainable Intensification Assessment Framework provides systematic approaches to outcome-based assessment and trade-off analysis (Grabowski et al. 2018).

Based on the strength of the evidence, **a second important action is to direct agricultural development investments towards agricultural diversification, local adaptation and pathways to scaling both**. Programme implementation experts indicated that promoting agricultural diversity can be a scalable intervention, and that it is often prioritised in programmes supporting agroecology. However, trends in agricultural development overall lean in the opposite direction, with widespread simplification of farms and cropping systems. Local adaptation can be promoted by supporting farmer innovation, co-learning and the adaptation of innovations to local contexts. Top-down technology packages are often promoted, rather than menus of farmer-co-designed options. Thus, diversification and local adaptation may require special attention at the policy and program levels.

In many countries, local and national agroecology platforms already exist, but can be strengthened to successfully use agroecology for climate change adaptation and mitigation in addition to the improvement of local livelihoods. Knowledge systems of agricultural producers need to be affirmed through networks of farmers and other stakeholders within the food systems to support the co-design of climate-friendly practices. To support farmer investment in diversified farms, women and men farmers' access and control over land and other elements of agroecosystems will be key enabling conditions (FAO 2012).

The limited information concerning agroecological approaches' response to extreme weather events and GHG emissions is a matter of great concern. **A third action is to develop national strategies and action to enhance resilience to extreme weather events and climate change mitigation outcomes**. This should build on the knowledge of countries with considerable experience of repeated extreme weather – such as the Philippines, Thailand, Haiti, and Honduras – to support strategies that will embed planning for extreme weather events in national policies. There is an urgent need to build the capacity of policymakers, scientists and institutions from the global South to work on these issues.

A fourth action is public investment in research to improve analysis of agroecology relative to other agriculture development approaches at multiple spatial and time scales so as to better evaluate alternative approaches to sustainable agriculture**.** Assessment is required for food security, environment and other dimensions of sustainable development, as well as the cost-effectiveness of different options in different contexts, including geographic regions. Assessment of cost-effectiveness should consider how to value environmental and social benefits and how assessment based on current policy contexts (e.g., subsidies) and short-time horizons might bias comparisons. Research includes comparative (alternatives versus conventional) and holistic (social, financial, environmental and agronomic) assessments. Reviews of French and Spanish-language literature would also enrich the foundation of evidence further, particularly for Latin America and West Africa.

Acknowledgements We would like to thank Ajay Vir Jakhar, Alan Tollervey, Alesha Miller, Anna De Palma, Barbara Gemmil- Herren, Batamaka Somé, Boru Douthwaite, Bruce Campbell, Christian Huyge, Christian Witt, Christophe Larose, Daniel France van Gilst, Dhanush Dinesh, Diana Salvemini, Emily Weeks, Fabio Leippert, Giles Henley, Guy Faure, Howard Standen, James Birch, Jean-Francois Soussana, Jerry Glover, Joanna Francis, Julian Gonzalez, Mercedes Bustamante, Michael Farrelly, Michael Okoti, Nick Remple, Noel Gurwick, Rachel Lambert, Rikin Gandhi, Stephanie Heiland, Tom Tomich, Ueli Mauderli, Vijay Kumar, Wijnand Van Ijssel, Ken Giller, Confidence Duku, Annemarie Groot, and Joachim von Braun. This work was funded by the New Venture Fund and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of these organisations.

References

Barrios E, Gemmill-Herren B, Bicksler A et al (2020) The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. Ecosyst People 16(1):230–247. https://doi.org/10.1080/26395916.2020.1808705

Baulcombe D, Crute I, Davies B et al (2009) Reaping the benefits: science and the sustainable intensification of global agriculture. The Royal Society, London. https://royalsociety.org/~/media/royal_society_content/policy/publications/2009/4294967719.pdf

Beillouin D, Ben-Ari T, Makowski D (2019) Evidence map of crop diversification strategies at the global scale. Environ Res Lett 14(12). https://doi.org/10.1088/1748-9326/ab4449

Biovision, IPES-Food (2020) Money flows: what is holding back investment in agroecological research for Africa? Biovision Foundation for Ecological Development & International Panel of Experts on Sustainable Food Systems. https://www.agroecology-pool.org/moneyflowsreport

Cacho MMTY, Giraldo OF, Aldasoro M, Morales H et al (2018) Bringing agroecology to scale: key drivers and emblematic cases. Agroecol Sustain Food Syst 42:637. https://doi.org/10.1080/21683565.2018.1443313

CIDSE (2020) Finance for agroecology: more than just a dream? Policy briefing. Coopération Internationale pour le Développement et la Solidarité (CIDSE). https://www.arc2020.eu/wp-content/uploads/2020/10/CIDSE-Agroecology-and-Finance-Briefing-Sept-2020-1.pdf

Connor DJ (2018) Organic agriculture and food security: a decade of unreason finally implodes. Field Crop Res 225:128–129. https://doi.org/10.1016/j.fcr.2018.06.008

Corbeels M, Cardinael R, Naudin K, Guibert H, Torquebiau E (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res 188:16–26. https://doi.org/10.1016/j.still.2018.02.015

FAO (2012) The voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of National Food Security. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/3/i2801e/i2801e.pdf

Feliciano D, Ledo A, Hillier J, Nayak DR (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agric Ecosyst Environ 254:117–129. https://doi.org/10.1016/j.agee.2017.11.032

Gattinger A, Muller A, Haeni M et al (2012) Enhanced top soil carbon stocks under organic farming. Proc Natl Acad Sci U S A (PNAS) 109(44). https://doi.org/10.1073/pnas.1209429109

Giller K, Andersson J, Hijbeek R, Sumberg J (2021) Regenerative agriculture: an agronomic perspective. Outlook Agric 50. https://doi.org/10.1177/0030727021998063

Gliessman S (2016) Transforming food systems with agroecology. Agroecol Sustain Food Syst 40(3):187–189. https://doi.org/10.1080/21683565.2015.1130765

Gliessman S (2018) Defining agroecology. Agroecol Sustain Food Syst 42(6):599–600. https://doi.org/10.1080/21683565.2018.1432329

Grabowski P, Musumba M, Palm C, Snapp S (2018) Sustainable agricultural intensification and measuring the immeasurable: do we have a choice? In: Bell S, Morse S (eds) Routledge handbook of sustainability indicators and indices. Taylor and Francis Press, Oxfordshire, pp 453–476. https://doi.org/10.4324/9781315561103-29

HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome

Kapgen D, Roudart L (2020) Proposal of a principle cum scale analytical framework for analyzing agroecological development projects. Agroecol Sustain Food Syst 44(7):876–901. https://doi.org/10.1080/21683565.2020.1724582

Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron Sustain Dev 39(5):47. https://doi.org/10.1007/s13593-019-0589-8

Leippert F, Darmaun M, Bernoux M, Mpheshea M (2020) The potential of agroecology to build climate- resilient livelihoods and food systems. FAO and Biovision. https://doi.org/10.4060/cb0438en

Lipper L, Thornton P, Campbell B et al (2014) Climate-smart agriculture for food security. Nat Clim Chang 4:1068–1072. https://doi.org/10.1038/nclimate2437

Mastrandrea MD, Field CB, Stocker TF, Edenhofer O et al (2010) Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC). https://archive.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf

Mugwanya N (2019) Why agroecology is a dead end for Africa. Outlook Agric 48(2):113–116. https://doi.org/10.1177/0030727019854761

Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C (2020) What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Front Sustain Food Syst 4. https://doi.org/10.3389/fsufs.2020.577723

Niether W, Jacobi J, Blaser WJ, Andres C, Armengot L (2020) Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environ Res Lett 15(10). https://doi.org/10.1088/1748-9326/abb053

Petersen B, Snapp S (2015) What is sustainable intensification: views from experts. Land Use Policy 58:1–10. https://doi.org/10.1016/j.landusepol.2015.02.002

Ponzio C, Gangatharan R, Neri D (2013) Organic and biodynamic agriculture: a review in relation to sustainability. Int J Plant Soil Sci 2(1):95–110. https://journalbank.org/IJPSS/article/view/1432/2860

Pretty J, Benton TG, Bharucha ZP et al (2020) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1:441–446. https://doi.org/10.1038/s41893-018-0114-0

Reich J, Paul SS, Snapp SS (2021) Highly variable performance of sustainable intensification on smallholder farms: a systematic review. Glob Food Sec 30. https://doi.org/10.1016/j.gfs.2021.100553

Rhodes CJ (2017) The imperative for regenerative agriculture. Sci Prog 100(1):80–129. https://doi.org/10.3184/003685017X14876775256165

Schreinemachers P, Sringarm S, Sirijinda A (2011) The role of synthetic pesticides in the intensification of highland agriculture in northern Thailand. Crop Prot 30(11):1430–1437. https://doi.org/10.1016/j.cropro.2011.07.011

Sinclair F, Wezel A, Mbow C, Chomba S, Robiglio V, Harrison R (2019) The contribution of agroecological approaches to realizing climate-resilient agriculture. Rotterdam and Washington, DC. Available online at www.gca.org

Skinner C, Gattinger A, Muller A et al (2014) Greenhouse gas fluxes from agricultural soils under organic and non-organic management — a global meta-analysis. Sci Total Environ 468–469: 553–563. https://doi.org/10.1016/j.scitotenv.2013.08.098

Smith OM, Cohen AL, Rieser CJ et al (2019) Organic farming provides reliable environmental benefits but increases variability in crop yields: a global meta-analysis. Front Sustain Food Syst 3:82. https://doi.org/10.3389/fsufs.2019.00082

Steiner A, Aguilar G, Bomba K et al (2020) Actions to transform food systems under climate change. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen. https://hdl.handle.net/10568/108489

Tamburini G, Bommarco R, Wanger TC et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6(45). https://doi.org/10.1126/sciadv.aba1715

Wezel A, Bellon S, Doré T et al (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29:503–515. https://doi.org/10.1051/agro/2009004

Wezel A, Herren BG, Kerr RB et al (2020) Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron Sustain Dev 40(6): 40. https://doi.org/10.1007/s13593-020-00646-z

Crop Diversity, Its Conservation and Use for Better Food Systems

Stefan Schmitz, Rodrigo Barrios, Hannes Dempewolf, Luigi Guarino, Charlotte Lusty, and Janet Muir

1 The Loss of Agrobiodiversity and Its Risks

Climate change, biodiversity loss and the food system crisis are among the major challenges of the twenty-first century, and they are closely interrelated. Climate change is threatening the survival of species and affecting crop yields, for example, and the destruction, degradation and fragmentation of ecosystems is accelerating climate change, driving biodiversity loss and affecting food security.

Biodiversity loss includes the depletion of ecosystem diversity, of species diversity and of genetic diversity within species. One of the strongest drivers of biodiversity loss is agriculture, for example, the conversion of forests and peatlands into arable land. However, there is also a loss of biodiversity within agriculture, for example:

- Loss of species diversity on agricultural land, both the number of crop and livestock species themselves and those of associated biota (e.g., weeds, soil microorganisms, pollinators) due to the use of fertilizers, herbicides and pesticides.
- Loss of genetic diversity within crop and livestock species, or genetic erosion, as the result of modern agricultural practices.

Agriculture is thus both the culprit and the victim.[1]

This loss of crop diversity poses a considerable risk to global food security. This is because the genetic diversity of cultivated plant species, and their wild relatives, is the raw material of crop improvement. It has been thousands of years since the

[1] After these introductory remarks on the entire range of agricultural genetic resources, i.e., plant, animal, etc., only the partial aspect of plant genetic resources will be pursued in the following.

S. Schmitz (✉) · R. Barrios · H. Dempewolf · L. Guarino · C. Lusty · J. Muir
The Global Crop Diversity Trust, Bonn, Germany
e-mail: stefan.schmitz@croptrust.org

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_29

advent of agriculture, and the need for it will only grow. The pressures on agriculture will increase in the future. The world population continues to grow, and grows richer and more demanding in the process. The climate is changing and, with it comes the likelihood of crop failure, including due to the emergence of new pests and diseases.

Meeting these challenges will only be possible if the genetic diversity contained in crops and their wild relatives remains available for use. This genetic diversity is the foundation of tomorrow's agriculture, allowing farmers and professional breeders to develop the new crop varieties that agriculture needs to adapt to changing conditions. The development of new varieties will be necessary for successful adaptation to climate change, and thus to secure the world's food supply in the future (Hawtin and Fowler 2012).

The maintenance of agrobiodiversity in situ, i.e., in nature and agricultural practice, remains indispensable, and is a task for protected areas and on-farm conservation efforts (Vincent et al. 2019). However, given the risks associated with this strategy, a second approach must be pursued consistently in parallel: the conservation of agrobiodiversity *ex situ* in genebanks.

2 Why *Ex-Situ* Conservation?

In view of the dramatic risk of loss of plant genetic diversity in nature and agricultural practice, its rescue before it is irretrievably lost is imperative. However, *ex-situ* conservation would make sense from a use point of view, even if there were no genetic erosion going on in the field at all.

This is because it would be tremendously complicated and expensive if, every time a plant breeder needed new genetic diversity, new material had to be collected from the wild or from farmers' fields, often in distant countries. It is true that there are many breeders who maintain their own working collections of germplasm, for short-term purposes. But there are clearly considerable efficiencies to be gained from collective efforts to build more comprehensive collections for long-term use in centralized genebanks at the national, regional and international levels. Such efforts are being made around the world, usually with the support of governments, and sometimes the international community. The values of conserving collections of plant genetic resources in genebanks are diverse and considerable (Hawtin and Fowler 2012):

- Having invested in collecting plant material from the wild or from farmers' fields – an expensive exercise – the cost of maintaining it in a genebank is often small by comparison.
- Samples are available from genebanks throughout the year, unlike plants growing in the wild or on farmers' fields that can generally only be collected in certain periods of the year, such as at harvest time.

- Genebanks are generally able to supply adequate quantities of good quality seed for research and breeding purposes. It is often difficult to collect adequate numbers of seeds of good quality from plants growing in the wild.
- Genebanks are generally able to supply samples that are free from pests and diseases. It is much harder to guarantee the health of material collected in the wild.
- Collections maintained in well-run genebanks remain genetically stable over time, unlike varieties maintained by farmers or populations under in situ conditions. This facilitates research and the generation of reliable information about samples, which, in turn, encourages their use in breeding programs.
- Genebanks offer a "one-stop" shop. Breeders are able to access a large range of diversity, often from many different countries, with a single request.
- Well-run genebanks have the facilities, administrative systems and experience not only to maintain samples, but also to distribute them nationally and internationally.
- Well-run *ex-situ* collections have reliable and readily available passport, characterization and evaluation data on samples, and, increasingly, data at the molecular level. Such data are critical to the ability of users to make informed choices about which materials to request, and how to use them.
- Over time, collections become ever more valuable as the data on the material in them become more comprehensive. Useful comparative data can be built up and made available for sets of samples grown across multiple environments.
- *Ex-situ* collections provide a "safety net" – a last resort – that enables locally adapted varieties and/or specific traits to be reintroduced into farming systems after they have been lost due to natural or human-induced disasters.

3 Status of *Ex-Situ* Conservation

The latest available data suggest that there are more than 1750 genebanks worldwide, of which about 130 hold more than 10,000 accessions each (FAO 2010). They are located on all continents barring Antarctica, though there are relatively few in Africa compared to the rest of the world. While it is estimated that about 7.4 million accessions are maintained globally, it is probable that, at most, only between 25% and 30% of these are unique, with the remainder being duplicates held either in the same or a different genebank. Clearly, there is a need for a measure of rationalization within and among collections (Hawtin and Fowler 2012).

While the majority of large collections are maintained at the national level, international collections are critically important because of their size and coverage, the availability of information on their contents and the ease of obtaining samples. Eleven of the CGIAR centers manage germplasm collections on behalf of the world community under Article 15 of the Plant Treaty, and, of these, the collections maintained by CIMMYT, ICARDA, ICRISAT and IRRI each comprises more than 100,000 accessions. Collectively, the CGIAR centers maintain more than

730,000 accessions of 3,000 species from 500 different genera. National genebanks managing more than 100,000 samples include those of Brazil, Canada, China, Germany, Japan, India, Russia, South Korea and the USA.

4 What Remains to Be Done

Unfortunately, many genebanks, especially in the Global South, are unable to guarantee the safety of the material they are responsible for, and valuable collections may be in jeopardy because their storage conditions and management are suboptimal. Further, the purpose of genebanks is clearly not just to conserve diversity, but also to create opportunities for plant breeding and more sustainable agriculture, i.e., for said diversity to be used. Much remains to be done. We focus here on three key interventions:

1. Strengthening the global system of *ex-situ* conservation
2. Making the global system fit for the purpose of caring for hard-to-conserve materials
3. Innovative funding of the global system

4.1 Towards a Stronger Global System of Ex-Situ *Conservation*

International and national genebanks operate within a worldwide community, or global system, that is made up not only of the institutes managing genetic resources, but also of a global plan of action, various technical standards, regional and crop networks and other instruments, all underpinned by the policy framework provided by the Plant Treaty, the Convention on Biological Diversity, the International Plant Protection Convention and the FAO Commission on Genetic Resources for Food and Agriculture.

The Crop Trust works with all parts of this community and has a unique role in helping to strengthen the global system so that it may become more effective, rationalized and collaborative. There are four main ingredients to strengthening the global system:

• A critical component in making the global system work is the availability of good quality data. It is only through good data that we know what is conserved, where and whether it is alive and available for use. Genesys, the online portal for accession-level data, provides a means for genebanks worldwide to share passport and characterization data on their collections, as part of the Plant Treaty's Global Information System. For such systems to reach their potential, genebanks require support to manage and share their data. For that reason, GRIN-Global

Community Edition is being developed for adoption by any genebank to help manage their data and their collections, and to build linkages with diverse data resources and systems that can enrich data holdings and help promote the use of diversity.

- Good quality data is intimately related to good operational practices and quality management. The Crop Trust, with CGIAR, has been developing a genebank quality management system (QMS) framework. Based on FAO genebank standards, the genebank QMS supports the documentation, review, improvement and sharing of genebank operations and practices. It provides a supportive tool for training and staff succession and an excellent vehicle for strengthening risk management and staff health and safety. Through QMS, new principles, protocols and research findings can be introduced into genebanks and spread among the global system as a whole.
- Armed with new data management tools and QMS, the Crop Trust has introduced new ways of building capacity through Genebank Operations and Advance Learning (GOAL) workshops, QMS Intensives, Genetic Resources on the Web (GROW) webinars, and communities of practice, each tailored for different levels of learning. The Crop Trust has also introduced performance targets to complement the FAO genebank standards, monitoring tools, audits and reviews, which are key to managing its long-term grants, but which can also apply to any genebank with an ambition to reach high standards of operation and fully participate in the global system.
- Finally, the global system has been growing and developing over several decades, and there is an opportunity now for different institutes to specialize and complement each other more coherently. The Svalbard Global Seed Vault, just over ten years old now, has already proven its worth in providing a unique mechanism for genebanks to deposit accessions for safe back-up. More institutions may be able to take up specialist roles on behalf of the community as a whole, whether it is conserving difficult crops and wild species, cryopreservation, or disease testing and cleaning for international germplasm movement. The Crop Trust would like to expand its work to help build capacity and partnerships to allow institutes to specialize and provide services for others.

4.2 Making the Global System Fit for the Purpose of Caring for Hard-to-Conserve Materials: Cryopreservation

The vast majority of crops have so-called orthodox seeds, which can be conserved relatively easily in cold stores if adequately dried. However, there are also other important crops – like bananas, cassava, cacao and coffee – that are propagated vegetatively, do not produce seeds or have seeds that are not orthodox. Their *ex-situ* conservation is therefore not possible through the typical drying and storage of seeds at −18 °C. Instead, these crops are usually conserved in field genebanks or in vitro, i.e., in tissue culture. Both of these require constant vigilance and are labor- and cost-intensive. Furthermore, as growing plants or plantlets, they are exposed to greater risks from contamination and disease, and safety duplication is also a major challenge. These factors all make collections of such crops particularly challenging to safeguard, especially when access to them is significantly reduced, e.g., because of social distancing during the Covid-19 pandemic.

Cryopreservation is the optimal method for safely maintaining genetic resources of such crops in the long-term. It is a process whereby organic material is conserved by cooling it to very low temperatures, typically −196 °C, using liquid nitrogen. It is a form of conservation that is technically challenging and requires high upfront investment. However, it is the most effective, long-term complement to the labor-intensive methods of conservation in field genebanks and *in vitro*.

Unfortunately, while there are abundant studies on how to cryopreserve plant genetic resources, only a handful of institutes have succeeded in cryopreserving collections on a large scale. This is due to the lack of investment in transforming research into routine application. Protocols need to be highly refined to work on the range of diversity in global collections and adequately tested to ensure that materials going into cryopreservation can come out of it and grow into healthy, whole plants. The organization required to build a successful cryo-pipeline is considerable, demanding both substantial investment and a donor who is not afraid to wait to see good results.

CGIAR genebanks have now established cryopreservation pipelines in Peru, Belgium, Nigeria and Colombia. More than 4,000 accessions of banana, cassava and potato are maintained in CGIAR cryobanks. The Centre for Pacific Crops and Trees (CePaCT) in Fiji is also in the process of setting up a cryopreservation pipeline for taro and coconut. However, more than 100,000 accessions are believed to be conserved in *in vitro* and field collections worldwide. Consequently, CGIAR is working with the Crop Trust and the Plant Treaty to engage national partners and cryopreservation experts in collaborating on a global initiative to secure this diversity in long-term conservation. Through setting up regional specialist hubs, CGIAR and partners hope to offer capacity-building and backstopping to support national programs bringing their own collections into cryopreservation and safely duplicating them.

4.3 Innovative Funding for the Global System of **Ex-Situ** *Conservation*

The Crop Trust was founded in 2004 and is recognized as an essential element of the funding strategy of the Plant Treaty. It provides sustainable, long-term funding for a rational, effective and efficient global system that can secure crop diversity forever.

The core activities of the Crop Trust are funded through sustainable investment income generated from an endowment fund. To strengthen the global system of *ex-situ* conservation as described above, an additional US$500 million need to be raised to achieve its total endowment target of US$850 million that will ultimately support implementation of SGD 2 by securing the world's crop diversity in perpetuity.

Unrestricted grant contributions to this endowment fund will always be the preferred means of funding the global system of *ex-situ* conservation. However, due to the slow growth of official development assistance and declining grants from governments, it is necessary and urgent for the Crop Trust to tap additional sources of funding.

The Crop Trust is exploring the issuance of a 30-year bond ("Food Security Bond" or "FSB") to private sector investors, which would be supported by (1) a government guarantee that commits the government to provide for any shortfall upon redemption in Year 30, and (2) government grants to pay the bond coupon in order to reduce the cost to the Crop Trust to zero. All bond proceeds would be invested in the existing endowment fund, with net investment returns to be used to fund the conservation of crop diversity in genebanks. In order for the FSB to be a success, it is absolutely critical that it has government support from one or more donor countries.

Overall, the advantages of issuing such a bond, combined with firm support from governments by way of guarantees and grants, include the following:

- Public/private engagement – The FSB has the potential to engage private market investors and government donors in a combined effort to support the global system and the conservation of crop diversity in perpetuity.
- The rating of the issuer – the higher the credit rating, the better the pricing in terms of the cost of funds. A highly rated government guarantee will mean lower coupons to be paid by the Crop Trust.
- The market environment – low interest rate market environments create the demand for yield up to and above current short-term issuances. Lack of alternatives to satisfy the needs of a section of investors, particularly pension funds and insurance companies, creates a demand profile for long/ultra-long maturity bonds.
- The guarantee provided by governments – a bond profile enhanced by a guarantee provides a layer of comfort for the investor and an attractive proposition to the market on behalf of the issuer, resulting in potential demand enhancement. For no money upfront, governments can help unlock substantial private capital for food security.
- The profile of the issuer – environmental, social and governance (ESG) issues are now one of the foremost attributes of investors and the need for them to gain exposure to ESG-related asset classes. In addition, as investors focus on the implementation of the Sustainable Development Goals, a Crop Trust bond supporting SGD 2 would be highly attractive to investors. The Crop Trust is also a signatory to the UN Principles of Responsible Investment and all endowment fund assets are invested in line with its responsible investment policy.

- Scalability – the bond could be issued in a number of tranches to raise vital funding, not just for the Crop Trust, but for other international organizations implementing SDG 2.
- Risk – as there is no recourse to donor contributions within the endowment fund, the risk of a shortfall upon redemption of the bond lies with the governments who have provided the guarantee, and not with the Crop Trust.

With this funding, the Crop Trust aims to scale up the endowment fund to provide critical support to national and regional genebanks around the world; continue support for routine budgets of the 11 CGIAR genebanks; and fund information system development, the Svalbard Global Seed Vault and the Crop Trust Secretariat with the aim of securing the foundation of global food security.

In addition, discussions are underway with the Secretariat of the Plant Treaty to explore whether a share of the annual income earned from this additional funding could be made available to the Plant Treaty for complementary activities to safeguard crop diversity in the field and in the wild.

References

FAO – Food and Agriculture Organization of the United Nations, Commission on Genetic Resources for Food and Agriculture (2010) The second report on the state of the world's plant genetic resources for food and agriculture. FAO, Rome

Hawtin G, Fowler C (2012) The global crop diversity trust. An essential element of the treaty's funding strategy. In: Frison C, Lopez F, Esquinas-Alcazar J (eds) Plant genetic resources and food security: stakeholder perspectives on the on the international treaty on plant genetic resources

Vincent H, Amri A, Castañeda-Álvarez NP, Dempewolf H, Dulloo E, Guarino L, Hole D, Mba C, Toledo A, Maxted N (2019) Modeling of crop wild relative species identifies areas globally for in situ conservation. Commun Biol 2(1):136–143

Safeguarding and Using Fruit and Vegetable Biodiversity

Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, and Luigi Guarino

1 Fruit and Vegetable Biodiversity Contributes to a Diverse Food Supply and Quality Diets

From a dietary perspective, fruits are reproductive plant parts with high sugar or oil content that are usually eaten fresh, as a snack, in desserts, or in drinks (Bioversity International 2021). Vegetables are plant parts, such as leaves, fruits, or immature pods, that are eaten raw or cooked, in salads and as part of savoury dishes in general

M. van Zonneveld (✉)
World Vegetable Center, Taiwan City, Taiwan
e-mail: maarten.vanzonneveld@worldveg.org

G. M. Volk
National Laboratory for Genetic Resources Preservation, U.S. Department of Agriculture, Fort Collins, CO, USA

M. E. Dulloo
Bioversity International, Port Louis, Mauritius

R. Kindt
World Agroforestry, CIFOR-ICRAF, Nairobi, Kenya

S. Mayes
Crops For the Future, London, UK

M. Quintero
International Center for Tropical Agriculture (CIAT), Cali, Colombia

D. Choudhury
International Centre for Integrated Mountain Development (ICIMOD), Patan, Nepal

E. G. Achigan-Dako
Laboratory of Genetics, Biotechnology and Seed Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

L. Guarino
Crop Trust, Bonn, Germany

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_30

(Grubben and Denton 2004). What both fruits and vegetables have in common is that they are rich in micronutrients and present an astonishing diversity of forms, tastes, and colors, adapted to myriad environments. Fruit and vegetable biodiversity is part of agrobiodiversity, underpinning diverse food production systems for both local and global economies and contributing significantly to worldwide health and nutrition (Willett et al. 2019). While agrobiodiversity can be defined as the sum of all organisms at the genetic, species, and ecosystem levels for food and agriculture, fruit and vegetable biodiversity can be defined more narrowly as the variety of fruits and vegetables at the genetic, species, and ecosystem levels, including crop wild relatives (CWR) and pollinators and other associated organisms.

Fruits and vegetables play an increasingly prominent role in a new global research and development agenda that emphasizes nutrition and healthy diets, alongside spurring climate action, safeguarding biodiversity, ending poverty, and improving livelihoods (Willett et al. 2019; Caron et al. 2018). Even so, most fruit and vegetable biodiversity, which is the foundation for fruit and vegetable supply, remains unexplored, poorly conserved, and increasingly threatened.

About 1100 vegetable species are recognized worldwide (Meldrum et al. 2018), and there are at least 1250 documented fruit species native to Latin America alone (Bioversity International 2021), although this number is likely to be higher (Van Loon et al. 2021). The global number of fruit species is even larger when considering native species from other continents (Maundu et al. 2009).

This pool of diversity includes fruit and vegetable species with exceptionally high nutritional values and some that are adapted to harsh environments: it offers an untapped resource to make nutrient-dense foods accessible and affordable to consumers under the challenges of global climate change. Examples include micronutrient-rich African leafy vegetables adapted to rain-fed conditions (Maundu et al. 2009) and vitamin-rich Amazonian fruit trees that withstand flooding and waterlogging (Borelli et al. 2020; van Zonneveld et al. 2020a).

Below the species level, local fruit and vegetable varieties grown by people are part of a cultural heritage with unique tastes and histories (Dwivedi et al. 2019). Varieties vary widely in levels of micronutrient concentrations and phytonutrient concentrations in general, including antinutrients (Simon et al. 2009). This variation allows us to identify varieties with high nutritional quality for developing new climate-adapted varieties with novel flavors, high nutritional values, and resistance to pests and diseases. At the landscape level, wild fruit and vegetable species, including those that are actively managed, are a substantial food source for communities around the world and support key ecosystem functions (Bharucha and Pretty 2010; Van Zonneveld et al. 2018). Fruit species can serve as a direct food source, contributing up to 30% of the daily vitamin intake of rural and forest communities in certain local settings (Jansen et al. 2020). In Africa in particular, the human consumption of wild vegetables is reported in many countries (Maundu et al. 2009; Achigan-Dako et al. 2011; van Zonneveld et al. 2021). CWR, including wild ancestors of domesticated fruit and vegetable species, are a special group of genetically-related species of targeted fruits and vegetables that are increasingly used in breeding because they can contain traits related to climate resilience and other desirable traits (Kilian et al. 2021; Schouten et al. 2019). In addition, most fruit species and some vegetable species depend heavily on pollinators for sustainable yields (Klein et al. 2007). These pollinators, together with seed dispersers, are also key to maintaining the viability of wild populations of fruit and vegetable species and their relatives.

2 Declining Biodiversity Limits Options for a Sustainable and Healthy Food Supply

Fruit and vegetable biodiversity continues to decline in farmers' fields and natural ecosystems (Pilling et al. 2020) in line with the global rapid decline in biodiversity (Díaz et al. 2019). The loss of this heritage, and the resulting narrowing options for developing climate-resilient and nutritious foods, as well as a yield gap due to pollinator decline, will likely limit progress in achieving the 2030 Sustainable Development Goals (SDGs): SDG 1, No Poverty; SDG 2, Zero Hunger; SDG 12, Responsible Consumption and Production; SDG 13, Climate Action; SDG 15, Life on Land; and any future goals set thereafter.

Globally, ecosystems in 88% of the 846 terrestrial ecoregions are poorly conserved, degraded, or disappearing in the Anthropocene (Dinerstein et al. 2017). The degradation and loss of these ecosystems under the pressures of land-use change, global climate change, and other threats leads to a decline in richness and abundance of fruit and vegetable species, CWR, and pollinators and dispersers at the landscape level (Pilling et al. 2020; Díaz et al. 2019). For example, 39% of 883 assessed wild fruit and vegetable species requires urgent conservation because they are either poorly conserved in genebanks and protected areas or not conserved at all; another 58% has a medium priority for conservation; for only 3% is genetic variation already well conserved (Khoury et al. 2019) (Table 1).

Four out of five studies on crop genetic erosion found evidence of crop diversity loss, the magnitude varying by species, taxonomic and geographic scale, and region, as well as analytical approach (Khoury et al. 2022). However, most genetic erosion studies have been done on cereal crops and their wild relatives; no global estimates

Table 1 Classification of 883 wild fruit and vegetable species in priority categories for conservation actions by Khoury and co-authors as part of a global conservation assessment of wild edible plants

Priority for conservation actions	Number of fruit species	Number of vegetable species	Number of species combined[a]
High	200	185	346
Medium	341	246	510
Low	11	25	27
Total	552	456	883

Source: Khoury et al. (2019)
[a]Includes species that have been classified as both fruit and vegetable.

have been made of the rate of varietal and genetic losses in fruit and vegetable species (Khoury et al. 2022). For some crops, such as tomatoes (*Solanum lycopersicum*), farmers have already replaced most local varieties in many regions (Walters et al. 2018; Cebolla-Cornejo et al. 2012) and the development of new varieties relies almost entirely on the diversity safeguarded in genebanks (Bauchet and Causse 2012).

In contrast to tomatoes, as noted above, the genetic resources of most fruit and vegetable species are poorly conserved by genebanks or not at all. A quarter of the 1,100 recognized vegetable species worldwide is not conserved in any genebank (Meldrum et al. 2018). Similarly, the conservation of wild relatives of vegetables is poor. For example, 65% of the wild relatives of eggplant (*Solanum melongena*) is conserved poorly or is not conserved *ex situ* in crop genebanks and botanic gardens (Syfert et al. 2016), while 50% of the wild relatives of chili peppers (*Capsicum* spp.) and 25% of the wild relatives of yard-long beans and cowpeas (*Vigna* spp.) are poorly conserved *ex situ* (van Zonneveld et al. 2020b; Khoury et al. 2020). The varietal diversity of most fruit tree species and their wild relatives, particularly those of tropical origin, are not maintained in genebanks or botanic gardens. Botanic gardens maintain a high richness of fruit species, although not necessarily a high intra-specific diversity (Pearce et al. 2020). The seed of most fruit species is recalcitrant and does not tolerate desiccation or the low temperatures of conventional seed storage, while maintaining fruit trees in high-quality field genebanks is expensive (Dawson et al. 2013). All of these fruit and vegetable genetic resources, in the absence of genebank back-up, are at risk of being lost forever.

Over the last four decades, populations of terrestrial insects were found to have declined, on average, by 45% across several studies, and the annual decline in abundance is estimated to be between 1% and 2% (Wagner et al. 2021; Dirzo et al. 2014). These studies are thought to represent global trends of rapid decline, because insect biodiversity is affected worldwide by a multitude of pressures, including habitat destruction, pesticide application, and climate change, among others (Wagner et al. 2021). During the same time period, the mean relative yield of crops that depend on these insects for pollination was 13% lower compared to pollinator-independent crops (Garibaldi et al. 2011). This pollination-yield gap will likely further increase under the current trends of pollinator decline. It can be anticipated that this will affect the yields of the many fruit species and some vegetable species that rely on these pollinators for crop production. This decline will also further increase the extinction risk of wild plant populations, including those of fruit and vegetable species and wild relatives that depend on cross-fertilization by pollinators for propagation (Cunningham 2000; Biesmeijer et al. 2006).

Complex access and benefit-sharing policies and regulations (Brink and van Hintum 2020), in particular, domestic policies and regulations that implement the Nagoya Protocol of the Convention on Biological Diversity (CBD), increasingly govern international efforts to conserve and use the diversity of local varieties and wild populations. Many of these policies recognize the rights of countries and local communities over genetic resources in their territories, yet these countries and communities from different countries depend on each other for genetic resources of fruit and vegetable crops for food and nutrition, including for neglected and underutilized ones (van Zonneveld et al. 2021; Khoury et al. 2016). This interdependence is expected to increase in this century under global climate change (Burke et al. 2009). The International Treaty on Plant Genetic Resources for Food and Agriculture (the Plant Treaty) has a multilateral system for a negotiated list of crops to enhance the exchange of germplasm—including seed and any other living plant tissue—between countries for food and agriculture. Unfortunately, most fruit and vegetable crops and their wild relatives are not included on this list, which limits germplasm exchange for these species (Brink and van Hintum 2020).

There are at least six important trends increasing the conservation and use of fruit and vegetable biodiversity in food systems at global and local levels. First, there is greater global awareness about the benefits of diverse diets with sufficient fruits and vegetables (Willett et al. 2019; Caron et al. 2018). Second, the proportion of fruit and vegetable crops contributing to global food production is increasing (Martin et al. 2019; Khoury et al. 2014; Gould 2017). Third, advanced biotechnologies are now accessible to public and private breeders and researchers globally for the purpose of mainstreaming the genetic diversity of fruits and vegetables into new crop varieties (Schouten et al. 2019; Jamnadass et al. 2020). Fourth, some neglected and underutilized fruit and vegetable species have regained relevance in urban diets through public and private initiatives in gastronomy and niche markets for local, healthy, or ethnic food (Borelli et al. 2020). Fifth, cities are becoming important hubs of crop diversity, because immigrants bring planting material from their home areas (Taylor and Lovell 2014; Rimlinger et al. 2021). Sixth, the coverage of protected areas has tripled in the last 40 years (Pringle 2017), and at least 35% of the terrestrial protected areas is owned and/or managed by local and indigenous communities, who play an important role in maintaining agrobiodiversity (Díaz et al. 2019).

Although these trends could possibly bend the curve of decline in fruit and vegetable biodiversity, they may not completely halt, let alone reverse, it.

For example, the expansion of protected areas provides some opportunities for conservation, but ecosystems in these areas may be degraded and wild populations of fruit and vegetable species within the landscape may decline (Pringle 2017). While cities can be hubs for new crop diversity, urban expansion is also a driver of biodiversity loss, because urban planning commonly does not consider crop biodiversity (Shackleton et al. 2017). Global increases in crop diversification with limited numbers of new crops may also lead to less use, and therefore a decline in the abundance and richness of local fruit and vegetable crops as diets tend towards becoming more homogenous globally (Khoury et al. 2014). In addition, successful national and international markets for previously underutilized species, such as cherimoya (custard apple, *Annona cherimola*) and avocado (*Persea americana*), both originating from Latin America, can lead to a decrease in local varieties in their primary centers of diversity due to product homogenization and consumer preferences (Vanhove and Van Damme 2013). While the proportion of fruit and vegetables in global food production has increased in the last decades, consumption of crops such as pineapple (*Ananas comosus*), banana (*Musa* spp.), and avocado rely on high-input monoculture production systems that lead to excessive environmental degradation and biodiversity loss (Magrach and Sanz 2020; Shaver et al. 2015; Schreinemachers et al. 2020). Even though genetic resources are increasingly used in the production of some crops such as tomatoes, production systems of other fruit and vegetable crops remain genetically impoverished and are susceptible to pest, diseases and climate stress. An extreme case is banana production, which is dominated by a single clone that is susceptible to the Panama disease, threatening the global banana supply (Ploetz 2021). Genebanks and seed saver networks where genetic resources are conserved allow people to re-introduce new and more varieties so as to make the fruit and vegetable supply more sustainable.

Policies and initiatives should stimulate the positive trends mentioned above while counteracting the negative effects with i) better conservation of fruit and vegetable biodiversity *in situ* (on farm, at the landscape level, and in protected areas); ii) with back-ups in genebanks and other *ex-situ* settings to reduce and reverse the decline of fruit and vegetable biodiversity (Dulloo et al. 2017); and iii) with sustainable use of fruit and vegetable biodiversity in production systems through good practices such as on-farm diversification and agroecological intensification (Attwood et al. 2017). This will require a global awareness campaign around safeguarding and sustainably using fruit and vegetable biodiversity and a concerted, coordinated global rescue plan.

3 Raising Awareness to Safeguard and Sustainably Use Fruit and Vegetable Biodiversity

Long-term support for biodiversity conservation can be gained by engaging with young people to create increased awareness about why biodiversity matters (Pringle 2017). For fruits and vegetable biodiversity in particular, governments and NGOs can engage young people and their families by showing the benefits of conserving and using fruit and vegetable biodiversity for diets and business opportunities. School-feeding programs, in combination with biodiversity education, are a promising tool for achieving this; they become successful when they involve multiple stakeholders, rely on stable procurement markets, and are embedded in national policies (Roothaert et al. 2021) (Fig. 1a). For example, government programs in Brazil use farm-to-school models to purchase fruits and vegetables of local crops from nearby producers for the purpose of offering diverse school meals and diversifying farm systems with shorter supply chains for fresh produce (Borelli et al. 2020). In this way, local crops are being maintained in local and diverse food systems. About 368 million children worldwide are estimated to be fed daily through school-feeding programs, with a yearly investment of between US$47–75 billion (WFP 2013). It can be anticipated that linking these programs and their budgets to

Fig. 1 Examples of activities to safeguard and use fruit and vegetable biodiversity: (**a**) Engaging young people through school-feeding programs with fresh vegetables in Burundi; (**b**) A traditional Thai meal with local bananas and a rich variety of vegetables; (**c**) A fruit vendor in Lima, Peru, holding a cherimoya fruit (*Annona cherimola*) of the locally-grown Cumbe variety; (**d**) Populations of the multi-purpose tree species néré (*Parkia biglobosa*) are maintained in parklands in Benin, and so far do not have a genebank back-up; (**e**) *Cucumis* spp. – a cucumber wild relative from Nyika National Park, delimited as a crop wild relatives (CWR) genetic reserve in Malawi as part of the Darwin Initiative SADC/CWR project 26-023; (**f**) Heirloom apple (*Malus domestica*) trees in Yosemite National Park in the United States are identified for conservation efforts. (Photo credits: (**a**) WFP, Hugh Rutherford; (**b**, **c**) WorldVeg; (**d**) University of Abomey-Calavi, Enoch Achigan-Dako; (**e**) Malawi PGR Centre; (**f**) USDA, Gayle Volk)

biodiversity education and school-feeding programs will help to promote the consumption and sustainable cultivation of local fruit and vegetable crops. This requires pilots for further testing, learning, and scaling in different settings, focusing especially on the fast-growing group of young people in sub-Saharan Africa.

Cooks, chefs, and other food innovators can promote local fruit and vegetable crops as a complement to global staples among urban consumers by emphasizing the taste, cultural, and health aspects of local crops (Moreau and Speight 2019; Pereira et al. 2019) (Fig. 1b). To be successful, these efforts must be linked to value-chain development so as to increase and sustain the supply of local crops, including investment in good agricultural practices, effective postharvest management, product preservation and processing, food safety, and market access for farmers (Schreinemachers et al. 2018; McMullin et al. 2021) (Fig. 1c). These farmers need good quality, safe, and appropriate planting material. Often, this planting material is not available, which is a major bottleneck preventing farmers from adopting these local crops (McMullin et al. 2021). To develop and deliver appropriate planting material of fruit and vegetable species now and in the future, their genetic resources need to be conserved, characterized and accessible. Genebanks play a crucial role in making this germplasm available (Lusty et al. 2021).

4 Rescuing Fruit and Vegetable Biodiversity

A global rescue plan is needed to bend and halt the curve of decline in fruit and vegetable biodiversity. This plan should focus on crop-based conservation strategies for globally important fruit and vegetable species and include conservation actions in global hotspots that harbor high levels of fruit and vegetable biodiversity, including Latin America, sub-Saharan Africa and Southeast Asia. This plan should also aim to protect wild populations of fruit and vegetable species, their relatives, and their pollinators and dispersers in natural habitats and traditional production systems.

Large national fruit and vegetable germplasm collections have been established in North America, South America, Asia and Europe (Byrne et al. 2018; Cunha Alves and Azevedo 2018; Jacob et al. 2015; Loskutov 2020). These crop genebanks conserve fruit and vegetable species and varietal diversity and make this diversity available for the development of new varieties and foods. For instance, the Vavilov Institute in Russia has a famous collection of 75,000 fruit and vegetable germplasm samples (Loskutov 2020). Australia has recently established a seed bank for native food plants (Cochrane 2017). These national efforts are complemented with international initiatives that have resulted in the collection of at least 1330 banana and 12,000 other fruit and 39,000 vegetable germplasm samples (Thormann et al. 2012; Engle and Faustino 2007), and have resulted in the establishment of international collections of banana and fruit tree germplasm at, respectively, Bioversity International and the World Agroforestry Centre, and of vegetable germplasm at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and the World Vegetable Center (Lusty et al. 2021; Engels and Ebert 2021). Wild relatives of fruit and vegetable crops, and neglected and underutilized fruit and vegetable species, poorly represented in this network, should be the focus of new plant explorations worldwide (Fig. 1d). Sub-Saharan Africa presents a gap in the genebank network; investment in genebank infrastructure in this region will help to maintain and document sub-Saharan African fruit and vegetable genetic resources.

At the same time, several collections from the existing genebank network are vulnerable because they have large backlogs of old or original fruit and vegetable germplasm samples (Fu 2017). These collections need investment in germplasm multiplication and rejuvenation. Without such support, there is a risk that part of this already-conserved diversity gets lost, too.

Workable agreements for germplasm access and benefit-sharing provide a framework for the better use of these collections and for new plant exploration efforts. The 2011–2021 global CWR Project led by the Crop Trust showed how global partnerships for collection, conservation, and germplasm availability are possible for wild relatives of fruit and vegetable crops that fall under the framework of the Plant Treaty including eggplant (*Solanum* spp.), carrot (*Daucus carota*), apple (*Malus* spp.), and bananas (Pearce et al. 2020). In this way, germplasm becomes available for farmers, breeders, and researchers under internationally established policies and regulations. Similar agreements should be made for germplasm exchange and new plant explorations for other fruit and vegetable species following all applicable current laws and regulations at the national and international levels.

For *ex-situ* conservation, seeds of most vegetable species are usually dried and stored at low temperatures in conventional seed banks for national and international distribution and long-term conservation. In contrast, fruit species are usually maintained in field or greenhouse conditions. Apart from the fact that the recalcitrant seed behavior of many fruit species impedes conventional storage, most fruit cultivars have specific genetic combinations that can be maintained only through vegetative propagation.

The lack of international fruit conservation programs—with the exception of bananas—results in increased reliance on national genebanks to protect cultivars and wild relatives of fruit crops. National fruit conservation programs must become more synergistic on a global scale, as field and greenhouse collections are particularly vulnerable to environmental threats, theft, and pests and diseases.

For some economically important clonal fruit and vegetable crops, such as bananas and garlic (*Allium sativum*), collections can be secured in tissue culture or by using cryogenic storage (Panis et al. 2020). The development and application of tissue culture and cryopreservation protocols to a broader range of species, in combination with global investment in cryo-capacity, are essential in order to safeguard the diversity of clonal and recalcitrant fruit and vegetable species in *ex-situ* conditions.

A global rescue plan must be accompanied with documenting genetic variation in traits of newly-collected and already-conserved fruit and vegetable germplasm. This documentation should include screening for nutritional quality for the purpose of developing and growing more healthy food. The information about intra-specific variation in nutrition composition will therefore help in making food and nutrition policies that promote and stimulate healthy diets and nutrition more precise and effective (Harris et al. 2022).

There is, however, still a poor understanding of the intra-specific variation of traits related to nutritional quality, as well as the heritability of high nutritional values and the impact of climatic factors on nutritional quality (Harris et al. 2022; Meckelmann et al. 2015; Rouphael et al. 2018; Lutaladio et al. 2010). Closing this knowledge gap towards a better understanding of the intra-specific variation in nutritional quality and of genotype x environment effects on said quality will help in selecting nutrient-dense and climate-resilient varieties. These varieties can be used to develop and grow nutrient-dense varieties, minimize effects of micronutrient dilution in breeding for yield increase, and develop varieties with special flavors for niche markets such as tasty tomatoes and gourmet chilies (*Capsicum* spp.) (Simon et al. 2009; Schouten et al. 2019; Tieman et al. 2017; Meckelmann et al. 2013). The mapping of genomic regions related to high or low phytonutrient concentrations will greatly enhance the development of varieties with high nutritional quality and specific taste profiles (Tieman et al. 2017).

Besides the micronutrients that are well-studied for nutrition, fruit and vegetable species harbor a wide range of phytonutrients and bioactive compounds that increase bioavailability and that are beneficially for health, including in ways that are not yet understood and that still represent a large knowledge gap for further research (Harris et al. 2022; Lutaladio et al. 2010; CBD 1992).

The rescue plan must be further complemented with conservation *in situ* (on farms, at the landscape level and in protected areas) to maintain local fruit and vegetable crops and varieties that play important ecological and dietary roles, and to stimulate the evolution of new traits through natural and human selection. Recognizing the importance of *in situ* conservation and the sovereign rights of countries over their natural resources, the CBD encourages contracting parties to take measures to protect natural ecosystems and viable populations both within and outside protected areas, restore degraded habitats, and control invasive species, among other threats (CBD 1992). Countries must put in place enabling policies and regulations to protect threatened species and populations, as well as promote sustainable use and the protection of local communities' traditional knowledge. Both the Plant Treaty and FAO Second Global Plan of Action provide further support to *in situ* conservation of plant genetic resources for food and agriculture (FAO 2009, 2011).

A common strategy for *in situ* conservation of CWR is for countries to carry out conservation planning exercises that prioritize CWR according to specific criteria, given that large numbers of CWR species may exist in a given country and it will not be possible to target them all in national strategies (Dulloo and Maxted 2019). The development of a National Strategy and Action Plan for *in situ* conservation of CWR is recommended to guide the implementation and monitoring of conservation activities such as the establishment of genetic reserves in protected areas (Fig. 1e). Wild relatives of fruit and vegetable crops are seldom included as a priority on national inventory lists; it is important to raise awareness of the need to conserve the wild relatives of these crops.

Local fruit and vegetable crops and varieties are still maintained by champion farmers, male and female, and communities in different production systems—diversified farms, home gardens, orchards, or other cultivated areas of high species and varietal diversity (Dulloo et al. 2017) (Fig. 1f). These plants provide nutritional and food security, income-generating opportunities, and ecosystem services, and contribute to cultural identity (Sthapit et al. 2016). Governments should recognize and protect unique and traditional production systems, such as some countries are doing already for important agricultural heritage systems (Koohafkan and Altieri 2011). They should further support these farmers and communities in maintaining these local crops and varieties by linking them to farm-to-school programs and niche markets for more resilient livelihoods, and by providing other types of incentives to maintain diversity in traditional production systems (Dulloo et al. 2017).

Finally, good agricultural practices and national and regional conservation strategies to protect pollinators and dispersers and their natural habitats must be implemented to safeguard these critical associated organisms of fruit and vegetable species (Wagner et al. 2021; Vasiliev and Greenwood 2020). These strategies should be embedded in various biodiversity and agricultural policy frameworks at national and international levels to stimulate integrated approaches for agrobiodiversity conservation. Pollinator conservation strategies have already been developed in the

United States, and in several countries of the European Union and the Global South; such strategies require urgent development and implementation elsewhere.

5 Conditions for success

An effective rescue plan requires clear goals, prioritizes actions, and tracks progress in line with the 2030 Agenda for Sustainable Development. It should be developed by a global team of experts from different sectors and disciplines in consultation with custodians and users of fruit and vegetable biodiversity worldwide, and then implemented in a concerted way under the umbrella of a global initiative endorsed by the Plant Treaty. Only with sufficient, sustained funding can a global rescue plan for fruit and vegetable biodiversity become a success. As a ballpark estimate, a 10-year global rescue plan for fruit and vegetable biodiversity would require at least 250 million USD.

Acknowledgments The authors wish to thank the United National Food Systems Summit Fruit and Vegetables Working Group for their original input to the original UNFSS working paper. Funding for this research was provided by long-term strategic donors to the World Vegetable Center: Taiwan, UK aid from the UK government, United States Agency for International Development (USAID), Australian Centre for International Agricultural Research (ACIAR), Germany, Thailand, Philippines, Korea, and Japan.

References

Achigan-Dako EG et al (2011) Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: Implications for domestication and utilization1. Econ Bot 65:129–145

Attwood S, Carmona NE, DeClerck F, Wood S (2017) Using biodiversity to provide multiple services in sustainable farming systems

Bauchet G, Causse M (2012) Genetic diversity in tomato (Solanum lycopersicum) and its wild relatives. In: Çalışkan M (ed) Genetic diversity in plants. (IN-TECH Education and Publishing, pp 133–162

Bharucha Z, Pretty J (2010) The roles and values of wild foods in agricultural systems. Philos Trans R Soc Lond B Biol Sci 365:2913–2926

Biesmeijer JC et al (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science (80) 313:351–354

Bioversity International (2021) New World Fruits. Database

Borelli T et al (2020) Local solutions for sustainable food systems: The contribution of orphan crops and wild edible species. Agronomy 10:231

Brink M, van Hintum T (2020) Genebank operation in the arena of access and benefit-sharing policies. Front Plant Sci 10

Burke MB, Lobell DB, Guarino L (2009) Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Glob Environ Chang 19:317–325

Byrne PF et al (2018) Sustaining the future of plant breeding: The critical role of the USDA-ARS National Plant Germplasm System. Crop Sci 58:451–468

Caron P et al (2018) Food systems for sustainable development: Proposals for a profound four-part transformation. Agron Sustain Dev 38:1–12

CBD (1992) Convention on Biological Diversity

Cebolla-Cornejo J, Soler S, Nuez F (2012) Genetic erosion of traditional varieties of vegetable crops in Europe: Tomato cultivation in Valencia (Spain) as a case Study. Int J Plant Prod 1:113–128

Cochrane A (2017) Saving seeds: Conserving our natural heritage. Aust Gard Hist 29:28

Cunha Alves AA, Azevedo VCR (2018) Embrapa network for Brazilian plant genetic resources conservation. Biopreserv Biobank 16:350–360

Cunningham SA (2000) Depressed pollination in habitat fragments causes low fruit set. Proc R Soc B Biol Sci 267:1149–1152

Dawson IK et al (2013) What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, in situ and ex situ settings? A review Biodivers Conserv 22:301–324

Díaz S et al (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. Science (80) 366

Dinerstein E et al (2017) An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67:534–545

Dirzo R et al (2014) Defaunation in the Anthropocene. Science (80) 345:401–406

Dulloo ME, Maxted N (2019) Special issue: Plant genetic resources conservation and utilization-crop wild relatives. Plant Genet Resour Characterisation Util 17:101–102

Dulloo ME et al (2017) Conserving agricultural biodiversity for use in sustainable food systems. In: Mainstreaming agrobiodiversity in sustainable food system: Scientific foundation for an agrobiodiversity index. Bioversity International, Rome

Dwivedi S, Goldman I, Ortiz R (2019) Pursuing the potential of heirloom cultivars to improve adaptation, nutritional, and culinary features of food crops. Agronomy 9:441

Engels JMM, Ebert AW (2021) A critical review of the current global ex situ conservation system for plant agrobiodiversity. II. Strengths and weaknesses of the current system and recommendations for its improvement. Plan Theory 10:1904

Engle LM, Faustino FC (2007) Conserving the indigenous vegetable germplasm of Southeast Asia. Acta Horticulturae 752:55–60

FAO (2009) International treaty on plant genetic resources for food and agriculture

FAO (2011) Second Global Plan of action for on plant genetic resources for food and agriculture. Commission on Genetic Resources for Food and Agriculture

Fu YB (2017) The vulnerability of plant genetic resources conserved ex situ. Crop Sci 57:2314–2328

Garibaldi LA, Aizen MA, Klein AM, Cunningham SA, Harder LD (2011) Global growth and stability of agricultural yield decrease with pollinator dependence. Proc Natl Acad Sci U S A 108:5909–5914

Gould J (2017) Nutrition: A world of insecurity. Nature 544:S6–S7

Grubben G, Denton O (2004) Plant resources of tropical Africa 2. Vegetables. PROTA foundation

Harris J et al (2022) Fruit and vegetable biodiversity for nutritionally diverse diets: challenges, opportunities, and knowledge gaps. Glob Food Sec 33:100618

Jacob SR, Tyagi V, Agrawal A, Chakrabarty SK, Tyagi RK (2015) Indian plant germplasm on the global platter: An analysis. PLoS One 10:e0126634

Jamnadass R et al (2020) Enhancing African orphan crops with genomics. Nat Genet 52:356–360

Jansen M et al (2020) Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. People Nat 2:1006–1020

Khoury CK et al (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci U S A 111:4001–4006

Khoury CK et al (2016) Origins of food crops connect countries worldwide. Proc R Soc B Biol Sci 283:1–9

Khoury CK et al (2019) Comprehensiveness of conservation of useful wild plants: An operational indicator for biodiversity and sustainable development targets. Ecol Indic 98:420–429
Khoury CK et al (2020) Modelled distributions and conservation status of the wild relatives of chile peppers (Capsicum L.). Divers Distrib 26:209–225
Khoury CK et al (2022) Crop genetic erosion: understanding and responding to loss of crop diversity. New Phytol 233:84–118
Kilian B et al (2021) Crop Science special issue: Adapting agriculture to climate change: A walk on the wild side. Crop Sci 61:32–36
Klein AM et al (2007) Importance of pollinators in changing landscapes for world crops. Proc R Soc B Biol Sci 274:303–313
Koohafkan P, Altieri MA (2011) Globally important agricultural heritage systems – a legacy for the future. FAO
Loskutov IG (2020) Vavilov Institute (VIR): Historical aspects of international cooperation for plant genetic resources. Genet Resour Crop Evol 67:2237–2253
Lusty C et al (2021) Envisaging an effective global long-term agrobiodiversity conservation system that promotes and facilitates use. Plan Theory 10:2764
Lutaladio NB, Burlingame B, Crews J (2010) Horticulture, biodiversity and nutrition. J Food Compos Anal 23:481–485
Magrach A, Sanz MJ (2020) Environmental and social consequences of the increase in the demand for 'superfoods' world-wide. People Nat 2:267–278
Martin AR et al (2019) Regional and global shifts in crop diversity through the Anthropocene. PLoS One 14:e0209788
Maundu P, Achigan-Dako E, Morimoto Y (2009) Biodiversity of African vegetables. In: Shackleton CM, Pasquini MW, Drescher AW (eds) African indigenous vegetables in urban agriculture. Routledge, pp 65–104
McMullin S et al (2021) Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. Glob Food Sec 28:100465
Meckelmann SW et al (2013) Compositional characterization of native Peruvian chili peppers (Capsicum spp.). J Agric Food Chem 61:2530–2537
Meckelmann SW et al (2015) Capsaicinoids, flavonoids, tocopherols, antioxidant capacity and color attributes in 23 native Peruvian chili peppers (Capsicum spp.) grown in three different locations. Eur Food Res Technol 240:273–283
Meldrum G, Padulosi S, Lochetti G, Robitaille R, Diulgheroff S (2018) Issues and prospects for the sustainable use and conservation of cultivated vegetable diversity for more nutrition-sensitive agriculture. Agri 8:112
Moreau T, Speight D (2019) Cooking up diverse diets: Advancing biodiversity in food and agriculture through collaborations with chefs. Crop Sci 59:2381–2386
Panis B, Nagel M, Van Den Houwe I (2020) Challenges and prospects for the conservation of crop genetic resources in field genebanks, in in vitro collections and/or in liquid nitrogen. Plan Theory 9:1634
Pearce TR et al (2020) International collaboration between collections-based institutes for halting biodiversity loss and unlocking the useful properties of plants and fungi. Plants, People, Planet 2:515–534
Pereira LM et al (2019) Chefs as change-makers from the kitchen: Indigenous knowledge and traditional food as sustainability innovations. Glob Sustain 2:1–9
Pilling D, Bélanger J, Hoffmann I (2020) Declining biodiversity for food and agriculture needs urgent global action. Nat Food 1:144–147
Ploetz RC (2021) Gone bananas? Current and future impact of fusarium wilt on production. Springer, Cham, pp 21–32. https://doi.org/10.1007/978-3-030-57899-2_2
Pringle RM (2017) Upgrading protected areas to conserve wild biodiversity. Nature 546:91–99
Rimlinger A et al (2021) Trees and their seed networks: The social dynamics of urban fruit trees and implications for genetic diversity. PLoS One 16:e0243017

Roothaert R, Mpogole H, Hunter D, Ochieng J, Kejo D (2021) Policies, multi-stakeholder approaches and home-grown school feeding programs for improving quality, equity and sustainability of school meals in northern Tanzania. Front Sustain Food Syst 5:43

Rouphael Y, Kyriacou MC, Petropoulos SA, De Pascale S, Colla G (2018) Improving vegetable quality in controlled environments. Sci Hortic 234:275–289

Schouten HJ et al (2019) Breeding has increased the diversity of cultivated tomato in the Netherlands. Front Plant Sci 10:1606

Schreinemachers P, Simmons EB, Wopereis MCS (2018) Tapping the economic and nutritional power of vegetables. Glob Food Sec 16:36–45

Schreinemachers P et al (2020) How much is too much? Quantifying pesticide overuse in vegetable production in Southeast Asia. J Clean Prod 244:118738

Shackleton CM, Hurley PT, Dahlberg AC, Emery MR, Nagendra H (2017) Urban foraging: a ubiquitous human practice overlooked by urban planners, policy, and research. Sustain 9. Page 1884 9, 1884 (2017)

Shaver I et al (2015) Coupled social and ecological outcomes of agricultural intensification in Costa Rica and the future of biodiversity conservation in tropical agricultural regions. Glob Environ Chang 32:74–86

Simon PW, Pollak LM, Clevidence BA, Holden JM, Haytowitz DB (2009) Plant breeding for human nutritional quality. Plant Breed Rev 31:325–392

Sthapit B, Lamers HAH, Ramanatha RV, A. & Bailey A. (2016) Tropical fruit tree diversity: Good practices for in situ and on-farm conservation. Earthscan

Syfert MM et al (2016) Crop wild relatives of the brinjal eggplant (Solanum melongena): Poorly represented in genebanks and many species at risk of extinction. Am J Bot 103:635–651

Taylor JR, Lovell ST (2014) Urban home food gardens in the Global North: Research traditions and future directions. Agric Human Values 31:285–305

Thormann I, Gaisberger H, Mattei F, Snook L, Arnaud E (2012) Digitization and online availability of original collecting mission data to improve data quality and enhance the conservation and use of plant genetic resources. Genet Resour Crop Evol 59:635–644

Tieman D et al (2017) A chemical genetic roadmap to improved tomato flavor. Science 355:391–394

Van Loon R et al (2021) Barriers to adopting a diversity of NUS fruit trees in Latin American food systems. In: Orphan crops for sustainable food and nutrition security. Taylor & Francis Group, pp 88–108. https://doi.org/10.4324/9781003044802-8

Van Zonneveld M et al (2018) Human diets drive range expansion of megafauna-dispersed fruit species. Proc Natl Acad Sci U S A 115:3326–3331

van Zonneveld M, Turmel MS, Hellin J (2020a) Decision-making to diversify farm systems for climate change adaptation. Front Sustain Food Syst 4:32

van Zonneveld M et al (2020b) Mapping patterns of abiotic and biotic stress resilience uncovers conservation gaps and breeding potential of Vigna wild relatives. Sci Rep 10:1–11

van Zonneveld M, Kindt R, Solberg S, N'Danikou S, Dawson IK (2021) Diversity and conservation of traditional African vegetables: Priorities for action. Divers Distrib 27:216–232

Vanhove W, Van Damme P (2013) Value chains of cherimoya (Annona cherimola Mill.) In a centre of diversity and its on-farm conservation implications. Trop Conserv Sci 6:158–180

Vasiliev D, Greenwood S (2020) Pollinator biodiversity and crop pollination in temperate ecosystems, implications for national pollinator conservation strategies: Mini review. Sci Total Environ 744:140880

Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D (2021) Insect decline in the Anthropocene: Death by a thousand cuts. Proc Natl Acad Sci 118:e2023989118

Walters SA, Bouharroud R, Mimouni A, Wifaya A (2018) The deterioration of Morocco's vegetable crop genetic diversity: An analysis of the Souss-Massa region. Agri 8

WFP (2013) State of school feeding worldwide

Willett W et al (2019) Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492

Reduction of Food Loss and Waste: The Challenges and Conclusions for Actions

Joachim von Braun, M. Sanchéz Sorondo, and Roy Steiner

1 Introduction

The global food system is malfunctioning, leaving large segments of the population undernourished or malnourished, and causing significant environmental damage. Food losses in the production, processing and marketing segments of food systems are part of the problem. Food-wasting at the retail, household and restaurant levels is a serious problem too. The analyses and calls for action in this volume are motivated by the United Nations Sustainable Development Goal (SDG) No. 12, i.e., Ensuring sustainable consumption and production patterns, and specifically, "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses."

This goal is very much in line with the Encyclical *Laudato Si′*, in which Pope Francis calls for changes for the purpose of overcoming "throwaway culture." Food Loss and Waste (FLAW) is a moral issue, because of the adverse effects on people and our planet (Grizzetti et al. 2013). It is detrimental to the planet due to greenhouse gas (GHG) emissions and the wasting of the water and land used as inputs (Kummu

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

M. S. Sorondo
Pontifical Academy of Sciences, Rome, Italy

R. Steiner
The Rockefeller Foundation, New York, NY, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_31

et al. 2012),[1] and to people – the poor in particular – whose labor is squandered and whose livelihoods are compromised when FLAW occurs.

Box 1: SDG 12 – Ensuring Sustainable Consumption and Production Patterns

> "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses."

Since loss and waste are related but distinct phenomena, each merits a unique indicator, as stated by FAO:

Sub-Indicator | Food Loss Index: The Food Loss Index (FLI) focuses on food losses that occur from production up to (and not including) the retail level. *http://www.fao.org/sustainable-development-goals/indicators/1231/en/*

and as developed by UNEP:

Sub-Indicator | Food Waste Index: A Food Waste Index, which comprises retail and consumption levels. *https://wedocs.unep.org/handle/20.500.11822/35280;jsessionid=37107F3730786C883BCABD606C13CBFE*

The aim of this chapter is to share the latest scientific evidence on how to reduce food loss and waste, and thereby contribute to global food and nutrition security. The second aim is to provide recommendations for expanded global and national actions, including public and private investments and initiatives by citizens, corporations, governments, and international organizations. We recognize that the alliance of actors must become broader in order to make significant improvements globally in reducing FLAW.

To fulfill these objectives, we focus on clearly defining food loss and waste, while adopting a value-chain approach. When considering the magnitude of the food loss and waste challenge, summing up the tonnage of different foods is not appropriate: not only must weight be considered, but also the economic and environmental cost of wasted and lost food must. The latest approaches to measurement in economic, caloric, or quality-adjusted weight terms are presented and discussed.

Further, food loss and waste reduction have huge benefits, but also costs, and these costs must not be ignored when aiming for efficient solutions (Aragie et al. 2018). Benefits and costs must consider environmental, as well as food and nutrition security, effects. We know that environmental change and people's health cannot be easily captured by economic calculations (Kuiper and Cui 2021; Chen et al. 2020).

---

[1] This chapter is based on the findings and recommendations for action identified by the participants of the International Conference by the Pontifical Academy of Sciences (PAS) with the Rockefeller Foundation. The book based on the conference is at https://www.pas.va/content/dam/casinapioiv/pas/pdf-volumi/scripta-varia/sv147pas.pdf

Successfully meeting SDG 12.3 requires approaches that foster education and awareness, behavioral change, a renewed global dialogue, and coordinated global action. Ultimately, we need to create incentives that will strengthen the business case for tackling food loss and waste and moving towards more sustainable consumption patterns (Qi et al. 2021).

As we aim to unite and improve our understanding and strengthen our conviction to act on food loss, we are aware that these phenomena are embedded within a broader food system context.

2 Food Loss and Waste

Until recently, there has been an absence of a uniform definition of food waste and loss (Xue and Liu 2019). Various definitions have been used in literature and in policy documents (Bellemare et al. 2017; Fabi et al. 2021). This lacuna stands in the way of analyses on food waste and loss, including its precise measurement at the national, regional and global scales. The FAO, therefore, provides a definition and defines food loss and waste as the "decrease in quantity or quality of food along the food supply chain" (FAO 2019). In this definition, *food losses* occur in the food supply chains from harvest to retail and *food waste* occurs in retail and consumption (Cattaneo et al. 2021). The definition has been expanded by others to include pre-harvest, quantitative and qualitative food losses (Delgado et al. 2021).

Food waste concepts have also been further clarified by UNEP with its Food Waste Index Report 2021, which ". . . for the purposes of the Food Waste Index, 'food waste' is defined as food . . . and the associated inedible parts removed from the human food supply chain in the following sectors: Retail, Food service, Households. 'Removed from the human food supply chain' means one of the following end destinations: landfill; controlled combustion; sewer; litter/discards/refuse; co/anaerobic digestion; compost/ aerobic digestion; or land application. Food is defined as any substance – whether processed, semi-processed or raw – that is intended for human consumption. 'Food' includes drink, and any substance that has been used in the manufacture, preparation or treatment of food. Therefore, food waste includes both 'edible parts': i.e., the parts of food that were intended for human consumption, and 'inedible parts': components associated with a food that are not intended to be consumed by humans. Examples of inedible parts associated with food could include bones, rinds and pits/stones" (United Nations Environment Programme 2021).

A lack of consensus on the definition spills into measurement of food loss and waste (Delgado et al. 2021; Bellemare et al. 2017). FLI (Box 1) measures the economic value of food losses based on commodity prices. FLI is helpful in cost-benefit analyses. FLI and FWI are also used to monitor SDG 12.3. Other measures, such as food loss in terms of calories or reduction in GHGs, are suitable for analyses of targeted interventions such as improvements in nutrition outcomes and impact on environmental sustainability (Xue and Liu 2019).

Actions to reduce food loss and waste are already planned or in place in many countries, but, so far do not add up to sufficient global impact and joint learning. The most promising actions can and must be enhanced. By bringing together a group of prominent leaders, actively engaged with this issue, from academia, religious communities, the private sector, government, civil society, and the United Nations (UN), we aim to create an interdisciplinary space for analysis, the sharing of knowledge and focused solutions. Ultimately, reducing FLAW requires a change in mindsets among those who waste food and large-scale investments in value chains that are losing food. The State of Food and Agriculture Report (2019) by the Food and Agriculture Organization (FAO) of the United Nations and Reducing Food Loss and Waste: Setting a Global Action Agenda (2019) by the World Resource Institute (WRI) and a coalition of partners, along with other reports, provide a basis for action. How to go about these challenges is summarized in the conclusions and proposed actions below.

3 Proposed Actions

1. *Increased Commitment for Action*

Food loss and waste (FLAW) has serious moral repercussions, in view of the prevailing hunger of more than 820 million people and the lack of access to healthy diets for 2 billion people (FAO's SOFI report 2019). Resources such as water and fertile land are becoming scarcer, because food is produced but never eaten.

FLAW significantly contributes to GHG emissions (SOFA 2019), and thereby to climate change and its consequences (Read et al. 2020). FLAW is detrimental to the planet and its people. It is morally, economically and environmentally unacceptable in the era of the SDGs. There is a need for an increased commitment to action from national, regional and global leaders towards SDG 12.3, i.e., by 2030, to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses – an achievable goal based on existing knowledge and technology. Yet, even though it is within our ability to tackle, FLAW reduction needs more attention and investment.

Successfully achieving Target 12.3 of the United Nations SDGs requires a new perspective on how to reduce the use of resources and increase the efficiency of the production, preservation, processing and distribution of food at the producer, intermediary, processor and wholesale levels (i.e., losses in the value chain). It also requires addressing our "throwaway culture." For that, education, awareness, and behavioral change among consumers and retailers are critical. A renewed global dialogue at the highest levels of government, business, religion, and civil society is urgently needed to achieve the target of halving FLAW by 2030.

2. *Localizing the FLAW problem, while tapping into global solutions*

Data deficiencies mask the diversity of the FLAW problem – which varies greatly across regions and value chains. While a high percentage of food is currently lost at the production, handling and processing stages in low-income and emerging economies, food is wasted in retail and consumption stages in higher income countries due to market design and consumer behavior (Min et al. 2021). Yet, market design and food waste patterns are increasing in low- and middle-income countries as the global middle class grows and urbanizes. Solutions are within reach for all country groups, but need to be tailored to specific contexts (Brander et al. 2021) and differentiated as to food loss versus food waste, as these are related but distinct concepts. Food waste happens due to a lack of appropriate infrastructure, regulations, profit-seeking, negligence, time scarcity and economic abundance at the consumer level. Food loss occurs due to unfavorable climatic conditions, improper post-harvest handling, and incentive structures that cause food loss to be seen as a rational economic option, as well as a lack of information, education, technology, infrastructure, affordable financing and market access. FLAW has social equity and gender implications. Food production, and not just that in low-income countries, involves large shares of unpaid labor done by women and often low-paid workers, including migrants, producing cheap food that might be undervalued, and thus is wasted by customers. In addition, all steps in supply chains should be reviewed and monitored in order to prevent the use of forced labor and modern slavery (according to SDG 8.7).

Value chains of perishable and nutrient-rich foods (both crops and animal-sourced protein) are significantly affected. More nutritious and healthier dietary patterns require managing and preserving these nutritious foods and fostering attention to food safety.[2]

FLAW requires attention, along with all aspects of wasteful processing, transportation, packaging (e.g., the plastics issue) and energy usage along food supply chains – issues that, it is hoped, a circular economy and bioeconomy can address systemically. Attention to prevention, not just reduction, should be considered, and solutions need to consider further the possible impacts on food access and affordability.

3. *Strengthening of information and data*

Only when sound data are gathered and made available will measurement and monitoring progress against benchmarks become feasible and viable for investors and companies (Xue and Liu 2019). When considering the magnitude of the FLAW challenge, summing up the tonnage of different foods does not appropriately capture food, environmental, and economic issues. We must move beyond a weight metric and assess the economic, environmental, institutional, health, and human costs of

[2] The issue has been addressed in the Conference by the Pontifical Academy of Sciences and the Global Alliance for Improved Nutrition on Food Safety and Healthy Diets in 2018 http://www.pas.va/content/accademia/en/events/2018/food/statement.html accessed on 08.12.2021.

lost and wasted food. The hotspots in value chains where food losses occur are increasingly identified, as are effects in terms of quality losses, economic costs and emissions costs (FAO's SOFA report 2019).

While FLAW reduction has huge benefits, the costs of action cannot be ignored when aiming for effective and efficient solutions. A comprehensive approach of cost of action versus cost of inaction may be helpful.

Efforts to collect and analyze data need to be doubled down, not only for reporting purposes, but also for the identification of causes of FLAW and decision-making for action by all players in value chains. We encourage agencies in charge of these metrics and analyses to step up efforts in these areas, donors to enhance financial support, and the private sector to report on a volunteer basis.

4. *Research in science, technology and extension*

Research initiatives by FAO, WRI, IFPRI (International Food Policy Research Institute), UNEP, the World Bank, the IADB, the InterAcademy Partnership, and universities, as well as others, highlight opportunities and challenges for research on food and nutrition security and sustainable food production, and propose priorities for natural science, social science and food post-harvest and food technology research on FLAW reduction.

Close cooperation among research communities and different stakeholders across food systems is called for to make progress on evidence-based FLAW reduction and action, including food market analysis, in order to understand the potential of solutions and innovations, as well as the feasibility of their adoption (Ellison et al. 2019). The FLAW problem needs further clarification as to what it means for people and the planet, and what it takes to move towards a more sustainable future. As waste is partly a behavioral issue, research on the behavioral aspects of FLAW needs more attention.

The causes of FLAW from a food system perspective need to be comprehensively investigated in order to avoid trade-offs across interventions if practiced within silos, and in order to point at their policy implications in the short and long term. The main knowledge gaps and the research agenda have been outlined in various recent publications, such as the InterAcademy Partnership report on "Opportunities for future research and innovations on food and nutrition security and agriculture" (2018). Urgent action, especially in Sub-Saharan Africa, Central and Southern Asia, and other developing regions affected by high incidence of food insecurity and food loss, is needed.

Pathways to effective alliances need to reflect a systemic approach to FLAW reduction, incorporating innovations in science and technology, and in monitoring food items transiting through the system. There is a role for extension services in dissemination, and for universities in building FLAW into their curricula. Information and communication technologies (ICT) and data science have proven to be game-changers in this respect. The research community must communicate, coordinate and collaborate, and governments, businesses and foundations must invest new resources to fund FLAW research.

5. Civil society actions

Civil society is taking action in areas related to FLAW. Different groups across the globe lead campaigns and disseminate information and good practices, educating consumers across all age groups, youths in particular, and advocating for more sustainable consumption patterns. Consumers are becoming aware of their environmental footprint when making choices about food purchases, portion sizes, packaging materials, and the distances that foods travel. Other groups, such as Food Banks, have developed models to collect, repurpose and re-distribute food in urban settings. Broadening efforts at the grassroots level from national or regional networks towards a global network will be fruitful. Efforts led by conscious youths need support, including consumer and producer/farmer perspectives that care about the sustainability of the planet and the people.

Education, for instance, through the global sharing of experiences in successful actions, can help countries identify solutions pertaining to issues of relevance tailored to specific circumstances. Toolkits in many languages for civil society organizations would be helpful. Dialogue on FLAW needs to be replicated more globally, reinforcing positive social norms and engaging influencers and role models.

Religious communities also have a role to play. These communities can engage in leading community initiatives against food waste and loss. Both loss and waste are moral issues causing harm beyond their economic and environmental tolls. Faith-based communities should initiate dialogues on acting together to support, advocate and collaborate on reducing FLAW.

6. *Government actions*

Governments at all levels need to set explicit, ambitious and realistic FLAW reduction targets, measure the level and change of FLAW, and implement an effective and economically efficient FLAW reduction strategy. Some countries have invested in developing plans and actions to reduce FLAW. So far, however, they do not add up to sufficient global impact and joint action.

Investments in critical value-chain infrastructure need to be prioritized in low- and middle-income countries. Such investments would allow for vertical coordination and modernization of value chains. The need for such investments is particularly acute when dietary patterns are changing and demand for a more diverse and nutritious food basket, especially in urban areas, is rising. Innovative solutions for financing such government plans as the Sustainable Development Bond launched by the World Bank and innovative financing solutions such as a fund for investments in FLAW reduction might facilitate progress in this area.

Governments should also seek to redress incentive structures (including through price and regulatory measures like standards) such as those that encourage farmers and other supply chain actors, as well as retailers and consumers, to adopt practices that help reduce FLAW.

Furthermore, two issues need government consideration at the macro scale: (1) diversion from rule-based free trade can accelerate FLAW and needs attention;

and (2) as FLAW accounts for a significant share of GHG emissions (Galford et al. 2020), the issue should feature on the action agenda of climate negotiations and Nationally Determined Commitments (NDCs).

7. *Business case and corporate actions*

A business case for addressing FLAW seems to exist, yet needs to be clearly demonstrated. Public support is initially required for implementation at scale and to reap societal benefits. A case in point is connecting to small farmers: As food companies aim to create value, business can lead the way in developing models that are more inclusive, such as sourcing from small-scale producers. New product lines that are more sustainable will result from implementing business solutions that create shared value and measure progress towards tangible targets (Martins et al. 2019). However, to convince customers, corporations need to assure transparency of actions and results in terms of FLAW targets.

Creativity is encouraged. For example, FLAW reduction can be a large domain for innovative start-ups targeted by the financial sector. Voluntary efforts being made by businesses can be an effective mechanism if transparency of results is assured. Market-based approaches can help, but attention to impacts on low-income people and to the indirect effects on environments is necessary. Given simple metrics, setting targets and following up company by company, including input suppliers and company employees, is a practical approach.

Taking a shared value approach is promising when FLAW issues are included in corporate monitoring, auditing and reporting to shareholders. There are also roles for farmers, farmer organizations and small- and medium-sized enterprises to create awareness of the benefits of FLAW reduction and, where possible, seek collaborative responses (e.g., cooperative-organized cold chain development and other value chain improvements).

8. *Joint actions, leadership and governance*

To address the FLAW challenge effectively requires collective action. Joint government and private sector action at the global, regional and national levels, with engagement by religious communities, civil society and consumers, is required. Such joint actions will need to keep the following ideas in mind:

1. Alliances of different actors require clearly defined strategies to reduce FLAW (e.g., among farmers, traders and the corporate sector, as well as among funders);
2. Government commitments to measure and report on FLAW metrics are essential for joint actions. For this, SDG 12.3.1.a (for losses) and SDG 12.3.1.b (for waste) are the indicators that need to be collected;
3. Institutional innovations and incentive systems are required to bring together broad, stable and well-funded alliances for the reduction of FLAW;
4. Examples of joint actions need to be systematically assessed and evaluated in relation to their effectiveness. This can provide the bases for good storytelling;

5. Increased, aligned and coordinated investments (and information on investment returns) will help to expand investments further;
6. Initiatives for complementary and joint action between civil society and businesses can be win-win if based on mutual respect and well-defined goals;
7. Joint action for FLAW must also address food safety, to ensure that foods are properly handled, stored and prepared according to strict health and consumer protection standards. Moreover, supply chains should be carefully checked to prevent the use of forced labor and modern slavery;
8. Pathways towards a global action plan and key commitments to address existing knowledge and research gaps and investments for the realization of SDG 12.3 need to be promoted;
9. A focused food loss and waste summit conference should be considered, and the planned 2021 United Nations Food Systems Summit led by FAO with IFAD, WFP, and others, in addition to further high-level global gatherings, should include a strong focus on FLAW reduction. FLAW reduction action for the achievement of SDG 12.3 needs a facilitating mechanism, adhered to by the United Nations, governments, civil society and the private sector;
10. We aim for coordinated communication efforts to raise the profile of the FLAW issue in the media and mobilize civil society and religious communities to embed FLAW reduction efforts as part of an inclusive and sustainable food system.

References

Aragie E, Balié J, MoralesOpazo C (2018) Does reducing food losses and wastes in sub-Saharan Africa make economic sense? Waste Manag Res 36(6):483–494

Bellemare MF, Çakir M, Peterson HH, Novak L, Rudi J (2017) On the measurement of food waste. Am J Agric Econ 99(5):1148–1158

Brander M, Bernauer T, Huss M (2021) Improved on-farm storage reduces seasonal food insecurity of smallholder farmer households–evidence from a randomized control trial in Tanzania. Food Policy 98:101891

Cattaneo A, Sánchez MV, Torero M, Vos R (2021) Reducing food loss and waste: five challenges for policy and research. Food Policy 98:101974

Chen C, Chaudhary A, Mathys A (2020) Nutritional and environmental losses embedded in global food waste. Resour Conserv Recycl 160:104912

Delgado L, Schuster M, Torero M (2021) Quantity and quality food losses across the value chain: a comparative analysis. Food Policy 98:101958

Ellison B, Muth MK, Golan E (2019) Opportunities and challenges in conducting economic research on food loss and waste. Appl Econ Perspect Policy 41(1):1–19

Fabi C, Cachia F, Conforti P, English A, Moncayo JR (2021) Improving data on food losses and waste: from theory to practice. Food Policy 98:101934

FAO (2019) The state of food and agriculture 2019. Moving forward on food loss and waste reduction. Licence: CC BY-NC-SA 3.0 IGO, Rome

Galford GL, Peña O, Sullivan AK, Nash J, Gurwick N, Pirolli G et al (2020) Agricultural development addresses food loss and waste while reducing greenhouse gas emissions. Sci Total Environ 699:134318

Grizzetti B, Pretato U, Lassaletta L, Billen G, Garnier J (2013) The contribution of food waste to global and European nitrogen pollution. Environ Sci Pol 33:186–195

Kuiper M, Cui HD (2021) Using food loss reduction to reach food security and environmental objectives–a search for promising leverage points. Food Policy 98:101915

Kummu M, De Moel H, Porkka M, Siebert S, Varis O, Ward PJ (2012) Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci Total Environ 438:477–489

Martins VG, Romani VP, Martins PC, da Silva Filipini G (2019) Innovative packaging that saves food. In: Saving food. Academic, pp 171–202

Min S, Wang X, Yu X (2021) Does dietary knowledge affect household food waste in the developing economy of China? Food Policy 98:101896

Qi D, Lai W, Roe BE (2021) Food waste declined more in rural Chinese households with livestock. Food Policy 98:101893

Read QD, Brown S, Cuéllar AD, Finn SM, Gephart JA, Marston LT et al (2020) Assessing the environmental impacts of halving food loss and waste along the food supply chain. Sci Total Environ 712:136255

United Nations Environment Programme (2021) Food waste index report 2021. Nairobi. https://wedocs.unep.org/handle/20.500.11822/35280;jsessionid=37107F3730786C883BCABD606C13CBFE

Xue L, Liu G (2019) Introduction to global food losses and food waste. In: Saving food. Academic, pp 1–31

Part V
Costs, Investment, Finance, and Trade Actions

The True Cost of Food: A Preliminary Assessment

Sheryl Hendriks, Adrian de Groot Ruiz, Mario Herrero Acosta, Hans Baumers, Pietro Galgani, Daniel Mason-D'Croz, Cecile Godde, Katharina Waha, Dimitra Kanidou, Joachim von Braun, Mauricio Benitez, Jennifer Blanke, Patrick Caron, Jessica Fanzo, Friederike Greb, Lawrence Haddad, Anna Herforth, Danie Jordaan, William Masters, Claudia Sadoff, Jean-François Soussana, Maria Cristina Tirado, Maximo Torero, and Matthew Watkins

1 Introduction

The vision of the UN Food Systems Summit was to "launch bold new actions, solutions and strategies to deliver progress on all 17 Sustainable Development Goals (SDGs), each of which relies on healthier, more sustainable and more equitable food systems" (UN 2021a, b). The Summit was seeking to transform the way in which the world produces, consumes and thinks about food and to build a just and resilient world where no one is left behind (UN 2021a, b). In various Summit platform discussions, questions have arisen relating to (a) the true cost of the food we eat,

With assistance from Prisca Atieno and Valiant Odhiambo (Kenya), Postgraduate Assistants, Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, South Africa.

S. Hendriks (✉)
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa
e-mail: sheryl.hendriks@up.ac.za

A. de Groot Ruiz · H. Baumers · P. Galgani · D. Kanidou
Impact Institute, Amsterdam, the Netherlands

M. H. Acosta
Cornell Global Development, Cornell Atkinson Centre for Sustainability, College of Agriculture and Life Sciences Cornell University, Ithaca, NY, USA

D. Mason-D'Croz
College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA

Agricultural Economics and Rural Policy Group, Wageningen University & Research, Wageningen, the Netherlands

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_32

(b) what costs would be involved in shifting to more sustainable patterns of production and consumption, (c) who would bear the cost of these changes and (d) what the implications are for the poorest consumers. Addressing these hidden externalities would be a significant, bold action.

Ensuring sustainable food systems entails ensuring that food systems provide affordable and healthy food to all people while respecting planetary and social boundaries. Current food systems are not sustainable. They generate substantial environmental, social and health costs while failing to provide affordable food to all (FAO et al. 2020. For example:

- The emissions associated with pre- and post-production activities in the global food system are estimated to be 21–37% of total net anthropogenic GHG emissions (IPPC 2019),
- The majority of the global working poor work under difficult conditions in agriculture (World Bank 2016),
- 690 million people were undernourished in 2019 (FAO et al. 2020), and
- More than 10 million lives are lost annually due to unhealthy eating patterns (Afshin et al. 2019).

C. Godde
The Commonwealth Scientific and Industrial Research Organisation (CSIRO) St Lucia, St Lucia, QLD, Australia

K. Waha
Agriculture and Food, Commonwealth Scientific and Industrial Research Organization (CSIRO) St Lucia, St Lucia, QLD, Australia

J. von Braun
Center for Development Research (ZEF), University of Bonn, Bonn, Germany

M. Benitez
responsAbility Investments AG, Zurich, Switzerland

J. Blanke
Syngenta Foundation for Sustainable Agriculture, Basel, Switzerland

P. Caron
Montpellier Advanced Knowledge Institute on Transitions, Montpellier, France

J. Fanzo
Berman Institute of Bioethics, Nitze School of Advanced International Studies, Bloomberg School of Public Health, Johns Hopkins University, Washington, DC, USA

F. Greb
Assessment and Monitoring Division, World Food Programme (WFP), Rome, Italy

L. Haddad
Lead: Food Systems Summit Action Track 1, Executive Director of the Global Alliance for Improved Nutrition (GAIN) Global Alliance for Improved Nutrition, Geneva, Switzerland

A transition to sustainable food systems will reduce their environmental, social and health costs while making healthy food affordable to all. Researchers have only recently begun investigating what dietary changes will be necessary to keep food systems within planetary boundaries (Herrero et al. 2017; Rockström et al. 2009). Even more recently, the question has arisen as to how changes in the food system and their resultant impacts on environments in which consumers acquire foods (food environments) affect our health, particularly the incidence of obesity and non-communicable diseases (Willett et al. 2019). For example, the EAT-Lancet report estimated that a transformation to healthy diets by 2050 would require substantial dietary shifts. This will include reducing the consumption of:

- Foods with added sugars (including harmful non-nutritive sweeteners),
- Refined grains (that can cause diabetes),
- Added sodium (that can cause hypertension),
- Harmful fats (especially harmful trans fats, and, to a lesser degree, other solid fats linked to cardiovascular disease), and
- Processed meats (associated with cancer).

A. Herforth
Friedman School of Nutrition, Tufts University, Boston, MA, USA

Harvard T.H. Chan School of Public Health, Boston, MA, USA

D. Jordaan
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa

W. Masters
Friedman School of Nutrition and Department of Economics, Tufts University, Medford, MA, USA

C. Sadoff
Consultative Group on International Agricultural Research, CGIAR System Management Office, Paris, France

J.-F. Soussana
French National Research Institute for Agriculture, Food and Environment (INRAE), Paris, France

M. C. Tirado
School of Public Health UCLA, Los Angeles, CA, USA

International Climate Initiatives at the LMU Center for Urban Resilience, Los Angeles, CA, USA

M. Torero
Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

M. Watkins
Food Reform for Sustainability & Health (FReSH), Geneva, Switzerland

Increasing the consumption of healthy, protective foods such as fruits and vegetables, legumes, nuts and seeds (Willett et al. 2019) will address multiple health-related issues. These protective foods are needed for their phytochemicals and fiber that may be absent from other foods. Often, unhealthy foods displace healthy alternatives (such as fruit, legumes, nuts, seeds and vegetables, along with beneficial forms of primary processing such as fermentation) that may be less convenient (Masters et al. 2021) and less marketed and, therefore, under-consumed.

Effective game-changing strategies[1] for achieving sustainable food systems should arguably not only treat the symptoms of the problem. Solutions should also address the root causes of why food systems impose environmental and health costs and fail to provide sufficient quantities of beneficial foods in the first place. One major root cause is that these costs and benefits of production and consumption are externalized, due to how markets are designed. These externalities are not reflected in market prices (Baker et al. 2020) and have no economic 'currency.' As a result, externalities are hidden effects of the choices of market players, and make sustainable and healthy food less affordable for consumers and less profitable for producers. Historically, business profits and the choices of all stakeholders have been based on market prices and recorded in economic statistics such as gross domestic product (GDP). External costs and benefits can also be documented in statistics on mortality and disease, climate change and pollution. However, the link between market activity and those social or environmental harms is not directly visible or reflected in the incentives that drive economic systems. As a result, the economic value of food, which drives economic choices by businesses, consumers and governments, is highly distorted. By providing distorted information and perverse (often unintended) incentives against affordable, sustainable and healthy food, externalities constitute a significant barrier to attaining sustainable food systems. Moreover, even with a full-cost approach, there are likely trade-offs across the health and sustainability considerations. There is considerable diversity in regional food systems and their externalities.

Internalizing the externalities of food systems requires redefining the value of food by measuring and pricing these externalities through 'true-cost accounting' (TCA) approaches. At the request of the Scientific Group of the UN Food Systems Summit, a working group set out to investigate the true costs of food and propose possible actions to address the problem.

[1]The UNFSS definition of a game changing and systemic solution' is a feasible action, based on evidence, best practice or a thorough conceptual framework that would shift operational models or underlying rules, incentives and structures that shape food systems, acting on multiple parts of – or across – the food system, to advance global goals that can be sustained over time. The key criteria that a 'game changing and systemic' solution must have are to (1) have impact potential at scale (including return on investment), (2) be actionable (taking into account politics, capacity, costs) and (3) be sustainable (i.e., the ability to keep delivering up to 2030 and beyond).

This chapter aims to inform food system stakeholders about how they can grasp an opportunity based on the most recent scientific insights in this young and emerging field of analysis. Section 2 summarizes the problem of externalities. Section 3 describes how TCA can be used to redefine the value of food. Section 4 provides an analysis of the current true environmental and health costs of food at the global level based on research from the working group. Section 5 outlines the potential benefits of dietary transitions. Section 6 outlines the study's limitations and future research avenues. Section 7 concludes and presents recommendations.

2 Externalities as Barriers to Sustainable Food Systems

Externalities refer to "situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided" (OECD 2003). Externalities can arise when people are affected by the market choices of others in which they have no say (Laffont 2008). For example, greenhouse gas (GHG) emissions from one person's actions affect people far away, as well as future generations who have no say in those decisions. Externalities can also be beneficial, such as disease prevention that lowers health care costs. There are other price-related market failures that lead to the inefficient allocation of resources. In addition to monopoly and monopsony, a lack of information or behavioral biases, for example, around health effects, can lead consumers to ignore the costs and benefits of their decisions (Gruber and Köszegi 2001; Wang and Sloan 2018). Due to missing markets, the well-being effects of affordable, healthy food on the poor will not translate to higher prices or drive the supply of more healthy food.

Externalities arise from several elements in the food system (see Table 1). The boundary between social and human capital is defined differently across frameworks, and health externalities can also be classified as human capital (TEEB 2018). There is considerable variation in costs between food products and regions. In some cases, traditional practices of animal husbandry can have positive effects on natural capital (Baltussen et al. 2019). Commodities involving production by smallholders in developing countries (such as cocoa or coffee) tend to have higher external social costs, including underearning for farmers.

Externalities create significant problems in food systems. The first problem is that externalities prevent societies from achieving their full potential by distorting the information about the value of food conveyed by market prices Gemmill-Herren et al. 2021. The market price of products does not reflect their true costs and benefits. Also, the value of companies and their decisions reflect expected future profits – the difference between the sum of the cost of outputs minus the sum of the cost of all

Table 1 Summary of the key externalities in food systems

Type of externality	Examples of externalities	Endpoint impact(s)
Environmental[1] (effects on natural capital)	Air, water and soil pollution GHG emissions Land use Overuse of renewable resources Soil depletion Use of scarce materials Water use	Contribution to climate change, health effects, depletion of abiotic resources, depletion of biotic resources, including ecosystem services and biodiversity
Social[2] (effects on social rights and human and social capital)	Animal welfare Child and forced labor Discrimination and harassment High and variable prices Training Underpayment and underearning	Poverty, well-being, food security and human skills
Health[3] (effects on human health)	Antimicrobial resistance Undernutrition Unhealthy diet composition Zoonoses	Human life (mortality and the quality of life), economic (medical costs, informal care, lost working days)
Economic[4] (effects on financial, manufactured and intellectual capital)	Food waste Tax evasion	Increased food demand, and a decrease in public funds

Sources
[1]FAO (2015), NCC (2015), Baltussen et al. (2016), Allen and Prosperi (2016), Nkonya et al. (2016), TEEB (2018, 2019), Dalin and Outhwaite (2019), FOLU (2019), and Galgani et al. (2021).
[2]Baltussen et al. (2016), Westhoek et al. (2016), IDH (2016), WBCSD (2018), Jaffee et al. (2019), and Galgani et al. (2021).
[3]Baltussen et al. (2016), FOLU (2019), TEEB (2018), Afshin et al. (2019), and FAO et al. (2020).
[4]FAO (2015), TEEB (2018, 2019), Impact Institute (2020), and FAO et al. (2020).

inputs, including labor (OECD 2002), all valued at market prices. If a company contributes to climate change, underpays workers or enables healthy and affordable food, this is not reflected in its profits (Serafeim et al. 2019). As the financial returns of companies are based on their (expected) profits, the financial value of investments does not reflect the actual value that these investments bestow upon society

(Serafeim et al. 2019). The economic value of the food sector is measured by its contribution to GDP, which is the sum of all companies' added value - the value of output minus the value of intermediate consumption measured at market prices (OECD 2001). Hence, the degree to which food systems contribute to climate change, deforestation or poor health is not factored into crucial economic indicators for policymakers (Stiglitz et al. 2018), and externalities, therefore, lead countries to have lower average living standards than would otherwise be possible.

A second problem with (negative) externalities is social injustice. The existing arrangement of property rights, institutions and infrastructure was constructed over time, reflecting the past choices of those in power who sometimes neglected or actively harmed marginalized groups, including women and girls, indigenous and minority populations, migrant workers, and other communities. Environmental harm such as air and water pollution is often concentrated in places inhabited by marginalized groups. Unhealthy products are often marketed most intensively to vulnerable populations such as children.

The result is a variety of involuntary harms that may include severe rights violations (forced labor, harassment of women or underpayment in the agricultural sector) and that breach the rights of the people who produce our food. A lack of affordable food is also a breach of the right to food for consumers. The erosion of natural capital breaches the rights of future generations to decent livelihoods (United Nations 1972).

The third problem with externalities is that they inadvertently reward unsustainable, unaffordable and unhealthy food production and consumption. As natural, health and social costs are externalized, it is more profitable to produce unsustainable and unhealthy food. Child labor, forced labor and underpaid workers represent cheap labor; consuming natural resources without replenishing them provides cheap inputs and the decision not to contain pollution saves costs. At the same time, adding calories, salt, poor quality fats, sugars and harmful sugar alternatives to food items, and promoting such foods, can increase sales, despite the negative effects on health (Stuckler et al. 2012). Food safety adds to the harmful effects on health, especially in developing countries (Devleesschauwer et al. 2018). One reason is that there is neurobehavioral evidence that some unhealthy foods elicit higher reward responses in the brain than healthy foods (Banerjee et al. 2020).

In the same way, encouraging high levels of food waste, e.g., through appealing packaging, can increase sales. Moreover, firms have no incentive to make healthy food affordable. Businesses set prices to optimize their business's profits (Laffont 2008), sometimes using inflated prices as signals of healthy food (Haws et al. 2017). As a result, sustainable and healthy food is more expensive to buy than unhealthy food (Stuckler et al. 2012).

Given that global markets allocate capital based on financial returns, most capital will flow to the companies most successful at externalizing costs to optimize profit (Serafeim et al. 2019). In an economy where consumers maximize purchasing power, businesses maximize profits. In addition, investors maximize returns, leading to the underproduction of food, which, in turn, leads to waste, overuse of natural resources and overconsumption of unhealthy food (Gemill-Herrero et al. 2021).

In summary, externalities form a significant barrier to the transition to sustainable food systems. It is difficult to imagine how policies aiming to foster sustainable food systems will be successful in an economic system where the erosion of natural capital, breaches of human rights, and unhealthy food are permissible and strongly incentivized.

3 True-Cost Accounting: Redefining the Value of Food

One first step to addressing externalities is to expose them and redefine the value of food. This can be realized through *TCA*, a tool for the systemic measurement and valuation of environmental, social, health and economic costs and benefits to facilitate sustainable choices by governments and food system stakeholders (Baker et al. 2020; Gemmill-Herren et al. 2021). TCA can serve different purposes, in which different actors have different applications (Baker et al. 2020):

- *Governments* can integrate TCA into local, national or regional policy and budgeting. For example, Brazil, China, Columbia, India, Indonesia, Kenya, Malaysia, Mexico, Tanzania, and Thailand have applied TCA through the TEEBAgriFood framework's participatory process to bring stakeholders together to identify agricultural land-use policies that would benefit from the valuation of ecosystem services (Baker et al. 2020). An interim TCA assessment in Indonesia contributed to agroforestry being included in the country's 2020 five-year development plan (Baker et al. 2020).
- *Businesses* can use these structured assessments to minimize negative impacts and enhance positive benefits across value chains (Serafeim et al. 2019; WBCSD 2021a). Companies can use TCA to produce impact statements or impact weighted accounts (monetized, multi-capital, multi-stakeholder accounts of all material business impacts, including true costs and benefits) (Baker et al. 2020) and manage their externalities (Impact Institute 2020).[2]
- *Financial institutions* use TCA for reporting, impact investment and risk assessment (WBCSD 2021a, b; Impact Institute 2020); and also to obtain assurance on their published impact statements (Schramade 2020).
- *Farmers* can use TCA as a means to account for the costs and benefits of their agricultural practices (Jones 2020). Various initiatives recognize farmers, peasants, indigenous peoples, pastoralists, and other food producers as important stewards of biocultural landscapes (Baker et al. 2020; Gemmill-Herren et al. 2021).

[2] A report by the Harvard Business School found that, by 2019, at least 56 companies worldwide had disclosed monetized information about their impact, five of which were in the food sector (Serafeim et al. 2019). By 2021, around ten food multinationals had become members of the Capitals Coalition (2021b)), and various leading multinational participate in WBCSDs True Value of Food project (WBCSD 2021b).

- *Consumers* can use TCA to become aware of the environmental and social externalities embedded in the food they buy (Lord 2020). Many labeling schemes incorporate TCA information to strengthen the transparency that they provide to consumers (Gemmill-Herren et al. 2021).

TCA recognizes that the economy's productive assets go beyond the assets currently accounted for, and include natural, social and human capital (TEEB 2018; Dasgupta 2021). A TCA assessment can be done at different levels: a food system, a policy, a region, an organization, an investment or a product (Baker et al. 2020). An overview of the approach and tools available is presented in Annex 1.

A TCA assessment typically starts by identifying the goal and scope of the assessment, establishing the unit of analysis and the system boundaries. Then, various externalities are assessed (qualitatively or quantitatively), valued and aggregated (TEEB 2018; Impact Institute 2019). It should be noted that the maturity of methods and data for measuring, valuing and attributing externalities varies greatly. The quantification of carbon emissions is relatively mature, whereas the quantification of health externalities is quite young and involves substantial uncertainty (Gemmill-Herren et al. 2021).

There is limited information available at this scale due to the young nature of TCA, the complexity of food chains and the large variety of disciplines and data required. Although TCA results will never be perfect or entirely objective, TCA provides actors in the food chain with much better information about the value of food than they currently have. However, given the ubiquity of externalities, the complexity of TCA, and the significant interests involved, actors in food systems need an abundant supply of affordable, comparable and reliable TCA information.

Available estimates (FOLU 2019) approximate the annual external costs of the global food system due to GHG emissions at 1.5 trillion (2018) USD, other 'natural capital costs' at 1.7 trillion USD and "Pollution, Pesticides & Anti-Microbial Resistance" at 2.1 trillion USD. The 2019 FOLU study estimated health costs due to obesity at 2.7 USD. An exploratory calculation by van Nieuwkoop (2019) estimated the annual external costs of the food system to be at least 6 trillion USD. A study by FAO (2015) estimated the natural capital costs of crop production at around 1.15 trillion USD.

4 Estimating the True Costs of Food Systems in the Context of the UNFSS Aspirations

A novel analysis was conducted by a working group of the UNFSS Scientific Group to estimate the true costs of the current food system and estimate the costs of changes towards a more sustainable system. The work brought together diverse sources of data and approaches. The core unit of analysis was the global food system, consisting of global food consumption and production, divided by country and food group. The environmental and health externalities (listed in Table 2) were

Table 2 Data included in the study

Type of externality	Externality	Endpoint impact(s)
Environmental	GHG-emissions	Contribution to climate change
	Nitrogen water pollution	Biodiversity loss
	Phosphorus water pollution	Biodiversity loss
	Scarce blue water use	Depletion of scarce water
	Land-use	Biodiversity, ecosystem services
	Air pollution (NH3)	Mortality and disability
Health (human life)	Contribution to cardiovascular diseases	Mortality
	Contribution to diabetes mellitus type 2	Mortality
	Contribution to neoplasms (cancers)	Mortality
Health (economic costs)	Contribution to cardiovascular diseases	Medical costs, informal care, lost working days
	Contribution to diabetes mellitus type 2	Medical costs, informal care, lost working days
	Contribution to neoplasms	Medical costs, informal care, lost working days

estimated based on the externalities for which data were available at this scale and level of granularity. The current analysis excluded economic externalities, social externalities, some environmental externalities (soil degradation, depletion of non-renewable resources, land use other than cropland, overuse of renewable resources and other air pollutants than NH_3), and health costs such as antibiotic resistance, zoonoses and undernutrition, as well as productivity losses due to disease. Although these are important sources of externalities, time, data availability, data coverage and compatibility limited the inclusion of these costs. In particular, the requirement that data be available per food group excluded many externalities.

The value chain scope for environmental externalities was primary production, feed for animal products, and inputs such as nitrogen and phosphate. Transportation, processing and food preparation costs were not considered in the analysis. Previous studies have shown that the vast majority of environmental externalities are in the primary process (FAO 2015; Baltussen et al. 2016).

Many data sources and methods were used to quantify the externalities, including Afshin et al. (2019) and Springmann et al. (2018b) to quantify the health impacts and Pozzer et al. (2017), Schipper et al. (2020), Willett et al. (2019) and WWF (2020) to quantify the environmental impacts. The effects were modeled per food group, as set out in Willett et al. (2019) health reference diet. Consumption per food group was based on expenditure. Production was based on production data per country and food group, but is presented here as an aggregate for the world. The environmental effects of imports were based on a global average of the environmental effects of exports per food group.

The monetization of environmental externalities was based on country-level monetization factors for restoration and compensation costs. The methodology adopted has been described by Galgani et al. (2021). A single median global value was used to monetize the loss of human life, based on a meta-study by the OECD (2012) on the value of a statistical life. An average value was used to estimate the direct and indirect economic effects of health loss.

The true annual cost of food was estimated to be around 7 trillion USD (range 4–11) for environmental costs, 11 trillion USD (range 3–39) in costs to human life and 1 trillion USD (range 0.2–1.8) in economic costs (Fig. 1). the annual estimate is based on the most recently available data.

Figure 2 shows that the mean estimate for the total cost of food was 29 trillion USD per year. Given that the current cost of food at current market prices is 9 trillion USD, the results show that the true cost of food is disproportionally high. There is substantial uncertainty in the estimates, particularly for the health costs, as impact pathways have not been extensively studied. The counterfactual is not self-evident, and externalities relate more to diets than to products. In addition, it should be stressed that this is not a complete picture, as some relevant externalities are not yet included, as indicated above.

Among the highest environmental costs are GHG emissions that lead to climate change; land use and land-use change that lead to the loss of ecosystems and biodiversity; and air pollution that leads to, amongst other things, loss of biodiversity and degradation of human health (Fig. 3).

It should be noted that there is substantial uncertainty in these, as well as in other existing estimates of the external costs of food, due to (i) an incomplete coverage of impacts, (ii) major uncertainties in primary data, (iii) uncertainties in trade data, (iv) uncertainties in the modeling of impact pathways and (v) uncertainty in the monetization of external costs. An uncertainty range was created for the results based on footprint and valuation uncertainty. Given that not all uncertainties can be captured and not all sources quantify their uncertainty, the ranges should be interpreted comparatively.

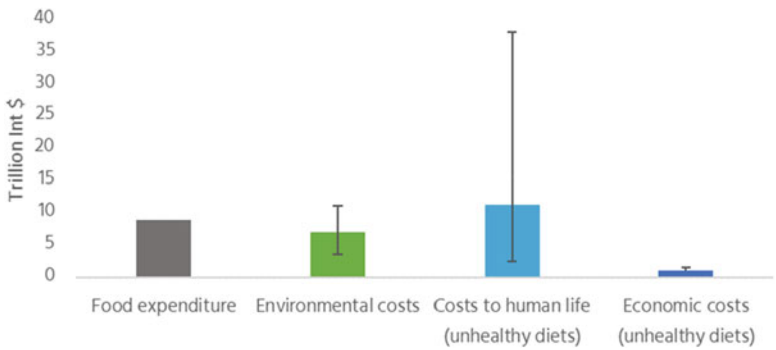


Fig. 1 The annual true cost of food for the globe. Note: The bar represents the range of possible costs

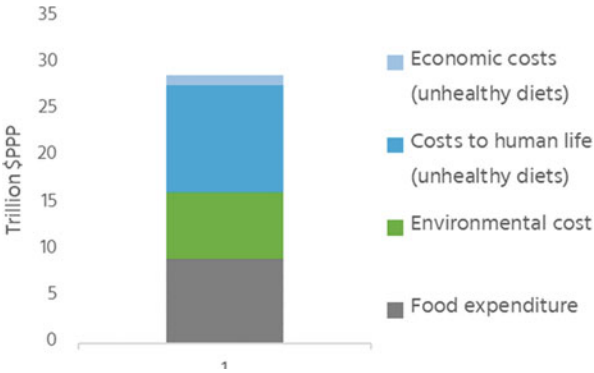


Fig. 2 Mean estimate of the total annual true cost of food, including the external costs in the scope of the analysis. Note: This estimate excludes relevant externalities, and estimates of included externalities include uncertainty

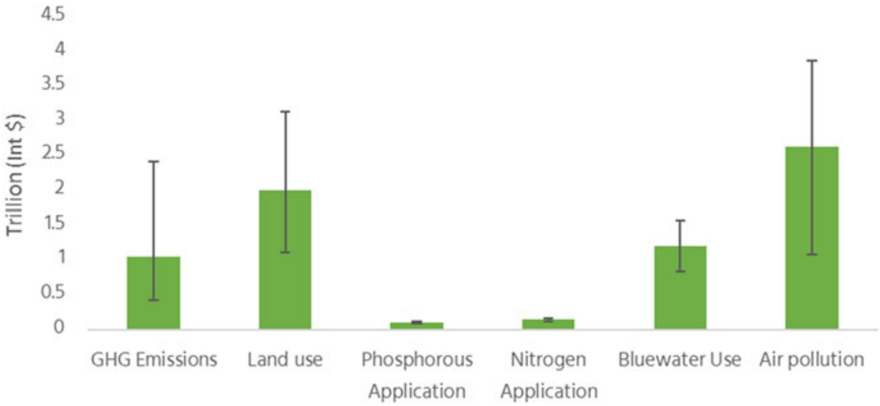


Fig. 3 Breakdown of the annual environmental cost of food systems

Environmental impact pathways that have high uncertainty include biodiversity and pollution. Quantifying and valuing the health impacts of diets is a novel field, and methodological choices around attribution, the rationality of consumers, the reference scenario and the valuation of a statistical life affect the estimates. Currently, no quantified dietary guide is available to support the analysis of achieving the ambitions of the UNFSS. This is an area that requires more attention and quantification.

Further research is required to include relevant externalities related to undernutrition (which ultimately affects human productivity and incomes), zoonoses, antimicrobial resistance (AMR), productivity losses due to diseases, soil degradation, land use other than cropland, and depleted resources. In addition, it is important to add social costs such as underpayment of workers, underearning of farmers, child labor and harassment throughout the value chain.

5 Potential Benefits of a Transition to More Sustainable Diets

Effective policy interventions for redesigning the economics of food also require an understanding of the effects of possible transitions on environmental and health externalities, as well as affordability. Such interventions involve realizing multiple goals and making trade-offs, which can be managed by developing well-planned transition pathways, carefully monitoring key indicators, and implementing transparent science targets at the local level (Herrero et al. 2021).

Hence, in addition to estimating current global external environmental and health costs of food, the working group also explored the potential benefits on health and the environment of dietary shifts and their implications for affordability. Due to a lack of availability of recent international dietary guidelines, the analysis used the only available EAT-Lancet alternative diets (Springmann et al. 2018a). The working group in no way promotes these as recommended diets. The EAT-Lancet's recommended dietary patterns were based on the assumption that plant food production is more environmentally sustainable compared to animal food production, primarily based on considerations of land and water use, energy conversion and GHG emissions. However, these recommended diets do not consider differences in protein quality and nutrient bioavailability (Moughan 2021). Still, the EAT-Lancet pescatarian, vegetarian and vegan diets offer a comparison to a healthy reference diet.

For illustrative purposes, the analysis of shifting consumption patterns to align with these four dietary alternatives showed that significant gains could be achieved in reducing environmental and health costs (Fig. 4). However, these shifts do increase the average cost of food, albeit at a small fraction of the gains.

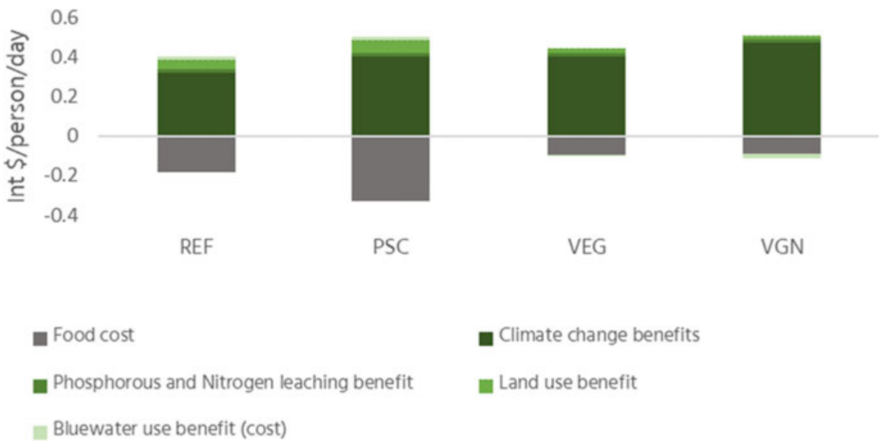


Fig. 4 Costs and benefits of potential dietary shifts. *REF* Healthy Referencek diet, *PSC* pescatarian, *VEG* vegetarian, *VGN* vegan diets

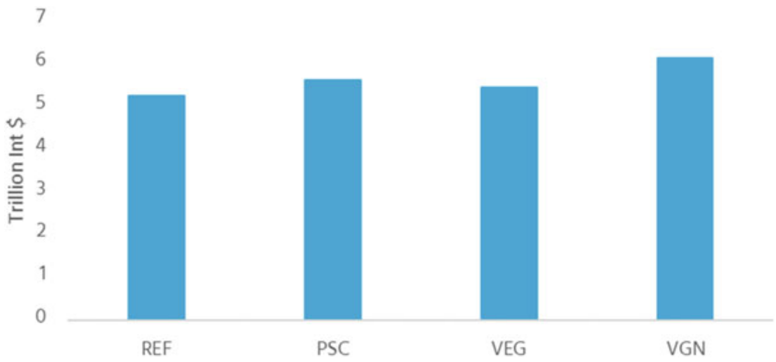


Fig. 5 Health benefits of potential dietary shifts. *REF* Healthy Reference diet, *PSC* pescatarian, *VEG* vegetarian, *VGN* vegan diets

The health benefits of global dietary shifts are potentially substantial (Fig. 5). Ensuring the affordability of (healthy) food for all requires detailed analysis about how any interventions affect the poorest groups in society. The current analysis does not cover the distributional effects of dietary shifts. This represents a critical area for future research.

6 Study Limitations

The methodology applied to estimate the true costs of the global food system and alternative diets has the following limitations:

- The environmental cost of dietary shifts did not take household food waste into account. The results were based on dietary guidelines for consumption.
- All scenarios were based on the environmental footprints per kg of product in the current system. Potential reductions in footprints due to a change in cultivation techniques were not taken into account.
- For the land-use of animal products, pastureland was not included. The biomes used for growing the feed and the mean species abundance of the land used were determined from global averages of these data for products frequently used as feed (mainly cereal products). For processed food products such as vegetable oils and sugar, the biomes used and the mean species abundance were estimated by averages within the country.
- Air pollution emissions referred to the agricultural sector as a whole, and not only food production.
- The impact of food safety on human health and food waste has not been considered, but is a cause of significant disease and mortalities.
- The effect of food production on AMR was not covered in the analysis. According to the AMR review (O'Neill 2016), each year, at least 700,000 deaths

are caused by AMR, which corresponds to a cost of 2.3 trillion USD using the same valuation approach as for other health impacts in this study. A substantial part of this is likely due to food production, but it is currently not clear how much.
- The bioavailability and quality of protein and nutrients were not considered in the dietary shifts, but they are important considerations for future research.

7 Recommendations

Given the high costs to the environment and human health presented in these findings, it is essential that UNFSS stakeholders actively identify externalities that represent 'hidden costs' in the food system and those that ignore or incentivize unsustainable and unhealthy food systems. These costs need to be quantified through TCA practices and pathways identified to reduce or eliminate these externalities through policies that: (i) internalize externalities and (ii) sanction those food system stakeholders who do not take appropriate steps to reduce and internalize these costs and/or incentivize those who do. Estimating the full scope of these costs is a priority for determining if such an adjustment to the food system would increase food prices to a point where a reassessment of poverty lines is necessary to ensure access to healthy diets for the poorest.

In the short term, policymakers can remove the barriers for stakeholders to engage in TCA and use TCA data to redefine the value of food to reflect its true costs and benefits. In particular, governments and other UNFSS stakeholders can:

- **Foster internationally accepted harmonized TCA principles across all applications.** Together, experts, practitioners and stakeholders from all fields in food and agriculture can develop harmonized TCA principles to ensure validity and comparability of results and alignment among the various levels,
- **Educate and build capacity among professionals in business and government around TCA.** It is important that the new discipline of TCA be built. Harmonized principles are necessary to bring experts and practitioners from all fields together. In addition, TCA can be integrated into educational systems, and current food professionals in government, civil society and business can be educated in TCA.
- **Provide professionals in business and governments with concrete tools to facilitate TCA.** Lowering the entry barriers of professionals to the complex field of TCA can be facilitated by providing practical skills and approaches (toolboxes) for analysis.

In the medium and long term, governments can look at ways to integrate TCA into economic metrics at all levels systematically:

- **Integrate TCA into national accounts and GDP.** This can provide a standardized account of how much inclusive welfare (realized welfare and changes in wealth) was created. This would provide a much better view of how the food sector contributes to welfare.

- **Integrate TCA into business sustainability reporting and controls.** By adding TCA information into their internal and external financial reports, businesses can compile impact-weighted accounts and impact statements, enabling them to report and manage the value that they create to all stakeholders via all capitals.
- **Integrate TCA into product labeling**. Products themselves can educate their customers as to their true costs (in monetized terms), as well as their true value (in monetized terms or otherwise).

Finally, policymakers can start to explore first-best mechanisms for the medium term:

- **Generate a global agreement and create public-private partnerships around a roadmap to realize the SDGs by 2030 and reach fully sustainable food systems by 2050**, providing affordable and healthy food without environmental, social and health-related costs.

Annex 1: How Does True-Cost Accounting Work?

A TCA assessment can be done at different levels: a food system, a policy, a region, an organization, an investment or a product (Baker et al. 2020). For each type of analysis, various frameworks exist. One major system-level framework is TEEB for Agriculture and Food (TEEB 2018). Recently, Lord (2020) also published a methodology for food systems analysis. These frameworks can be applied at other levels. At the regional level, the UN System of Environmental Economic Accounting provides a mature framework for natural capital valuation (UN 2021a, b). For other aspects, few well-accepted frameworks exist (Hoekstra 2019), although inclusive wealth is a promising approach (Dasgupta 2021 Various TCA frameworks are being developed for the organizational level, often focusing on corporate reporting (Natural Capital Coalition 2021; Impact Institute 2019). Also, frameworks have been developed specifically for products such as coffee and bananas (Serafeim and Trin 2020; Galgani et al. 2021) and investments (Addy et al. 2019; Olsen 2020; Impact Institute 2020).

A TCA assessment starts by defining the goal, scope and unit of analysis ('functional unit'). Consequently, the relevant externalities have to be identified. Once these externalities have been identified, they have to be assessed, qualitatively or quantitatively. Quantification starts with measuring or assessing inputs and outputs, the direct measurable effects of production and consumption (Impact Institute 2020). These inputs and outputs can be measured using primary data. In practice, inputs and outputs often have to be estimated with macro-level models through (environmentally) Extended Input-Output and Computable General Equilibrium models (Malik et al. 2018), micro-level models such as life-cycle accounting (LCA) (Hauschild et al. 2018) and social LCA (Huertas-Valdivia et al. 2020), or through hybrid approaches (Nakamura and Nansai 2016). Consequently, these outputs have to be translated into impacts via impact pathways (Impact Institute 2019).

For many environmental externalities, there are databases for such pathways, such as those based on Recipe (Huijbregts et al. 2016), although pathways for ecosystem and biodiversity are more complex (TEEB 2018; Dasgupta 2021). Impact pathways for social and, in particular, health externalities are less mature. If the functional unit is a product, investment or organization, the final quantification step is the attribution of impact to the functional unit (Capitals Coalition 2021a; Impact Institute 2020; VBA 2021). This process yields quantified impacts in *natural units*, such as CO_2-equivalents, liters of scarce blue water extraction or loss mean species abundance for environmental externalities, full-time equivalents (FTE) of child labor, FTE of forced labor and underpayment for social externalities, and disability adjusted life years (years of life lost + years lived with a disability) for health externalities.

After externalities have been quantified, they can be valued, in monetary terms or otherwise, so that they are expressed in a common unit. To capture value not reflected in market prices, a TCA assessment requires an (implicit or explicit) measure of welfare. Although terminology differs significantly in the literature, there is wide recognition that multiple dimensions exist (Stiglitz et al. 2018), and common welfare dimensions include:

- The preference satisfaction or well-being of people (Stiglitz et al. 2018; TEEB 2018; Dasgupta 2021; Impact Institute 2020).
- An equitable distribution of income and other resources (Stiglitz et al. 2018).
- Adherence to social limits such as a living wage, labor standards and the right to food security, which can be derived from human rights. (TEEB 2018).
- Adherence to environmental limits, such as the conservation of climate, abiotic resources and biodiversity. These limits can be derived from planetary boundaries for a livable planet (Rockström et al. 2009; Stiglitz et al. 2018), the intrinsic value of nature (TEEB 2018) and/or the rights of current and future generations.

The first dimension generally coincides with traditional measures of ordinal or cardinal utility that economists have used to measure collective welfare (Van Praag 1991; Galgani et al. 2021). The second dimension is linked to traditional measures of income inequality such as the GINI coefficient (Bowles and Carlin 2020). Nonetheless, these measures cannot accommodate central issues of sustainability, such as biophysical limits, human rights, social equity and intergenerational equity (Dore and Burton 2003; Gowdy and Erickson 2005). Hence, the valuation of environmental and social damages has met with resistance from non-economists, policymakers and civil society (McCauley 2006). As a result, in TCA, additional welfare dimensions emerged (Stiglitz et al. 2018; TEEB 2018; Impact Institute 2020). Depending on the welfare dimension, different valuation methods, such as cardinal utility, abatement costs, shadow pricing or remediation costs, are used (Galgani et al. 2021). A relevant discussion point is to which degree externalities can be summed and netted. Economists would traditionally sum all positive and negative externalities into one number, whereas some TCA frameworks hold that welfare dimensions ought to be considered separately (Stiglitz et al. 2018; Impact Institute 2019) and human rights violations or deforestation cannot be offset by an equal amount of profit, for example (Capitals Coalition 2021a).

References

Addy C et al (2019) Calculating the value of impact investing: an evidence-based way to estimate social and environmental returns. Harvard Business Review, January – February 2019. Available at https://hbr.org/2019/01/calculating-the-value-of-impact-investing

Afshin A et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the global burden of disease study 2017. Lancet 393(10184):1958–1972

Allen T, Prosperi P (2016) Modeling sustainable food systems. Environ Manag 57(5):956–975. https://doi.org/10.1007/s00267-016-0664-8

Baker L, Castilleja G, De Groot Ruiz A, Jones A (2020) Prospects for the true cost accounting of food systems. Nat Food 1:765–767. Available at. https://doi.org/10.1038/s43016-020-00193-6

Baltussen W, Achterbosch T, Arets E, de Blaeij A, Erlenborn N, Fobelets V, Galgani P, de Groot RA, Hardwicke R, Hiemstra SJ, van Horne P, Karachalios OA, Kruseman G, Lord R, Ouweltjes W, Tarin RM, Vellinga T, Verkooijen L (2016) Valuation of livestock eco-agri-food systems: poultry, beef and dairy: executive summary. Wageningen economic research report; no. 2016-023. https://doi.org/10.18174/389545

Baltussen W, van Berkum S, Dijkxhoorn Y, Helmes R, ÖzkanGülzari Ş, Vellinga T, Massawe GD, Galgani P, Borniotto D, van den Elzen F, Smith T (2019) Traditional livestock systems in Tanzania; An application of the TEEBAgriFood EvaluationFramework. TEEB for Agriculture and Food, UNEP

Banerjee T, Chattaraman V, Zou H et al (2020) A neurobehavioral study on the efficacy of price interventions in promoting healthy food choices among low socioeconomic families. Sci Rep 10:15435. https://doi.org/10.1038/s41598-020-71082-y

Bowles S, Carlin W (2020) Inequality as experienced difference: a reformulation of the Gini coefficient. Econ Lett 186:108789. https://www.sciencedirect.com/science/article/pii/S0165176519303969

Capitals Coalition (2021a) Principles of integrated capitals assessments. Available at: https://capitalscoalition.org/wp-content/uploads/2021/01/Principles_of_integrated_capitals_assessments_final.pdf

Capitals Coalition (2021b) Capitals Coalition. Organization directory Available at: https://capitalscoalitionorg/the-coalition/. Accessed: 10 May 2021

Dalin C, Outhwaite CL (2019) Impacts of global food systems on biodiversity and water: the vision of two reports and future aims. One Earth 1(3):298–302. https://doi.org/10.1016/j.oneear.2019.10.01

Dasgupta MK (2021) The inclusive wealth index and sustainable development goals. Sustain Sci. Available at https://link.springer.com/article/10.1007/s11625-021-00915-0

Devleesschauwer B, Haagsma JA, Mangen MJJ, Lake RJ, Havelaar AH (2018) The global burden of foodborne disease. In: Food safety economics. Springer, Cham, pp 107–122

Dore MHI, Burton I (2003) Environmental degradation and remediation: is economics part of the problem. Environ Monit Assess 86:47–61

FAO (2015) Natural capital impacts in agriculture. Supporting better business decision making. http://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/Natural_Capital_Impacts_in_Agriculture_final.pdf

FAO, IFAD, UNICEF, WFP, & WHO (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. Food and agriculture organisation of the United Nations. FAO, Rome. https://doi.org/10.4060/ca9692en

Food and Land Use Coalition (FOLU) (2019) Growing better: ten critical transitions to transform food and land use. The global consultation report of the food and land use coalition, https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf

Galgani P, Woltjer G, de Adelhart Toorop R, de Groot Ruiz A, Varoucha E (2021) Land use, land use change, biodiversity and ecosystem services: true pricing method for agri-food products. Wageningen University & Research

Gemmill-Herren B, Baker LE, Daniels PA (eds) (2021) Forthcoming. True Cost accounting for food balancing the scale. Routledge
Gowdy D, Erickson JD (2005) The approach of ecological economics. Camb J Econ 29:207–222. https://doi.org/10.1093/cje/bei033
Gruber J, Köszegi B (2001) Is addiction “rational”? Theory and evidence. Q J Econ 116(4): 1261–1303
Hauschild MZ, Rosenbaum RK, Olsen SI (2018) Life cycle assessment: theory and practice. Springer, Cham
Haws KL, Walker Reczek R, Sample KL (2017) Healthy diets make empty wallets: the healthy = expensive intuition. J Consum Res 43(6):992–1007. https://doi.org/10.1093/jcr/ucw078
Herrero M, Thornton PK, Power B, Bogard JR, Remans R, Fritz S et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planetary Health 1(1):e33–e42
Herrero M et al (2021) Articulating the effect of food systems innovation on the sustainable development goals. Lancet Planet Health 5(1):e50–e62
Hoekstra R (2019) Replacing GDP by 2030: towards a common language for the Well-being and sustainability community. Cambridge Univerity Press, Cambridge. http://www.fao.org/documents/card/en/c/cb1699en/
Huertas-Valdivia I et al (2020) Social life-cycle assessment: a review by bibliometric analysis. sustain 12:6211. https://doi.org/10.3390/su12156211
Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM et al (2016) ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017(22):138–147. https://doi.org/10.1007/s11367-016-1246-y
Impact Institute (2019) Framework for impact statements. Available at: https://www.impactinstitute.com/framework-for-impact-statements
Impact Institute (2020) Guide for funders to assess and value impact. Available at https://www.impactinstitute.com/guide-for-funders-to-assess-and-value-impact/
IPPC (2019) Climate change and land, an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, IPPC. www.ipcc.ch/report/srcc
Jaffee S, Spenser H, Unnevehr L, Grace D, Cassou E (2019) The safe food imperative: accelerating Progress in low- and middle-income countries. The World Bank, Washington, DC
Jones A (2020) The sustainable food trust pushing forward with pilot framework for sustainability metrics. Sustainable food trust (3 April 2020). Available at: https://sustainablefoodtrust.org/articles/the-sustainable-food-trust-pushing-forward-with-pilot-framework-for-sustainability-metrics/
Laffont JJ (2008) Externalities. In: The new Palgrave dictionary of economics Palgrave Macmillan, London. Available at https://doi.org/10.1057/978-1-349-95121-5_126-2
Lord S (2020) Valuing the impact of food: towards practical and comparable monetary valuation of food system impacts. Food SIVI. Available at: https://foodsivi.org/wp-content/uploads/2020/06/Valuing-the-impact-of-food-Report_Foodsivi.pdf
Malik A et al (2018) Advancements in input-output models and indicators for consumption-based accounting. J Ind Ecol 23:2
Masters WA, Martinez EM, Greb F, Herforth A, Hendriks SL (2021) Cost and affordability of preparing a basic meal around the world. UN Food Systems Summit Brief Prepared by Research Partners of the Scientific Group for the Food Systems Summit. https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Cost_of_Basic_Meals.pdf
McCauley DJ (2006) Selling out on nature. Nature 443:27–28
Moughan PJ (2021) Population protein intakes and food sustainability indices: the metrics matter. Glob Food Sec 29:100548. https://doi.org/10.1016/j.gfs.2021.100548
Nakamura S, Nansai K (2016) Input-output and hybrid LCA. In: Finkbeiner M (ed) Special types of life cycle assessment. LCA compendium– the complete world of lIfe cycle assessment. Springer. https://doi.org/10.1007/978-94-017-7610-3_6
Natural Capital Coalition (2015) Valuing natural capital in business. Taking stock: existing initiatives and applications. https://capitalscoalition.org/wp-content/uploads/2016/07/Valuing_Nature_in_Business_Part_2_Taking_Stock_WEB.pdf

Natural Capital Coalition (2016) Natural capital protocol. https://capitalscoalition.org/capitals-approach/natural-capital-protocol/?fwp_filter_tabs=guide_supplement
Van Nieuwkoop (2019) Do the costs of the global food system outweigh its monetary value? World Bank Blogs. June 17, 2019. Available at: https://blogs.worldbank.org/voices/do-costs-global-food-system-outweigh-its-monetary-value. Accessed: 10 May 2021
Nkonya E, Mirzabaev A, von Braun J (2016) Economics of land degradation and improvement – a global assessment for sustainable development. https://link.springer.com/book/10.1007/978-3-319-19168-3
O'Neill J (2016) Tackling drug-resistant infections globally: final report and recommendations. Government of the United Kingdom
OECD (2001) Glossary of statistical terms. Gross value added. Available at https://stats.oecd.org/glossary/detail.asp?ID=3215
OECD (2002) Glossary of statistical terms. Profit. https://stats.oecd.org/glossary/detail.asp?ID=3288
OECD (2003) Glossary of statistical terms. Externalities. http://www.oecd.org/dataoecd/8/61/2376087.pdf. Accessed 17.02.2022
OECD (2012) Recommended value of a statistical life numbers for policy analysis. In: Mortality risk valuation in environment health and transport policies. OECD Publishing, Paris. https://doi.org/10.1787/9789264130807-9-en
Olsen, S. (2020) Impact monetisation. Impact management project. Available at https://impactmanagementproject.com/wp-content/uploads/IMP_Impact-monetisation-discussion-document.pdf
Pozzer A et al (2017) Impact of agricultural emission reductions on fine-particulate matter and public health. Atmos Chem Phys 17:12813–12826. Available at. https://doi.org/10.5194/acp-17-12813-2017
Rockström J, Steffen W, Noone K, Persson A, Chapin FS III, Lambin E, T. M. et al (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14(2):32. http://www.ecologyandsociety.org/vol14/iss2/art32/
Schipper AM, Hilbers JP, Meijer JR, Antão LH, Benítez-López A, de Jonge MM, Leemans LH, Scheper E, Alkemade R, Doelman JC, Mylius S (2020) Projecting terrestrial biodiversity intactness with GLOBIO 4. Glob Chang Biol 26(2):760–771
Schramade, W (2020) ABN AMRO's impact statements: a case study on making societal value visible. Available at: https://www.rsm.nl/fileadmin/Images_NEW/Erasmus_Platform_for_Sustainable_Value_Creation/Case_study_ABN_AMRO_Schramade.pdf
Serafeim and Trin (2020) Preliminary framework for product impact weighted accounts. Harvard Business School. Available at: https://www.hbs.edu/impact-weighted-accounts/Documents/Preliminary-Framework-for-Product-Impact-Weighted-Accounts.pdf
Serafeim G, Zochowski TR, Downing J (2019) Impact-weighted financial accounts: the missing piece for an impact economy. Harvard Business School. Available at https://www.hbs.edu/impact-weighted-accounts/Documents/579%20Impact-Weighted-Accounts-Report-2019_preview.pdf
Springmann M et al (2018a) Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet 2(10):e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7
Springmann M et al (2018b) Options for keeping the food system within environmental limits. Nature 562(7728):519–525. https://doi.org/10.1038/s41586-018-0594-0
Stiglitz J, Fitoussi J, Durand M (2018) Beyond GDP: measuring what counts for economic and social performance. OECD Publishing, Paris. https://doi.org/10.1787/9789264307292-en
Stuckler D, McKee M, Ebrahim S, Basu S (2012) Manufacturing epidemics: the role of global producers in increased consumption of unhealthy commodities including processed foods, alcohol, and tobacco. PLoS Med 9(6):e1001235. https://doi.org/10.1371/journal.pmed.1001235
The Economics of Ecosystems and Biodiversity (TEEB) (2018) TEEB for agriculture & food: scientific and economic foundations. UN Environment, Geneva

The Economics of Ecosystems & Biodiversity for Agriculture and Food (TEEBAgriFood) Global Symposium (2019) Summary report, 25–27 February 2019. https://enb.iisd.org/events/economics-ecosystems-biodiversity-agriculture-and-food-teebagrifood-global-symposium-2019-3

The Sustainable Trade Initiative, IDH (2016) Annual report. Building business cases for impact on global goals. https://www.idhsustainabletrade.com/uploaded/2017/07/IDH_AR2016_final_150817.pdf

United Nations (1972) Declaration of the United Nations conference on the human environment. Stockholm. Available at: https://www.un.org/ga/search/view_doc.asp?symbol=A/CONF.48/14/REV.1

United Nations (2021a) System of environmental economic accounting. Available at https://seea.un.org/

United Nations (2021b) Food systems summit compendium. Available at https://foodsystems.community/food-systems-summit-compendium/. Accessed 17.02.2022

Van Praag MS (1991) Ordinal and cardinal utility: an integration of the two dimensions of the welfare concept. J Econ 50(1–2):69–89

VBA (2021) VBA methodology V0.1 Impact statement. Available at: https://www.value-balancing.com/_Resources/Persistent/2/6/e/6/26e6d344f3bfa26825244ccfa4a9743f8299e7cf/20210210_VBA%20Impact%20Statement_GeneralPaper.pdf

Wang Y, Sloan FA (2018) Present bias and health. J Risk Uncertain 57(2):177–198. https://doi.org/10.1007/s11166-018-9289-z

WBCSD (2018) Social and human capital protocol. Available at: https://www.wbcsd.org/Programs/Redefining-Value/Business-Decision-Making/Assess-and-Manage-Performance/Social-Human-Capital-Protocol

WBCSD (2021a) Vision 2050. Pathway food. Available at https://timetotransform.biz/wp-content/uploads/2021/03/WBSCD_Vision2050_Pathway-Food.pdf

WBCSD (2021b) True true value of food. 2021. https://www.wbcsd.org/Programs/Food-and-Nature/Resources/The-True-Value-of-Food. Accessed at: May 10, 2021

Westhoek H, Ingram J, van Berkum S, Özay L, Hajer M (2016) Food systems and natural resources. United Nations Environment Programme. https://www.resourcepanel.org/reports/food-systems-and-natural-resources

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S et al (2019) Food in the Anthropocene: the EAT-lancet commission on healthy diets from sustainable food systems. Lancet 393(10170):447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

World Bank (2016) The world bank annual report 2016. Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/24985 license: CC BY-NC-ND 3.0 IGO

WWF (2020) Country comparison – factors v5.0. Available at https://waterriskfilter.panda.org/en/Explore/CountryProfiles#compare/1/2

The Cost and Affordability of Preparing a Basic Meal Around the World

William A. Masters, Elena M. Martinez, Friederike Greb, Anna Herforth, and Sheryl L. Hendriks

1 Introduction

A nutritious diet is essential for an active and healthy life, but is unaffordable for about 3 billion people, almost 40% of the world's population, who have insufficient income to afford enough of even the least costly foods needed for a healthy diet (FAO et al. 2020). The unaffordability of nutritious foods prevents many people from consuming a healthy diet, but market prices for raw agricultural produce are not the only barrier to improved diet quality. To form an inclusive and sustainable food system for all, policies and programs should address other obstacles, such as:

- the time burden and fuel use needed to cook safe and nutritious meals at home, especially in households with poor kitchen facilities and other constraints,

W. A. Masters (✉)
Tufts University, Medford, MA, USA
e-mail: William.Masters@tufts.edu

E. M. Martinez
Friedman School of Nutrition at Tufts University, Medford, MA, USA

F. Greb
Research, Assessment and Monitoring Division of the World Food Programme (WFP), Rome, Italy

A. Herforth
Tufts University, Medford, MA, USA

Harvard T.H. Chan School of Public Health, Boston, MA, USA

S. L. Hendriks
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_33

- high prices of healthy items that would be lightly processed in ways that preserve and enhance nutritional value while reducing the time and fuel required for meal preparation, and
- the rapidly growing availability of ultra-processed foods whose convenience, taste and brand reputation meet some of peoples' immediate wants and needs, but are linked to displacement of minimally processed foods and diet-related disease later in life.

This chapter extends earlier work on market prices such as Bai et al. (2021b), Herforth et al. (2020), Hirvonen et al. (2020), Masters et al. (2018), and others, to consider the hidden costs of meal preparation, including home-cooked versus pre-cooked versions of similar foods, as well as the relative costs of plant- and animal-sourced ingredients.

Focusing on the hidden costs of meal preparation that affect food choice complements other work on true cost accounting, including research on external harms from unhealthy or unsustainable foods and cooking methods, as well as the external benefits of healthier or more sustainable practices, as described in a separate chapter of this book. In that chapter, we use the data and methods developed for SOFI 2020 and related work from a larger project on Food Prices for Nutrition (2021).

To illustrate how meal preparation costs could influence food choice, we use the "Basic Plate" approach developed by the World Food Programme (WFP 2017), identifying the most affordable ingredients for a typical meal that might be consumed in any country of the world. The baseline meal consists of a starchy staple made from 75 g of a dry cereal grain or equivalent, accompanied by a bean or lentil stew made from 57.25 g of dry pulses, cooked with onions (16.25 g) and tomatoes (55 g) in a vegetable oil (28.13 g). Such a meal would contain about one-third of an adult's daily energy requirement, and is not itself a healthy diet. To meet all needs, a person's overall diet would require greater diversity, including additional vegetables and fruits, but those complements to the basic meal are often more location-specific, as shown in our previous work, such as Herforth et al. (2020).

Measuring the market prices and hidden costs of preparing a single basic plate allows us to begin addressing the diverse costs of meal preparation, accounting for differences across countries and among households in time use, cooking fuel and other aspects of nutrient preservation and delivery. Using global data, we compare the most affordable basic plate with pulses to alternative meals that use animal-sourced foods (red meat, poultry, or fish), and alternative meals that would reduce the energy and time required for meal preparation by using lightly processed, often pre-cooked versions of various foods such as bread or canned fish, beans, and tomatoes.

The composition of each basic plate used for this study is shown in Table 1. To begin, we identify the most affordable items from which to prepare these basic plates in 168 countries around the world, using nationally representative retail prices for calendar year 2017 provided by government statistical organizations through the World Bank's International Comparison Program (ICP 2021). Details on the food items are shown in annex Tables A1 and A2, while the least costly items in each

Table 1 Basic and alternative versions of the WFP plate of food

Basic plate	Animal-sourced foods	Lightly processed foods
		
Pulses & beans Plant oils Onions Tomatoes Starchy staples	Replace pulses with animal-sourced foods, including red meat, poultry, and fish	Replace raw with pre-cooked foods such as canned beans instead of dry pulses, canned tomatoes or fish instead of fresh or dried and salted fish, and bread instead of other starchy staples

Note: Each basic plate allows for substitution of the most affordable item available in that country for the starchy staple (75 g of a dry cereal grain or equivalent, totaling 270 kcal) with a stew made from pulses (57.25 g of a dry bean or equivalent, totaling 191 kcal), tomatoes (55 g = 10 kcal) and onion (16.25 g = 6.5 kcal) in vegetable oil (28.1 g = 242 kcal). Available foods and their prices are from ICP (2021), matched to food composition using methods detailed in Food Prices for Nutrition (2021) country drawn from the candidate foods in each category are listed in Tables A3 and A4.

To assess affordability, we divided the cost of each plate by average total spending per person in that country, as measured by Gross National Income (GNI) per capita in real purchasing power parity (PPP) terms. All prices and costs reported here are in PPP dollars for 2017, so they can be directly compared to the international poverty line of $1.90/day and other benchmarks expressed in real PPP dollars. As shown in Table 2, we find that the average cost of the most affordable items with which to prepare the basic plate is $0.71, excluding costs of meal preparation. Choosing lightly processed, often pre-cooked foods such as canned beans, fish or tomatoes and bread more than doubles that cost to $1.77/day. Substituting animal-source foods also raises the cost substantially to $1.03 for a plate with red meat, $1.07 with poultry, and $1.30 with fish. For the plates with animal-sourced foods, however, the pre-cooked or more convenient foods are actually less costly at face value.

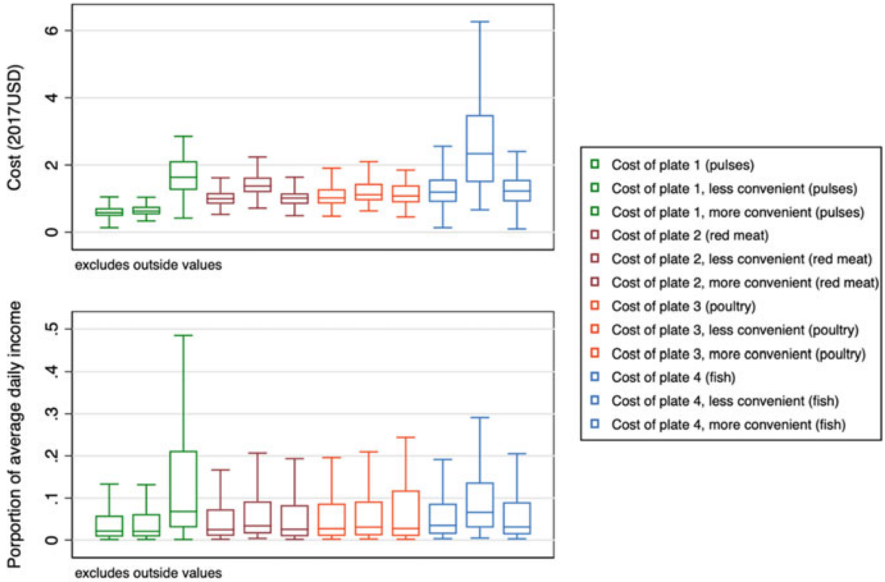
The cost of each of the basic and alternative plates generally takes a small portion of each country's total national average income, but it takes a large fraction of the international poverty line at $1.90/day and often exceeds the daily income of resource-poor households. In one-fourth of countries where these foods are least affordable, the basic plate costs about 6% or more of average daily income, meaning the value of all goods and services in that society. That cost rises to 20% of all goods and services if the meal is made with lightly processed items and 10% of all goods and services if the plate includes red meat, poultry or fish. The plate is also slightly more expensive when using fresh fish instead of tinned fish (Fig. 1).

When considering the cost per meal shown above, it is important to note that this basic plate meets about one-third of daily caloric needs in a safe and acceptable manner, but other foods would be needed to meet nutritional needs for an active and healthy life. For example, comparing this basic meal to an entire day's diet that would meet requirements specified in a variety of national food-based dietary guidelines (FBDGs), the meal contains about 80% of what would be an entire day's recommended intake of vegetable oil (28 out of 35 g in a typical FBDG), but only 23% of the day's protein-rich foods (57 of 250 g), and 24% of the day's vegetables (71 of 300 g), as well as none of the recommended fruit or dairy and other foods. Analysis of the overall cost of a healthy diet is outside the scope of this chapter and is addressed in earlier work, such as Herforth et al. (2020).

Table 2 Global average cost per day of the WFP basic plate and alternatives (2017 USD)

	Basic plate	With animal-source foods		
	Pulses	Red meat	Poultry	Fish
With most affordable items	0.71	1.03	1.07	1.30
With pre-cooked, packaged items	1.77	1.03	1.16	1.32
With raw or whole items	0.73	1.44	1.21	2.64

Note: Data shown are the mean over 168 countries for which all required data are available



Note: Data shown are the range of meal costs across 168 countries with available data. For each type of meal, the box shows median meal costs and its interquartile range from the 25th to 75th percentile (at the middle, top and bottom of each box), and whiskers show the outer range of 1.5 times that interquartile range. Outliers beyond the range are omitted for visual clarity

Fig. 1 Global range of costs of the WFP basic plate and alternatives (2017 USD)

2 Price Premiums for the Most Affordable Items in Each Category

To address food choice within the overall diet, we examine the added cost of lightly processed items and alternative proteins at the item level. Pulses are only slightly more costly than starchy staples per calorie (a difference of about $0.001/kcal, or $0.10 per 100 kcal). Red meat and poultry are about $0.50 per 100 kcal more expensive than starchy staples, as are onions, while including tomatoes adds roughly $1.80 per 100 kcal. All of those premiums are for the raw form of the product.

Using canned beans instead of dry beans adds as much cost as switching to red meat or poultry, which have about the same cost in whole raw form versus a lightly processed and packaged version (for example, ground beef is not systematically more or less expensive than beef for stew). On the other hand, fish and tomatoes are much less expensive when purchased in lightly processed canned form, making tinned fish about the same cost per 100 kcal as uncooked raw red meat or poultry (Fig. 2).

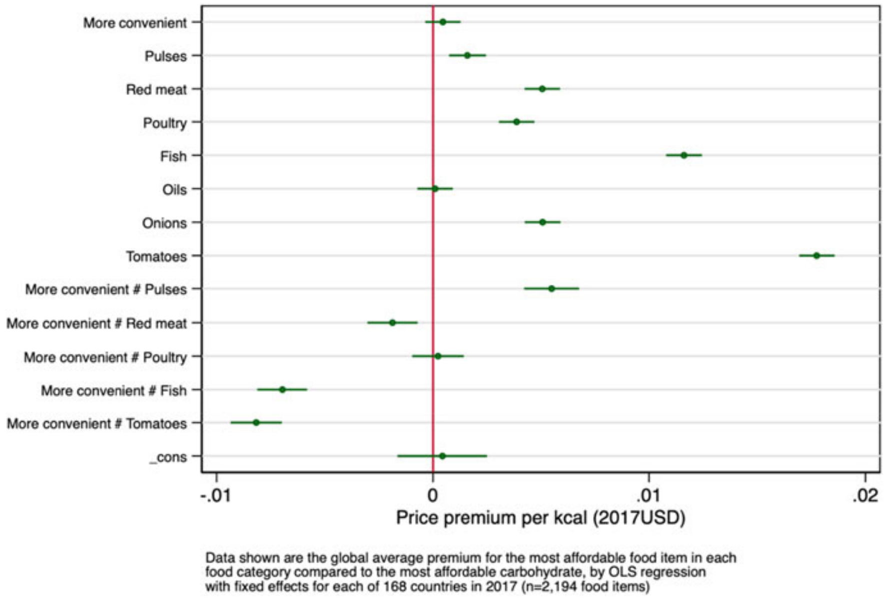


Fig. 2 Average premium required to obtain the least costly item with each attribute

3 The Hidden Cost of Home Cooking: Time and Fuel Use

Our analysis of ingredient prices reveals that preparing a basic plate with pre-cooked pulses such as canned beans is much more expensive than the plate with dried pulses, while the same with canned fish is less expensive than with fresh fish. Moreover, preparing the plate with pre-cooked pulses raises its costs beyond using the most affordable fish as the protein component. Given the high preparation time and cost of cooking for meals using dried pulses, and the high environmental impacts of animal-sourced food production, the high cost of helpful, healthy processing could be an important obstacle to inclusive and sustainable dietary transformation.

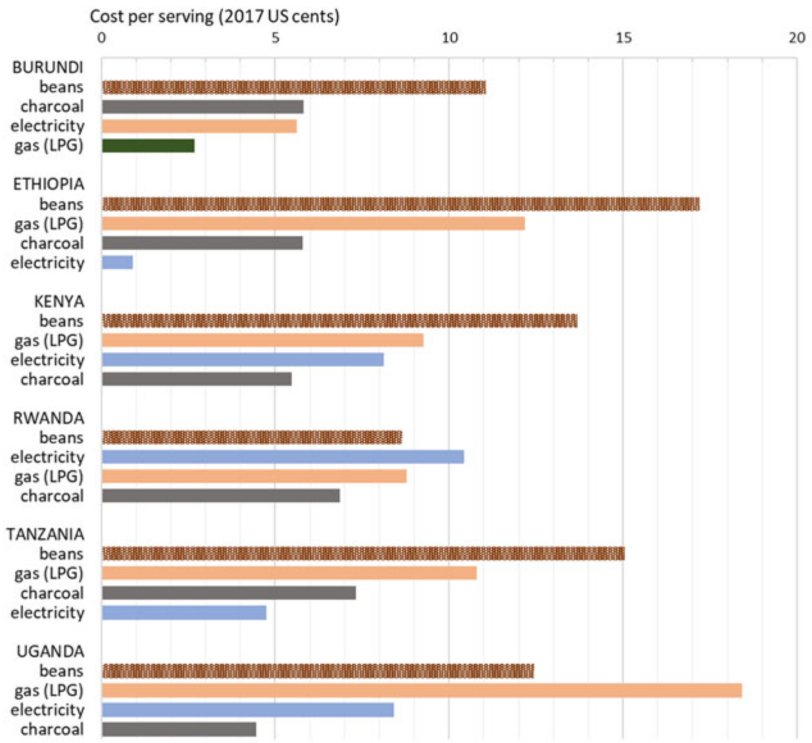
Data on the time and resources required for food acquisition and meal preparation across countries are not yet available. Still, we can begin to illustrate differences in the cost of meal preparation by focusing on energy use for cooking beans in East Africa, extending our previous research on food price variation in this region (Bai et al. 2020). We focus on the portion of the pulse in the basic plate, because preparing and cooking dry beans for a meal requires considerable time and fuel. Home-cooked beans have similar nutritional composition to tinned beans that are available in retail food outlets. We cannot account for all factors that go into meal preparation, but can use this example to address differences in fuel cost as one influence on the cost and affordability of each food.

To compare the cost of cooking beans or other pulses, we focus on the fuel needed to cook dry beans in East Africa, as estimated by MECS (2019), which is a simplified version of more detailed analyses such as Nerini et al. (2017). To compute fuel cost per serving, we consider the quantity of fuel needed to cook 500 g of dry beans (enough for 8.7 servings in the basic plate), which is estimated by MECS (2019) to require 0.675 kg of charcoal, 0.2 kg of gas (LPG), or 1.5 kWh of electricity when using the most common, conventional types of stove in this region. On a per-serving basis, that amounts to 77 g of charcoal, 23 g of LPG gas, or 0.17 kWh. We applied this estimate to six East African countries that are likely to use similar food preparation technologies and techniques – Burundi, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda. The mix of fuels and cooking methods actually used vary widely, with the fraction of households that have access to electricity in 2017 ranging from a majority of households in Kenya (63.6) to a smaller proportion in Ethiopia (44.3), Rwanda (34.1), Tanzania (32.7), Uganda (31.8) and Burundi (9.3), as reported in World Bank (2021).

For each country, we compare the fuel costs for cooking to the cost of the food itself. In each case, the least costly pulse in the dataset is spotted beans, whose nationally-representative cost per 57 g serving in 2017 USD ranged from 8.6 cents in Rwanda to 17.2 cents in Ethiopia. We then compare that to the cost of each type of fuel. The results shown in Fig. 3 reveal no consistent ranking in fuel costs, but in two cases (Rwanda electricity and Uganda gas), the cost of fuel exceeds the cost of the beans themselves.

Our analysis so far focuses only on meal costs at national average market prices for ingredients and fuel. How each food is actually cooked varies with household circumstances, including the availability of kitchen equipment, local variation in costs at each time and place, and cultural or demographic factors that influence each household's division of labor related to meal preparation. Home cooking may also impose large health costs from indoor smoke, and how foods are prepared and served or stored can also have important consequences for foodborne illness and food waste, as well as externalities associated with deforestation and emissions. Reducing the inequities and total costs associated with inefficient cooking might sometimes be possible with innovations in food processing that would preserve and even enhance the nutritional value of foods. For the basic meal with pulses in East Africa, however, using canned beans would cost roughly 3–4 times the cost of dry beans, plus the required cooking fuel, at a price per serving that ranges from $1.25 in Kenya to $1.37 in Tanzania, $1.42 in Burundi and Ethiopia, $1.55 in Uganda and $1.66 in Rwanda.

This case study is just one small step towards including the costs of meal preparation in future work on the cost and affordability of a healthy diet. In so doing, we build on a long and diverse literature on meal preparation as a determinant of diet quality and health outcomes, and studies of cooking fuel as a driver of household health and environmental harms. Regarding diet quality in low- and middle-income countries, the recent literature was pioneered by Kennedy and Reardon (1994) on how urbanization in Kenya and Burkina Faso led to shifts from coarse to refined grains, and includes many papers on how time use in rural



Note: Data shown are the nationally-representative retail price of 57.25g for the most affordable kind of pulse, which, in each country, is spotted beans, compared to the cost of fuel use quantities from MECS (2019) and prices from ICP (2021), as detailed in the text.

Fig. 3 Cost per serving of the most affordable pulse and fuel for a plate of beans in East Africa

households relates to nutrition as reviewed by Johnston et al. (2018), plus later contributions on time use that include Seymour et al. (2019, 2020) and Vemireddy and Pingali (2021). Similar issues arise in studies of time use and diet quality for higher-income settings, such as Raschke (2012), Smith et al. (2013), Yang et al. (2015), and Carpio et al. (2020) in the US, or Mackay et al. (2017) in New Zealand. Regarding the health effects of indoor smoke and the environmental consequences of wood and charcoal, several studies address the prevalence of each fuel type and the drivers of change (Heltberg 2004; Bonjour et al. 2013; Shupler et al. 2019), in some cases tracing their effects to time management and fuel choice (Anderman et al. 2015).

This chapter links meal preparation to the cost and affordability of healthier diets, focusing on the relative cost of raw ingredients as opposed to pre-cooked and packaged foods, and comparing the ingredient costs to fuel costs for beans in East

Africa. To address how the costs of meal preparation and the increasing availability of processed foods affect food choice, it will be especially important to identify forms of food processing that preserve and enhance nutritional values, as opposed to the growing health risks associated with existing types of ultra-processed food that have been shown in observational studies reviewed by Pagliai et al. (2021) and Lane et al. (2021), as well as one randomized control trial. The need for policies and programs to distinguish between healthier and less healthy packaged foods is important for the food safety agenda (Jaffee et al. 2020), and could help ensure that food system transformations bring healthy and nutritious diets within reach for all people at all times, in every country of the world.

4 Opportunities for Action

A basic plate of healthy food is unaffordable for many of the world's most resource-poor households, due not only to the high cost of growing or purchasing raw ingredients, but also the high cost of meal preparation within the home. Government policies and programs could build on past work such as the SOFI 2020 report, CFS (2021) and other initiatives to ensure food security for all through two specific kinds of action suggested by our findings:

1. **revised poverty lines and safety nets** to ensure that all people at all times can acquire the foods needed for a healthy diet, using locally appropriate criteria for targeting and forms of assistance, including cash transfers, vouchers and in-kind assistance; and
2. **improved cooking and processing** to reduce the health and environmental burdens of meal preparation, for example, through electrification using renewable energy sources, as well as support for helpful processing that preserves the nutritional value of foods, in distinction to ultra-processing that may remove beneficial components and add attributes that are associated with illness later in life, and displacement of minimally processed healthy foods.

The first of these potential game-changers calls on governments to make healthy diets affordable for all by using the minimal cost of a healthy diet to examine food poverty thresholds and inform eligibility for nutritional safety nets that provide cash transfers, vouchers, or in-kind support to supplement a household's own income or food production. Safety nets designed around access to a healthy diet can be the foundation for social inclusion, using twenty-first century data analysis to target and deliver assistance in all countries of the world. Recent improvements in market monitoring and analysis of diet costs allow governments to target and deliver nutrition assistance tailored to local needs, with food-based poverty lines to guide programme design parameters suited to each population, targeting by demographic group and delivering through locally adapted instruments, including cash, vouchers and in-kind assistance. As noted by Hendriks (2018), making healthy diets affordable by tackling poverty is a necessary, but not sufficient, step towards food security and nutrition, which also requires improvements in the quality and price of available foods to enable behavior change for food and nutrition security of all people at all times.

The second of these game-changers addresses hidden costs in the "last mile" of food security for households to acquire foods and prepare each meal. Food acquisition and preparation often places high burdens on caregivers' time and can impose additional financial costs for cooking fuel, equipment, and transportation. Governments should support the development of infrastructure that will reduce the burden of food acquisition and preparation, such as rural electrification, and support agri-food processing that reduces the time and fuel cost of home cooking while preserving the nutritional value of foods.

The main action step within the food system is to distinguish between helpful processing that preserves or even adds to the healthfulness of food versus harmful ultra-processing that transforms food, removing healthful aspects of foods such as whole grains and sometimes adding health risk factors such as refined carbohydrates and sugars, sodium, and trans fats. Actively making that distinction allows for support for the helpful kinds of healthy processing, often by local small and medium-sized enterprises (SMEs), while also using regulation and taxation to limit harmful forms of ultra-processing.

To guide these interventions, governments will need to continue investing in improved data collection regarding food prices, the externalities involved in true cost accounting, and the hidden costs of food acquisition and meal preparation within the home. Governments routinely collect nationally-representative market prices for a variety of foods each month to calculate their consumer price indexes, and international agencies such as the WFP, FAO and FEWS NET also collect rural market prices to target food assistance (Bai et al. 2021a). The World Bank is expanding its global office so that the ICP can focus on food prices and diet costs, in collaboration with national statistical organizations around the world (Food Prices for Nutrition 2021).

As shown in this chapter, governments can complement this work with attention to other barriers to affordability beyond market prices, such as the time and resources required for food acquisition, meal preparation and the use of cooking fuel. Accurately measuring these hidden costs is also helpful for true cost accounting of externalities associated with the environmental footprint of food production, processing, and distribution, as well as the health effects of food consumption. These costs differ among different types of agricultural ingredients, and also differ among types of processing. The hidden costs of meal preparation, as well as the environmental costs and health burden associated with diet-related disease, call for attention not only to different kinds of farm production, but also to a new kind of distinction between helpful, healthy kinds of food processing and ultra-processed foods that are an increasingly important cause of diet-related disease around the world.

In summary, the data described in this chapter lead to two game-changing actions:

(i) the establishment of poverty lines and safety nets informed by the cost of a healthy diet to ensure that all people at all times can acquire the foods needed for lifelong health, using appropriate targeting and forms of assistance, including cash transfers, vouchers, and in-kind assistance; and

(ii) actions to reduce the burden of meal preparation for healthy diets through electrification using renewable energy sources, as well as support for helpful processing that preserves the nutritional value of foods, in distinction to ultra-processing that may remove beneficial components and add attributes that are associated with illness later in life.

Through these actions, governments can use new kinds of data and analytical methods to meet universal needs in locally appropriate ways, thereby ensuring food and nutrition security for all.

Annex

Table A1 Reference food items selected to convert food weight (g) to dietary energy (kcal)

Food category	Reference item	Food name in FCT	FCT code
Pulses	White beans, dried	Beans, white, mature seeds, raw	16,049
Oils	Vegetable oil	Vegetable oil, palm kernel	4513
Onions	Fresh onions	Onions, raw	11,282
Tomatoes	Fresh tomatoes, round	Tomatoes, red, ripe, raw, year-round average	11,529
Starchy staples	Medium-grain rice	Rice, white, medium-grain raw, unenriched	20,450

Note: FCT code numbers refer to the USDA SR28 database

Table A2 Energy content of each item for isocaloric substitution within food categories

Food category	Weight (g) per serving	Kcal per 100 g	Kcal per serving
Pulses	57.25	333	190.6
Oils	28.13	862	242.5
Onions	16.25	40	6.5
Tomatoes	55.00	18	9.9
Starchy staples	75.00	360	270.0

Note: The quantity of oil from the original WFP basic plate has been reduced by 10% to more closely approximate daily lipid needs. Substitutions within food categories are among versions of the food with different moisture content, but similar nutrient density per calorie, for example, switching the 270 kcal of carbohydrate-rich starchy staples from dry raw rice grains to potatoes, or the 190.6 kcal of dry beans into 190.6 kcal of canned beans, or switching the 9.9 kcal of whole tomatoes with 9.9 kcal of concentrated tomato paste. Different items in the oils and onions categories are all roughly similar in weight per kcal, so either unit of measure would yield the same result

Table A3 Macronutrient adequacy of the basic plate

Source	Protein	Lipids	Carbohydrates
Pulses	13.37	0.49	34.50
Oils	0.00	28.13	0.00
Onions	0.18	0.03	1.52
Tomatoes	0.48	0.11	2.14
Rice	4.96	0.44	59.51
Total	18.99	29.19	97.67
Total (kcal)	76	263	391
Percent of kilocalories	10.4%	36.0%	53.6%
Acceptable range	10–35%	20–35%	45–65%

Note: Data shown are grams of each macronutrient from each food and in total for the basic meal. The bottom row shows the Acceptable Macronutrient Distribution Range (AMDR), as specified by the Dietary Reference Intakes of the U.S. Institute of Medicine (2005). Composition of each food is based on the USDA National Database for Standard Reference, Release 28 (SR-28) and the reference food items listed in Table A1

Table A4 Items selected for the basic plate and its variants, by food category (n = 152)

Food	Raw (more work required)	Transformed (less time required)
Starchy staples	Long-grain rice, not parboiled, WKB	Short pasta, BL
	Fresh sweet potatoes	Baguette, BNR
	Wheat flour, not self-rising, BL	Bread, white, loaf, BNR
	Brown flour	Lebanese bread
	Long-grain rice, parboiled, WKB	Spaghetti, WKB
	Maize grains, white	Egg noodles, WKB
	Maize, BL	Samoon bread
	Wheat	Instant noodles, any flavor, WKB
	Medium-grain rice, BNR	Dried noodles, WKB
	Broken rice, 25%, BNR	Vermicelli, BL
	Sticky rice, WKB	Roll, BNR
	Short-grain rice, BNR	Bread, whole wheat, loaf, BNR
	Long-grained rice-25–50 KG, BNR	Round bread
	White rice #3, BNR	Bread, white, sliced, WKB
	Wheat flour, loose, BNR	Spaghetti, BL
	Corn (maize) flour, white, WKB	Short pasta, WKB
	Maize flour, yellow	Lasagna (sheets)
	Wholemeal flour, Atta, BL	Sliced brown bread (AFR)
	Oats, rolled, WKB	Couscous, BNR
	White rice #1, BNR	Sliced brown bread (WAS)
	White rice #10, prepacked, BL	Spaghetti, BARILLA
	Wheat semolina (suji), WKB	Bread unpacked
	Plantains, fresh green	
	Long grain rice, family pack, WKB	

(continued)

Table A4 (continued)

Food	Raw (more work required)	Transformed (less time required)
Pulses	Spotted beans	Green peas, tinned, WKB
	Dried peas, WKB (CIS)	Hommus
	Peas (AFR)	White beans in tomato sauce, tinned, HEINZ
	Dhal, Khesari, BL	
	Peas (WAS)	
	Green/mung beans, dried, BL	
	Dhal, Split peas, BL	
	Dried broad beans	
	Moong dahl, loose, BL	
	Dhal, Musur, BL	
	White beans, dried, BL	Canned black beans
Onions	Fresh onions	–
Tomatoes	Fresh tomatoes, round	Tomato paste, WKB
		Tomato paste (large), WKB
		Chopped tomatoes, BL
Oils	Soybean oil, WKB	–
	Palm oil unrefined, BL	–
	Peanut oil, WKB	–
	Vegetable oil, WKB	–
	Palm oil, WKB	–
	Olive oil, extra virgin, WKB	–
	Sunflower oil, WKB	–
	Corn oil, WKB	–
	Cottonseed oil (CIS)	–
Fish	Squid	Mackerel fillet, tinned, in tomato sauce, WKB
	Fresh small sardines	Dried sardines, BNR
	Carp	Sardines, tinned, with skin, in vegetable oil, WKB
	Tuna steaks	Salty herring (CIS)
	Rainbow-trout (Salmo gairdneri)	Tuna flakes, tinned, WKB
	Red snapper	Dried small fish, BNR
	Mackerel, un-cleaned	Mackerel fillet, tinned, in vegetable oil, WKB
	Tilapia	Dried Machoiron, BNR
	Sea bass	Dried shrimp, BNR
	Red snapper (AFR)	Fishball, BNR
	Cod (gadus morhua)	Salted and semi-dried fish, BL
	Tuna steak	Mackerel in vegetable oil, WKB
	Shrimp, whole, fresh	Sardines in tomato sauce, WKB
	Small fresh fish	Smoked shrimp/prawns, BNR

(continued)

Table A4 (continued)

Food	Raw (more work required)	Transformed (less time required)
	Catfish	
	Fissikh	
	Black pomfret	
	Tuna	
	Sunflower oil, BL	
Poultry	Chicken, whole, fresh	Chicken, whole, frozen
	Chicken legs	Chicken burger
	Chicken, live	Chicken, non-specific cuts, frozen
	Whole duck, fresh	Canned chicken
	Chicken breast, with skin and bones	Breakfast sausage, chicken, BNR
	Native house chicken, fresh	
	Chicken wings (WAS)	
	Chicken, traditionally bred, live	
	Chicken, non-specific cuts, fresh	
Red meat	Beef, center brisket	Sausage
	Beef liver, BNR	Sausages, whole/frankfurter
	Pork, loin chop	Beef, minced
	Veal breast, with bones	BEEF SAUSAGE
	Pork, belly (C)	Salami, sold loose
	Beef, rump steak	Pork ham, pressed, WKB
	Sirloin steak	Bacon, smoked, WKB
	Lamb, whole leg	Luncheon meat
	Beef, with bones	Canned beef, chunks, WKB
	Pork, shoulder	Sliced ham, pork, WKB
	Pork, ribs	Beef merguez (spiced)
	Pork liver, BNR	Burger
	Mutton, mixed cut	
	Mutton tripe	
	Pork thigh, with bones	
	Pork, fillet	
	Beef without bones	
	Mutton chop	

Table A5 Candidate food items whose prices and availability are reported in ICP 2017

Food	Raw (more work required)	Transformed (less work required)
Pulses	Dhal, Khesari, BL	Canned black beans
	Dhal, Musur, BL	Foul Medammas, canned
	Dhal, Split peas, BL	Frozen peas, small/fine, WKB
	Dried broad beans	Green peas, tinned, WKB
	Dried peas, WKB (CIS)	Hommus
	Green beans (pulses)	White beans in tomato sauce, tinned, HEINZ
	Green/mung beans, dried, BL	
	Moong dahl, loose, BL	
	Peas (AFR)	
	Peas (WAS)	
	Spotted beans	
	White beans, dried, BL	
Red meat	Beef liver, BNR	Beef sausage
	Beef without bones	Bacon, smoked, WKB
	Beef, silverside (F2a)	Beef merguez (spiced)
	Beef, sirloin steak (H1)	Beef, cubes for stew or curry
	Beef, center brisket	Beef, fillet, frozen, tenderloin
	Beef, center brisket, with bones (B2)	Beef, minced
	Beef, fillet, tenderloin	Burger
	Beef, rump steak	Canned beef, chunks, WKB
	Beef, with bones	Corned beef, WKB
	Beef, without bones, non-specific cut	Ham, air dried, sold loose
	Buffalo, without bones, non-specific cut	Ham, from the thigh, cooked and smoked, sold loose
	Goat leg	Luncheon meat
	Goat, mixed cut, with bones	Pork ham, pressed, WKB
	Lamb liver	Pork, schnitzel/escalope (A)
	Lamb, chops	Salami, WKB
	Lamb, hindLeg (hindquarters A)	Salami, sold loose
	Lamb, whole leg	Sausage
	Live goat	Sausage, frankfurter/wiener type, artificial skin, WKB
	Live sheep	Sausage, fresh and raw, sold loose
	Mutton tripe	Sausages, whole/frankfurter
	Mutton chop	Sliced ham, pork, WKB
	Mutton chops	Veal, schnitzel/escalope (A5)
	Mutton, mixed cut	
	Mutton/goat liver, BNR	
	Pork liver, BNR	
	Pork loin, without bones	
	Pork thigh, with bones	

(continued)

Table A5 (continued)

Food	Raw (more work required)	Transformed (less work required)
	Pork, belly (C)	
	Pork, collar (B1)	
	Pork, fillet	
	Pork, joint piece for roasting (B2)	
	Pork, loin chop	
	Pork, ribs	
	Pork, shoulder	
	Pork, with bones, non-specific cut	
	Pork, without bones, non-specific cut	
	Round steak	
	Sirloin steak	
	Veal breast, with bones	
	Veal chops	
	Veal, loin (B2)	
	Veal, with bones	
Poultry	Chicken breast, with skin or bones	Breakfast sausage, chicken, BNR
	Chicken breast, without skin or bones	Canned chicken
	Chicken legs	Chicken breast, fillets, shreds or dices
	Chicken wings (ASI)	Chicken burger
	Chicken wings (WAS)	Chicken nuggets/dippers, frozen, WKB
	Chicken, traditionally bred, live	Chicken soup
	Chicken, for roasting, free range	Chicken, non-specific cuts, frozen
	Chicken, live	Chicken, whole, frozen
	Chicken, non-specific cuts, fresh	Grilled/roasted chicken
	Chicken, whole, fresh	Ham, Turkey, WKB
	Native house chicken, fresh	Luncheon chicken
	Turkey	
	Turkey breast, fillet	
	Whole duck, fresh	
Fish	Black pomfret	Breaded fish fillet (Cod), 2–5 pieces, frozen, WKB
	Capitaine	Breaded fish fillet (Pollock), 2–4 pieces, frozen, WKB
	Carp	Calamari rings, frozen, WKB
	Catfish	Canned sprats in oil, WKB (CIS)
	Cod (gadus morhua)	Cod (Gadus morhua), frozen, WKB
	Fissikh	Cold-smoked salmon, WKB
	Fresh small sardines	Dried Machoiron, BNR

(continued)

Table A5 (continued)

Food	Raw (more work required)	Transformed (less work required)
	Giant shrimp	Dried sardines, BNR
	Grouper (Hamour) fish	Dried shrimp, BNR
	Lobster	Dried small fish, BNR
	Mackerel, un-cleaned	Fish fingers, BL
	Mud crab	Fish fingers, from fillet, WKB
	Mullet	Fishball, BNR
	Prawns/shrimp, medium	Hake (Merluccius merluccius), Alaska Pollock (Theragra chalcogramma), fillet, frozen, WKB
	Prawns/shrimp, small	Mackerel fillet, tinned, in tomato sauce, WKB
	Rainbow-trout (Salmo gairdneri)	Mackerel fillet, tinned, in vegetable oil, WKB
	Red snapper (AFR)	Mackerel in vegetable oil, WKB
	Red snapper	Pangasius catfish (Pangasius hypophthalmus), fillet, frozen, BL
	Safi	Salmon in natural juice, WKB (CIS)
	Sea bass	Salted and semi-dried fish, BL
	Sea crab	Salty herring (CIS)
	Sea lobster	Sardines in tomato sauce, WKB
	Shrimp, whole, fresh	Sardines, tinned, with skin, in vegetable oil, WKB
	Small fresh fish	Shrimp, peeled, frozen
	Sole	Smoked mackerel (Scomber scombrus), fillet, WKB
	Spanish mackerel	Smoked shrimp/prawns, BNR
	Squid	Tinned pink tuna (Skipjack, Thunnus Thynn, Albacares = yellow fin), WKB
	Squid, small	Tinned sardines, in olive oil, with skin and bones, WKB
	Tilapia	Tinned tuna flakes, in vegetable oil, BL
	Tuna	Tuna flakes, tinned, WKB
	Tuna fish fresh	Tuna in vegetable oil, exclude tuna steaks, WKB
	Tuna steak	
	Tuna steaks	
	White pomfret	
Carbo-hydrates (starchy staples)	Basmati rice, WKB	Baguette, BNR
	Broken rice, 25%, BNR	Bread unpacked
	Brown flour	Bread, mixed
	Brown rice, family pack, BL	Bread, multicorn
	Brown rice, loose	Bread, multicorn, industrially packed, WKB
	Buckwheat (CIS)	Bread, white, industrially packed, WKB
	Corn	Bread, white, loaf, BNR
	Corn (maize) flour, loose, BL	Bread, white, sliced, WKB
	Corn (maize) flour, white, WKB	Bread, white, toast, large pack, WKB
	Egyptian rice	Bread, white, unsliced, WKB

(continued)

Table A5 (continued)

Food	Raw (more work required)	Transformed (less work required)
	Fresh cassava/manioc/yuca	Bread, white, large loaf
	Fresh potatoes, brown	Bread, whole wheat, loaf, BNR
	Fresh potatoes, industrially packed	Burger bread
	Fresh potatoes, white	Couscous, BNR
	Fresh sweet potatoes	Dried noodles, WKB
	Fresh taro	Egg noodles, WKB
	Hard loose bulgur	Fresh rice noodles, BL
	Jasmine rice, WKB	Instant noodles, cup, WKB
	Long grain rice, family pack, WKB	Instant noodles, any flavor, WKB
	Long-grain rice, not parboiled, BL or WKB	Lasagna
	Long-grained rice-25–50 KG, BNR	Lasagna (sheets)
	Long-grain rice, parboiled, WKB	Lebanese bread
	Maize flour white (Maizena)	Long-grain rice, parboiled in cooking bags
	Maize flour, yellow	Roll or bun, prepacked, BNR
	Maize grains, white	Roll, BNR
	Maize, BL	Roll, multicorn
	Medium-grain rice, BNR	Round bread
	Millet (CIS)	Samoon bread
	Millet, sorghum, BL	Short pasta, BL
	Oats, Quaker	Short pasta, WKB
	Oats, rolled, WKB	Sliced brown bread (AFR)
	Plantains, fresh green	Sliced brown bread (WAS)
	Plantains, fresh ripe	Spaghetti, BARILLA
	Premium rice #1, prepacked, BL	Spaghetti, BL
	Premium rice #2, prepacked, BL	Spaghetti, WKB
	Premium rice #3, BNR	Sweet bread
	Premium rice #4, BNR	Uncle Ben's rice
	Rice flour, Atta, WKB	Vermicelli, BL
	Risotto rice, WKB	Wheat tortillas, WKB
	Round-grain rice, WKB	
	Short-grain rice, BNR	
	Sticky rice, WKB	
	Sun white Rice - Australia	
	Wheat	
	Wheat flour, WKB	
	Wheat flour, loose, BNR	
	Wheat flour, not self-rising, BL	
	Wheat semolina (suji), WKB	
	White rice #1, #3 or #5, BNR	

(continued)

Table A5 (continued)

Food	Raw (more work required)	Transformed (less work required)
	White rice #10, prepacked, BL	
	White rice #7, prepacked, BL	
	White rice #8, prepacked, BL	
	White rice #9, prepacked, BL	
	Wholemeal flour, Atta, BL	
Oils	Coconut oil, BL	
	Corn oil	
	Corn oil, WKB	
	Cottonseed oil (CIS)	
	Olive oil, extra virgin, BL	
	Olive oil, extra virgin, WKB	
	Olive oil, standard, WKB	
	Palm oil unrefined, BL	
	Palm oil, WKB	
	Peanut oil, WKB	
	Soybean oil, WKB	
	Sunflower oil, BL	
	Sunflower oil, WKB	
	Tahina	
	Vegetable oil, WKB	
Onions	Fresh leek	
	Fresh onions	
Tomatoes	Fresh tomato cluster	Chopped tomatoes, BL
	Fresh tomatoes, round	Chopped tomatoes, WKB
		Tomato paste (large), WKB
		Tomato paste, WKB
		Tomato puree (Passata di Pomodoro), WKB

References

Anderman TL, DeFries RS, Wood SA, Remans R, Ahuja R, Ulla SE (2015) Biogas cook stoves for healthy and sustainable diets? A case study in southern India. Front Nutr 2:28. https://doi.org/10.3389/fnut.2015.00028

Bai Y, Naumova EN, Masters WA (2020) Seasonality of diet costs reveals food system performance in East Africa. Sci Adv 6(49):eabc2162. https://doi.org/10.1126/sciadv.abc2162

Bai Y, Costlow L, Ebel A, Laves S, Ueda Y, Volin N, Zamek M, Herforth A, Masters WA (2021a) Review: retail consumer price data reveal gaps and opportunities to monitor food systems for nutrition. Food Policy 104:e102148. https://doi.org/10.1016/j.foodpol.2021.102148

Bai Y, Alemu R, Block SA, Headey D, Masters WA (2021b) Cost and affordability of nutritious diets at retail prices: evidence from 177 countries. Food Policy 99:101983. https://doi.org/10.1016/j.foodpol.2020.101983

Bonjour S, Adair-Rohani H, Wolf J, Bruce NG, Mehta S, Prüss-Ustün A, Lahiff M, Rehfuess EA, Mishra V, Smith KR (2013) Solid fuel use for household cooking: country and regional estimates for 1980–2010. Environ Health Perspect 121(7):784–790. https://doi.org/10.1289/ehp.1205987

Carpio CE, Kalenkoski CM, Moyeda-Carabaza AF, Murimi M (2020) The effect of time use and food cost on dietary quality. Public Health Nutr 23(18):3284–3294. https://doi.org/10.1017/S1368980020001615

CFS (2021) Voluntary guidelines on food systems and nutrition. Forty-seventh session "Making a Difference in Food Security and Nutrition", 8–11 Feb 2021. Committee on World Food Security, Rome. http://www.fao.org/3/ne982en/ne982en.pdf

FAO, IFAD, UNICEF, WFP, WHO (2020) The state of food security and nutrition in the world 2020: transforming food systems for affordable healthy diets. FAO, Rome. http://www.fao.org/publications/sofi

Food Prices for Nutrition (2021) Diet cost metrics for a better-fed world (project website). Tufts University, Boston. https://sites.tufts.edu/foodpricesfornutrition

Heltberg R (2004) Fuel switching: evidence from eight developing countries. Energy Econ 26(5):869–887. https://doi.org/10.1016/j.eneco.2004.04.018

Hendriks SL (2018) Food policy and nutrition economics in the SDG era. Agrekon 57(3–4):167–180. https://doi.org/10.1080/03031853.2018.1479974

Herforth A, Bai Y, Venkat A, Mahrt K, Ebel A, Masters WA (2020) Cost and affordability of healthy diets across and within countries: background paper for the state of food security and nutrition in the world 2020, Agricultural development economics technical study no. 9. Food and Agriculture Organization of the UN, Rome. www.fao.org/documents/card/en/c/cb2431en

Hirvonen K, Bai Y, Headey D, Masters WA (2020) Affordability of the EAT–lancet reference diet: a global analysis. Lancet Glob Health 8(1):e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

ICP (2021) The International Comparison Program. The World Bank, Washington, DC. https://www.worldbank.org/en/programs/icp

Jaffee S, Henson S, Grace D, Ambrosio M, Berthe F (2020) Why food safety matters to Africa: making the case for policy action. Chapter 10. In: Resnick D, Diao X, Tadesse G (eds) Sustaining Africa's agrifood system transformation: the role of public policies. IFPRI/AKADEMIYA2063, Washington, DC/Kigali, pp 112–129. 10.2499/9780896293946_10

Johnston D, Stevano S, Malapit HJ, Hull E, Kadiyala S (2018) Time use as an explanation for the agri-nutrition disconnect: evidence from rural areas in low and middle-income countries. Food Policy 76:8–18. https://doi.org/10.1016/j.foodpol.2017.12.011

Kennedy E, Reardon T (1994) Shift to non-traditional grains in the diets of East and West Africa: role of women's opportunity cost of time. Food Policy 19(1):45–56. https://doi.org/10.1016/0306-9192(94)90007-8

Lane MM, Davis JA, Beattie S, Gómez-Donoso C, Loughman A, O'Neil A, Jacka F, Berk M, Page R, Marx W, Rocks T (2021 March) Ultraprocessed food and chronic noncommunicable diseases: A systematic review and meta-analysis of 43 observational studies. Obes Rev 22(3):e13146. https://doi.org/10.1111/obr.13146. Epub 2020 Nov 9. PMID: 33167080

Mackay S, Vandevijvere S, Xie P, Lee A, Swinburn B (2017) Paying for convenience: comparing the cost of takeaway meals with their healthier home-cooked counterparts in New Zealand. Public Health Nutr 20(13):2269–2276. https://doi.org/10.1017/S1368980017000805

Masters WA, Bai Y, Herforth A, Sarpong DB, Mishili F, Kinabo J, Coates JC (2018) Measuring the affordability of nutritious diets in Africa: price indexes for diet diversity and the cost of nutrient adequacy. Am J Agric Econ 100(5):1285–1301. https://doi.org/10.1093/ajae/aay059

MECS (2019) The Kenya eCookbook: beans and cereals edition. Modern Energy Cooking Services (MECS), Loughborough University. https://mecs.org.uk/the-ecookbook

Nerini FF, Ray C, Boulkaid Y (2017) The cost of cooking a meal. The case of Nyeri County, Kenya. Environ Res Lett 12(6):065007. https://doi.org/10.1088/1748-9326/aa6fd0

Pagliai G, Dinu M, Madarena MP, Bonaccio M, Iacoviello L, Sofi F (2021) Consumption of ultra-processed foods and health status: a systematic review and meta-analysis. Br J Nutr 125(3):308–318. https://doi.org/10.1017/S0007114520002688

Raschke C (2012) Food stamps and the time cost of food preparation. Rev Econ Househ 10(2):259–275. https://doi.org/10.1007/s11150-011-9128-3

Seymour G, Masuda YJ, Williams J, Schneider K (2019) Household and child nutrition outcomes among the time and income poor in rural Bangladesh. Glob Food Sec 20:82–92. https://doi.org/10.1016/j.gfs.2019.01.004

Seymour G, Malapit H, Quisumbing A (2020) Measuring time use in developing country agriculture: evidence from Bangladesh and Uganda. Fem Econ 26(3):169–199. https://doi.org/10.1080/13545701.2020.1749867

Shupler M, Hystad P, Gustafson P, Rangarajan S, Mushtaha M, Jayachtria KG, Mony PK, Mohan D, Kumar P, Lakshmi PVM, Sagar V (2019) Household, community, sub-national and country-level predictors of primary cooking fuel switching in nine countries from the PURE study. Environ Res Lett 14(8):085006. https://doi.org/10.1088/1748-9326/ab2d46

Smith LP, Ng SW, Popkin BM (2013) Trends in US home food preparation and consumption: analysis of national nutrition surveys and time use studies from 1965–1966 to 2007–2008. Nutr J 12(1):1–10. https://doi.org/10.1186/1475-2891-12-45

Vemireddy V, Pingali PL (2021) Seasonal time trade-offs and nutrition outcomes for women in agriculture: evidence from rural India. Food Policy 102074. https://doi.org/10.1016/j.foodpol.2021.102074

WFP (2017) Counting the beans: the true cost of a plate of food around the world. World Food Programme, Rome. https://www.wfp.org/publications/2017-counting-beans-true-cost-plate-food-around-world; https://cdn.wfp.org/2020/plate-of-food/

World Bank (2021) Sustainable Energy for All (SE4ALL) database, reproduced in World Development Indicators as EG.ELC.ACCS.ZS. https://databank.worldbank.org

Yang Y, Davis GC, Muth MK (2015) Beyond the sticker price: including and excluding time in comparing food prices. Am J Clin Nutr 102(1):165–171. https://doi.org/10.3945/ajcn.114.101444

The Global Cost of Reaching a World Without Hunger: Investment Costs and Policy Action Opportunities

Bezawit Beyene Chichaibelu, Maksud Bekchanov, Joachim von Braun, and Maximo Torero

1 Introduction

At the heart of the 2030 Agenda[1] was a promise to prioritize two objectives: to eradicate poverty and end hunger in all their forms. Worldwide, over 650 million people are estimated to have been undernourished in 2019. World hunger increased further in 2020 to 720–811 million people, exacerbated by the impact of COVID-19 (FAO, IFAD, UNICEF, WFP, & WHO 2021). Recent global projections of hunger show that the world is not on track to achieve zero hunger[2] by 2030. Estimates in 2020 projected that the number of people affected by hunger will surpass 840 million by 2030, or 10% of the global population (FAO, IFAD, UNICEF, WFP, & WHO 2020). Updated estimates in 2021 projected lower, but still alarming levels of hunger

Bezawit Beyene Chichaibelu, Maksud Bekchanov, Joachim von Braun and Maximo Torero 2021. The global cost of reaching a world without hunger: Investment costs and policy action opportunities. In Food Policy. Volume 104, October 2021, 102151. https://doi.org/10.1016/j.foodpol.2021.102151_34.

[1] In 2015, all of the UN member states adopted seventeen goals as part of the 2030 Agenda for Sustainable Development, which set out a fifteen-year plan to achieve the goals.

[2] Most studies define 'zero hunger target' as the reduction of hunger levels to less than the 5 or 3% of population. 'Absolute zero hunger target' is used throughout this manuscript to refer to a complete eradication of hunger.

B. B. Chichaibelu (✉) · J. von Braun
Center for Development Research, University of Bonn, Bonn, Germany
e-mail: bchichai@uni-bonn.de

M. Bekchanov
Research Unit Sustainability and Global Change, Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany

M. Torero
Food and Agriculture Organization (FAO), Rome, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_34

that will affect about 660 million people by 2030 (FAO, IFAD, UNICEF, WFP, & WHO 2021). The world is also not on track to achieve the 2025 and 2030 targets for child malnutrition. In 2019, 21.3% of children under five years of age were stunted globally, or 144 million (UNICEF, WHO & World Bank 2020). In 2021, the number of children suffering from stunting increased further to 149.2 million. Although there has been some progress globally since 2000, rates of stunting reduction are far below what is needed to reach the targets of 40% reduction for 2025 and 50% reduction for (FAO, IFAD, UNICEF, WFP, & WHO 2021).

COVID-19 is expected to further worsen the overall prospects for food security and nutrition. Food insecurity may appear in countries and population groups that were not previously affected. In 2020, the number of undernourished people increased by about 118 million people compared to the 2019 level as COVID-19 disrupted economies, job markets and supply chains, and inflated food prices. The pandemic is also expected to have a lasting effect beyond 2020, adding about 30 million more people to the total number of undernourished in the world in 2030 (FAO, IFAD, UNICEF, WFP, & WHO 2021). Additionally, early estimates on the impact of COVID-19 on child malnutrition suggested an additional 6.7 million children suffered from wasting in 2020 as compared to pre-COVID-19 projections. The combined effect of the increase in wasting and a 25% reduction in the coverage of nutrition and health services due to COVID-19 could cause an additional 128,605 deaths in children younger than five years in 2020 (Headey et al. 2020). While these projections are an early estimate and may not fully capture the impact of COVID-19 on food security and nutrition, they emphasize the urgent need for actions to get back on track towards achieving targets 2.1 and 2.2 of Sustainable Development Goal No. 2 (SDG2).

Investments needed to end hunger are anticipated to be extensive, costly and difficult to implement, even without considering the impacts of the COVID-19 pandemic. As policymakers still need to prioritize the allocation of resources, identifying optimal and least-cost investment options is important for practical policy. In this regard, this study developed a marginal abatement cost curve (MACC) as an original contribution to identify a mix of least-cost investment options with the highest potential for reduction in hunger. Twenty-two different interventions are considered for reducing hunger. The information about the interventions are drawn from the findings of various model- and cost-benefit and impact evaluation studies on hunger reduction measures. Some of them are more short-term interventions (such as social protection), and some are more long-term (such as agricultural R&D, or soil fertility management). The MACC of hunger reduction can be considered when asking "what are the costs of ending hunger?", depending on the number of people who are to be brought out of risk of hunger by 2030. The assessment can broadly guide global and country efforts to achieve the SDG 2 targets by 2030.

The results from the MACC indicate that ending hunger would not be prohibitively expensive, provided that a mix of least-cost measures with large hunger reduction potential are prioritized. Ending hunger by 2030 is estimated to require US$ 39–50 billion annually until 2030. Of that, the G7 would need to contribute US$ 11–14 billion to meet their Elmau commitment of lifting 500 million people out of hunger by 2030,[3] effectively doubling current aid flows for agriculture, food and rural development. A bundle of promising investments that deliver short-term and long-term impacts would meet the goal of ending hunger by 2030. Short-term measures are needed to reach the hungry soon – including those adversely affected by COVID-19 related job losses and other socio-economic consequences – with social protection and nutrition programs. Long-term measures, such as agricultural R&D and expansion of small- and large-scale irrigation, which require high up-front investments but also have a high long-term impact, also need to be included. Optimally phasing investments is crucial: those with longer-term impact should be frontloaded to reap their benefits soon before 2030.

2 Review of Selected Estimates of the Cost of Ending Hunger

Here we review several estimates of the cost of achieving SDG 2, in particular, ending hunger and improving nutrition. We focus on the five most up-to-date estimates conducted by FAO, IFAD, and WFP (2015), Rosegrant et al. (2017), Torero and von Braun (2015), Laborde et al. (2016), and Shekar et al. (2017). Since some of these studies, for example, the studies by FAO, IFAD and WFP (2015) and Torero and von Braun (2015), use the same methodology as earlier works, i.e. Schmidhuber and Bruinsma (2011) and Hoddinott et al. (2013), these earlier works are not included in our review. In the case of others, for example, in the paper by Laborde et al. (2016) titled "Ending Hunger: What Would It Cost", the applied methodology is similar to another ongoing work by Ceres2030 research group; we therefore present only the studies for which the final results are readily available (see also Fan et al. 2018). Summary of the findings of the reviewed studies are presented in Table 1. We further discuss the details and interpretations of these studies in the remaining part of this section.

The "Achieving Zero Hunger" study by the Food and Agriculture Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD), and the World Food Programme (WFP) (2015) presents the most extensive, but also most costly set of measures, including extensive social protection programmes and targeted pro-poor investments. The basic premise of the 'Achieving Zero Hunger' framework is that hunger is a result of lack of purchasing power which translates into a lack of access to sufficient and nutritious food, and therefore the target of eliminating hunger (SDG 2) can be achieved only by eliminating poverty (SDG 1). Unlike other models, it aims for absolute-zero levels of hunger globally by

[3] G7 heads of states at their Summit in Elmau in 2015 committed to lifting 500 million people out of hunger and malnutrition by 2030 as part of a broader effort to be undertaken with partner countries to support the 2030 Agenda for Sustainable Development, i.e. Sustainable Development Goal 2 (SDG 2) to end hunger and malnutrition by 2030.

Table 1 Overview of selected costing studies

Model/framework and institution/author(s)	Research question/time frame	Undernourishment reduction target	Investments/interventions considered to achieve the target	Method used in the analysis	Discussed financial sources to reduce hunger	Total annual cost (billion US$) of reducing hunger	Per capita total cost of hunger eradication (US$) over 2015–2030 *
Achieving Zero Hunger (FAO, IFAD & WFP 2015)	What are the additional investments needed to end poverty and hunger in all countries by 2030?	Zero hunger; eradicating extreme poverty	Pro-poor investments: primary agriculture and natural resources, agro-processing operations, infrastructure, institutional framework, R&D, extension; Social protection	Global partial-equilibrium model of country-wise projections of food supply and demand (called GAPS)	Public and private	**265, out of which 198 for pro-poor investments**	**4035**
IMPACT (IFPRI/Rosegrant et al. 2017)	How much would hunger decrease given investments to achieve target yield increases by 2030?	5% hunger	Agricultural R&D; irrigation expansion; water use efficiency; soil management; transport and energy infrastructure	Agricultural sector partial-equilibrium model linked to biophysical models and CGE model; impacts of climate change included	Public	**52**	**929**

Toward a Zero-Hunger by 2030 (Torero and von Braun 2015)	What is the global cost to accelerate undernourishment reduction to a level that would almost eliminate hunger by 2030?	3% hunger; improved nutrition	Accelerating yield enhancements (agricultural R&D); market innovations (information and communication technologies, increasing competition in the fertilizer market); interventions that reduce micronutrient deficiencies (vitamin A, iodine, iron, zinc) and reduce stunting	Builds up on the Hoddinott et al. (2013) which used agricultural partial-equilibrium model (called IMPACT) for assessing the impacts of R&D investments and cost-benefit analysis for the remaining options	Public, including ODA	**30**, out of which **15** for ending hunger	**312**
MIRAGRODEP (IFPRI& IISD/ Laborde et al. 2016)	What is the minimum cost to end hunger for vulnerable households by 2030?	5% hunger	Social safety nets: food subsidies; farm support: production subsidies, fertilizer subsidies, investment grants, R&D, extension; rural development and infrastructure: reduction of post-harvest losses, irrigation, roads	Global multi-regional CGE model combined with household surveys for targeted interventions	Public, including ODA	**11**	**368**

(continued)

Table 1 (continued)

Model/ framework and institution/author (s)	Research question/ time frame	Undernourishment reduction target	Investments/ interventions considered to achieve the target	Method used in the analysis	Discussed financial sources to reduce hunger	Total annual cost (billion US$) of reducing hunger	Per capita total cost of hunger eradication (US$) over 2015–2030 *
Investment Framework for Nutrition (WB/ Shekar et al. 2017)	What is the minimum cost to meet the World Health Assembly targets on nutrition by 2025?	40% reduction in child stunting; 50% reduction in anaemia in women; 50% increase in exclusive breastfeeding rates; 5% child wasting	Targeted nutrition interventions (micronutrient and protein supplementation, public provision of complementary food, promoting good health and hygiene) and selected nutrition-sensitive interventions (staple food fortification and pro-breastfeeding policies)	Investment cost minimization ad cost-benefit-analysis	Public, including ODA, and private, including household contributions and innovative financing mechanisms	**7**	**Not applicable**

Source: Adapted from Mason-D'Croz et al. (2019)

Note: * Total cost per person is calculated as total net discounted cost over the fifteen-year period (only for the 'Achieving Zero Hunger' study, the time frame is fourteen years, i.e. 2016–2030). The discount rate is assumed to be 5% (Hoddinott et al. 2013). For each modelling framework, the absolute number of people lifted out of hunger by the proposed investments is calculated as the difference between the projected number of hungry people in the 'business as usual 2030'scenario and the projected number of hungry people in the '2030 investment' scenario. These figures are retrieved from each model. The per capita total cost of hunger eradication is then calculated as the total net discounted cost divided by the number of people lifted out of hunger. We calculate only the cost per person for the investments towards hunger reduction, but not for the investments towards improvement in nutrition due to the very specific nature and outcomes of each intervention

2030. Note that hunger is measured here by the prevalence of undernourishment (PoU), defined as chronically inadequate dietary energy intake, in line with the methodology adopted in the FAO's 'The State of Food Security and Nutrition in the World 2019' report (FAO, IFAD, UNICEF, WFP, & WHO 2019). The 'Achieving Zero Hunger' study draws upon a methodology previously used by Schmidhuber and Bruinsma (2011) and employs the partial-equilibrium model called Global Agriculture Perspectives System (GAPS). According to the modelling simulations, the twin-track approach of social protection and pro-poor development is expected to bring relatively fast but also sustainable eradication of poverty and hunger. In the short-term, public investment in social protection is expected to close the poverty gap and increase incomes, both directly and through increased productivity. In the long run, the effects of social protection will be reinforced and sustained by targeted private and public pro-poor investments, especially in rural areas, and particularly so in agriculture (see Table 1). The overall cost of achieving zero hunger would be US$ 265 billion annually, out of which US$ 198 billion will cover pro-poor investments and US$ 67 billion social protection.

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) by the International Food Policy Research Institute's (IFPRI) was applied to analyze the potential contribution of agricultural investments to achieving SDG 2, and proposes a comprehensive investment package that can reduce hunger to 5% of the global population (Rosegrant et al. 2017). These investments focus on agriculture and include agricultural research and development (R&D); resource management, especially water and irrigation; and infrastructure, mainly transportation and energy. Out of the five estimates this is the only framework explicitly modelling the impact of R&D on agricultural productivity and hunger reduction; it is also the only one to account for climate change impacts. The IMPACT model is a highly disaggregated, global partial-equilibrium multi-market model. To overcome the limitations of a partial-equilibrium model, it is linked to a global computable general equilibrium (CGE) model (GLOBE) which allows for estimating the impacts of investment in agriculture on the broader economy. Hunger is proxied by the risk of hunger based on the estimated calorie availability per day per capita. The cost of the agricultural investment package is estimated at US$ 52 billion annually for the developing world. These investments are expected to result in a reduction of the share of the population at risk of hunger to 5%, except for Eastern and Central Africa where hunger will remain at 10% level (Rosegrant et al. 2017).

The "Toward a Zero-Hunger by 2030" study by Torero and von Braun (2015) provides global estimates for the investments necessary to reduce hunger to near zero by 2030, with the assumption that transitory undernourishment at around the 3% level, related to conflict and crises, would require different measures. The estimates are to a great extent extrapolated from Hoddinott et al. (2013) and consider hunger reduction through investing in: (i) accelerating yield enhancements, i.e. investments in agricultural R&D; (ii) market innovations, i.e. information and communication technologies (ICTs) and improving the functioning of fertilizer markets; (iii) and interventions that reduce micronutrient deficiencies (vitamin A, iodine, iron, zinc) and reduce stunting.

This framework of the study is somewhat similar to the work of Rosegrant et al. (2017) presented above, as both studies rely on IMPACT modelling assessments. Hunger level is also measured using a similar approach as in the "Achieving Zero Hunger" study (e.g., Rosegrant et al. 2017). However, the conceptual framework and the underlying assumptions vary to some extent. Agricultural R&D is expected to increase productivity, and the elasticity of yields to R&D expenditure is estimated based on a literature review. This yield growth entails both income and price effects, which will then affect the incidence of hunger. The original cost estimates for agricultural R&D in the underlying paper by Hoddinott et al. (2013) show that it would cost US$ 733 per person to reduce the number of undernourished by 210 million by 2050 (the original time frame of the baseline paper), which translates into a prevalence of hunger reduced to 5.9%. Torero and von Braun (2015) suggest to accelerate these investments up to 2030, and couple them with the remaining investment strategies, i.e. food markets and ICTs, as well as with programmes to reduce micronutrient deficiencies and stunting, which would lift 500 million people out of hunger and attain the objective of near-zero hunger. The total cost of all measures addressing hunger and malnutrition would be US$ 30 billion annually; out of which the cost of ending hunger would be US$ 15 billion annually.

The "Ending Hunger: What Would It Cost" study by IFPRI and the International Institute for Sustainable Development (IISD) combines micro-, meso- and macro-level inputs (Laborde et al. 2016). This modelling framework is based on a dynamic multi-country multi-sector CGE model (MIRAGRODEP) combined with household surveys. The framework that combines modelling with household surveys allows for more efficient targeting of interventions in the model assessment due to more detailed classification of households at risk of hunger. Based on the surveys, households are differentiated in accordance with their location (urban or rural), income sources and levels (farm or non-farm), and farm ownership. Consequently, strategies of social protection are matched with the households with lower income, measures of supporting farm production are considered for households which owns farm, and rural support were proposed to the rural households. This household-level targeting in the model is expected to result in estimations of improved spending efficiency of the hunger reduction investments in comparison to the other models which are based on national averages (Laborde et al. 2016). As noted by Fan et al. (2018), the MIRAGRODEP model's targeting approach, together with the narrow focus on reducing hunger in isolation of other SDGs, produces one of the lowest cost estimates, US$ 11 billion annually. Hunger is measured by the PoU, as defined above in the discussion of the "Achieving Zero Hunger" study. Rather than targeting absolute zero hunger the MIRAGRODEP's objective is set to reducing the PoU to 5% or less. Two other sub-goals of SDG 2, i.e. raising agricultural productivity and doubling smallholders' income (target 2.3) and ensuring sustainable agricultural systems (target 2.4) are also accounted for in the design of interventions. Three types of interventions are included in the MIRAGRODEP model: social safety nets, directly targeting consumers through food subsidies; farm support to increase farmers' productivity and incomes; and rural development, mainly through infrastructure investments (see Table 1). These interventions are expected to affect calorie consumption by increasing poor households' incomes, as in 'Achieving Zero Hunger' study, or by decreasing food prices. The importance of interventions addressing nutrition are also acknowledged, however because of household data limitations, they are not accounted for in the modelling framework (Laborde et al. 2016).

Finally, the "Investment Framework for Nutrition" was proposed by the World Bank (WB) (Shekar et al. 2017). This framework has a narrow scope in comparison to the other models and frameworks presented here, because its adopted methodological framework is very simple and transparent. Rather than aiming at reducing hunger, as in the other models, the WB framework estimates the financial needs for improved nutrition targets. More specifically it aims to (i) reduce the number of stunted children under five by 40%, (ii) reduce the number of women at reproductive age affected by anaemia by 50%, (iii) increase the rate of exclusive breastfeeding in the first six months up to at least 50%, and (iv) reduce and maintain childhood wasting to less than 5%. These targets correspond to the World Health Assembly's Targets for Nutrition, but also contribute to SDG 2 (Shekar et al. 2017). The case for investing in nutrition is very strong: ending malnutrition is critical for long-term human capital, labor productivity and broad economic development (Fink et al. 2016; Horton and Steckel 2013; Hoddinott et al. 2008). At the same time, nutrition interventions are considered to be among the most cost-effective (Horton and Hoddinott 2014). The interventions included in the framework are identified based on two criteria: (1) strong evidence of their impact; (2) relevance for low- and middle-income countries. The selected interventions range from staple-food fortification and micronutrient supplementation to public provision of supplementary food and behavior promotion campaigns. To estimate the total cost of scaling up the selected nutrition interventions, financial needs are first analyzed for the highest-burden countries based on the unit-cost data obtained from a literature review; these results are then extrapolated to all low- and middle-income countries. The estimates suggest that to reach the nutrition targets it will cost around US$ 7 billion annually between 2015 and 2025; more than half of this amount targeted at reducing stunting (Shekar et al. 2017).

The five estimation approaches presented above provide a very wide range of estimates for the total investment necessary to achieve SDG 2, i.e. ending hunger and improving nutrition. These differences are largely attributable to the different objectives and policy questions asked, interventions and investment strategies considered, as well as definitions, methods and assumptions used (Mason-D'Croz et al. 2019; Fan et al. 2018). The differences in the approaches adopted by the costing frameworks make it difficult to directly compare the resulting estimates. We calculated the estimated cost per person of hunger eradication for all the modelling frameworks except the WB's Investment Framework for Nutrition that only provides estimates of nutrition-specific interventions (Table 1). These estimated costs per person vary widely, from more than US$ 4,000 in the 'Achieving Zero Hunger' study to just above US$ 300 in Torero and von Braun (2015). The number of people lifted out of hunger also differs substantially, from 650 million in the 'Achieving Zero Hunger' study, 580 million in the IMPACT modelling study, 500 million in Torero and von Braun (2015), to only 290 million in the MIRAGRODEP modelling study. These differences are accounted for by differences in modelling assumptions, and the scope of each framework in terms of suggested investments and interventions. Rather than providing clear-cut answers, the studies suggest that a variety of diverse investment strategies can contribute to ending hunger.

Although all five estimation approaches address the issue of financial needs for the achievement of SDG 2, the scope of each framework is narrower than the scope of SDG 2 itself. SDG 2 has five targets, the first two concerned with ending hunger and ending all forms of malnutrition by 2030. The remaining three targets concern doubling agricultural productivity and the income of small-scale food producers by 2030, ensuring sustainable food production systems by 2030, and maintaining the genetic diversity of seeds, plants and animals, including wild species by 2020. Three of the models focus on either eradicating or substantially reducing hunger. However, the definitions of hunger vary between the studies, and are based either on food access, as in the 'Achieving Zero Hunger' and the MIRAGRODEP modelling studies, or food availability, as in the IMPACT modelling study; none consider all four dimensions of food security, i.e. food availability, access, utilization, and stability. Only two frameworks, the WB's Investment Framework for Nutrition and the estimates by Torero and von Braun (2015), explicitly model the nutrition outcomes; with the latter being the only one to address both objectives of hunger eradication and improved nutrition in one framework. The other four studies only assume that investment to reduce hunger will also help to reduce malnutrition. Finally, only one of the studies, MIRAGRODEP based 'Ending Hunger: What Would It Cost', factors in the question of sustainability in agriculture.

There are important trade-offs between the scope of a modelling framework and the complexity of the methodology used. Looking at the five frameworks reviewed here, it seems that the narrower the scope of the study, the more detailed and accurate the estimates, as in the case of the MIRAGRODEP model. The combination of macro-level and household-level data in the MIRAGRODEP model is an interesting methodological development in comparison to studies based on national averages of dietary intake, as it allows not only for assessing the cost-effectiveness of interventions but could also better capture the distributional effects of investments across heterogeneous households based on their specific socio-economic characteristics, which are largely omitted in most analyses. Also, only a few models explicitly include the investments necessary to create enabling environments for achieving SDG 2; admittedly, these are relatively difficult to present in monetary terms.

Last but not least, the financing strategy with respect to the pacing of investments, allocation of financial resources between competing objectives, distribution of the burden of investment between various financing sources, and the sustainability of results beyond 2030, especially in the context of large economic, climatic or political shocks, is rarely considered in detail in the reviewed frameworks. In particular, the issue of how to spread investments over time is not discussed in much detail in any of the models; instead, the costing estimates are presented in terms of annual averages. However, this has serious implications not only for the resource mobilization strategy and therefore the feasibility of timely investments, but can also affect the economy-wide outcomes of the intervention.

Another question is how to allocate limited financial resources between the various SDGs and the development targets specific to SDG 2. Of course, the case for investing in zero hunger target is evident, as the right to food is considered to be among the most basic of human rights. However, in the context of scarce financial resources, the potential synergies between different objectives, as in the case of eradicating hunger (SDG 2) and poverty (SDG 1), need to be found. Also, potential conflicts, for example between doubling agricultural productivity (SDG 2.3) while preserving the natural environment (Sachs et al. 2019), e.g. ensuring sustainable food production systems (SDG 2.4), need to be addressed to make the proposed investment strategies efficient. Additionally, the long-term sustainability of the proposed investment frameworks are rarely explicitly addressed. The time horizon of the models ends in 2030, aside from the 'Investment Framework for Nutrition' which ends in 2025 (Shekar et al. 2017). The latter is the only one to include a 5-year maintenance period (2021–2025); in general, however, the question of how to sustain the results beyond 2030 is not discussed. In the broader frameworks, like the 'Achieving Zero Hunger' or MIRAGRODEP frameworks, the implicit assumption is that pro-poor investments in agriculture and their expected long-term economy-wide growth effects will be sufficient to maintain zero or 5% hunger levels worldwide. While this might hold if the proposed frameworks' scenarios hold, the reduction in hunger might be reversed in the case of major economic, climate or political shocks, as the last decade has proven (FAO 2018). Only the IMPACT model-based study includes the effects of climate change in its modelling framework (Rosegrant et al. 2017); and none of the models discuss the challenges of achieving zero hunger in fragile states, i.e. conflict and post-conflict states.

3 Overview of Approaches to Reducing Hunger

Despite continued global agricultural output growth and considerable reduction in hunger since the 1960s, food insecurity still persists, albeit with huge differences between countries, within countries and even households (FAO et al. 2015). The nature of food insecurity has been also changing as increasing demand for processed food and consequently higher consumption of unhealthy fats, sugars and salts are exacerbating obesity and micronutrient deficiency (Barrett 2021). Thus, interventions focused on agricultural productivity improvement alone will not be enough to achieve the goal of sustainable food security. Achieving global food security would require not only improvements along food supply chains but also additional efforts in health, education, information and research systems. A sustainable development of the food system should go along with ensuring food and nutrition security and without compromising the social, economic and environmental futures for the generations to come (HLPE 2014). This study looks within and beyond agricultural system to identify the intervention options and investments needed to alleviate hunger or undernourishment.[4] Performing food systems analysis considering multiple interventions entails an assessment of the relevant processes that influence the four dimensions of food security food availability, access, utilization and stability.[5] Food availability emphasizes the need to address the supply side of food security to ensure sufficient quantities of food is available to individuals either through food production or imports. Food access on the other hand points to the importance of ensuring individuals have the resources necessary to obtain sufficient quantities of food. Going beyond availability and access to food, food utilization focuses on dietary quality and highlights the importance of ensuring individual's ability to utilize the energy and nutrients in the food they consume. Food stability reflects the stability of the three dimensions and reminds us of the importance of taking into consideration seasonal or temporary food prices and shocks in hunger prevention policies.

Food security can be enhanced through multiple investment options that intensify agricultural production and improve agricultural productivity. For instance, agricultural R&D and extension efforts to enhance crop and livestock production can boost food supply. Innovations in improved crop varieties, methods to improve soil fertility, and efficient irrigation technologies can also increase agricultural productivity and address food availability. The resulting increase in agricultural productivity further contributes to increased agricultural income, improved purchasing power and reduced food prices, which when combined with innovations in post-harvest technologies can improve access to food, increase calorie consumption, increase dietary diversity, and thus enhance food accessibility and utilization.

Market platform and infrastructure improvements help in reducing post-harvest losses and enhance access to food. Improved storage systems, better roads, availability of food processing, and equitable food distribution systems can greatly improve access to food by consumers. Trade rules at the international and intranational level also greatly impact on food access. Some infrastructural improvements such as electricity access and information and communication technologies (ICTs) can improve food supply, distribution and access systems. For example, using mobile phones, farmers can access information about the weather and market conditions, allowing them to better manage water resources and fetch higher prices for their produce. ICT and storage systems are also important to plan and predict food supplies and hence, stabilize food market prices. At the same time,

[4]This study uses the prevalence of undernourishment (PoU) as the main indicator for hunger. The PoU identifies the proportion of the population whose habitual, daily, per capita dietary energy consumption (DEC) level is lower than their dietary energy requirement (Cafiero and Gennari 2011). It is computed from aggregated country-level data on food availability that is annually compiled in FAO's Food Balance Sheets and data on food consumption from surveys which is available for certain countries.

[5]Future work on estimating the cost of ending hunger could further consider interventions that can address the two additional dimension "agency" and "sustainability" that have become crucial for transforming food systems towards the direction needed to meet the SDGs (HLPE 2020)

interventions that can enhance the incomes and purchasing capacity of the population can improve food affordability, which is an important aspect of food access. For some marginalized groups with inadequate income and informal jobs, social security programmes such as food vouchers and financial assistance can be considered.

Severe cases of child malnutrition, caused by nutrient insufficiency and certain diseases, require nutrition-specific interventions. According to Bhutta et al. (2013), at least 20.3% of the current child stunting rate could be averted if ten evidence-based nutrition-specific interventions were scaled up to cover 90% of the population in countries with high stunting burden. These interventions include periconceptional folic acid supplementation or fortification, maternal balanced energy protein supplementation, maternal calcium supplementation, multiple micronutrient supplementation in pregnancy, promotion of breastfeeding, appropriate complementary feeding, vitamin A and preventive zinc supplementation in children aged 6–-59 months, management of severe acute malnutrition, and management of moderate acute malnutrition.

The quality of maternal- and child-care practices is also one of the non-nutritional factors that affect the nutritional outcomes of children (Smith and Haddad 2015). Women play a key role in children's nutritional outcome as they give birth to them, breastfeed them and are their primary caretakers. Hence, maternal education has numerous positive impacts on the quality of maternal care that mothers receive during and after pregnancy and consequently on the quality of care that their children receive, ranging from the amount of breastfeeding to seeking health care in case of illnesses (Ruel et al. 2013). The strong link between female education and nutritional outcomes of children, particularly for stunting, has been well established (Headey 2013; Smith and Haddad 2015). The specific intervention options considered in this study are described in the next section.

4 Marginal Abatement Cost Curve Approach and Investment Scenario Assumptions

4.1 The Marginal Cost Curve and Key Steps of the Process

Policymakers need to prioritize the allocation of resources to competing hunger reduction measures by identifying the sets of least-cost investment options that have the potential to yield the greatest reduction in hunger in a defined time horizon. It is therefore essential that policymakers and practitioners can compare the different hunger reduction measures and make economically efficient investment decisions. In this regard, MACCs can be helpful as a policy tool in ranking investments options. Applications of MACCs are common in the economic assessment of climate change mitigation options (Schneider et al. 2007; Kesicki and Ekins 2012; Bockel et al. 2012; IPCC 2014; Eory et al. 2018) and have been also extended into the assessment of effective water policies (Addams et al. 2009). This study implements MACC approach in hunger reduction research. By developing a realistic and policy-relevant global MACC of different hunger reduction measures, the study allows to assess their cost-effectiveness and contributes to the evaluation of actions that should be prioritized and implemented to achieve target 2.1 of SDG 2 by 2030.

MACCs are developed based on either modelling outcomes or multiple expert opinions (Kesicki 2013). MACCs derived from top-down modelling provides internally consistent estimations, follows to smooth and continuous dynamics but do not account for the effects of specific interventions (Klepper and Peterson 2006). Expert based MACCs, despite being criticized for double counting and interaction possibility, are richer in terms of reflecting technology details as they are constructed by summarizing and synthesizing the average costs and abatement effects of multiple interventions. As our assessments are based on the cost and hunger reduction effects of multiple interventions from multiple studies, the framework of expert-based MACC is relevant here.

The global hunger reduction MACC represents the relationship between the cost-effectiveness of different hunger reduction interventions and the hunger reduction potential of each intervention. It reflects the additional costs of lifting people out of hunger by each intervention. Elaboration of the MACC were conducted step-by-step, by first identifying the variety of intervention options that can effectively reduce hunger, and then by determining the cost and hunger reduction potential of the interventions. The related assessment is conducted through a literature review and an integrated evaluation of model-based, econometric or cost-benefit analysis studies. While the cost and hunger reduction potential (number of people lifted out of hunger) were readily found in the literature for some of the interventions, additional calculations or assumptions based on expert assessments were considered for others. Particularly, hunger reduction potential was derived through additional calculations considering conversion factors and elasticity coefficients when food security enhancement effects such as additional food supply, income, or prevented levels of undernourishment due to the interventions are available. The cost of implementing some interventions were also estimated considering the prices of food, costs of social protection, or transaction costs of trade (details of these calculations and assumptions behind are provided in the Supplementary Material of the original publication). Finally, the interventions are ranked from the cheapest to most expensive, based on their marginal costs (average cost of lifting an individual out of hunger) to represent the cost of achieving incremental levels of hunger reduction.

4.2 Reference Scenarios of Hunger Trend and Investment Options

In a MACC based economic assessment of investment options, reference scenarios are built either based on a "business as usual" scenario, using historical trends to identify future developments, or based on alternative scenarios that consider climate

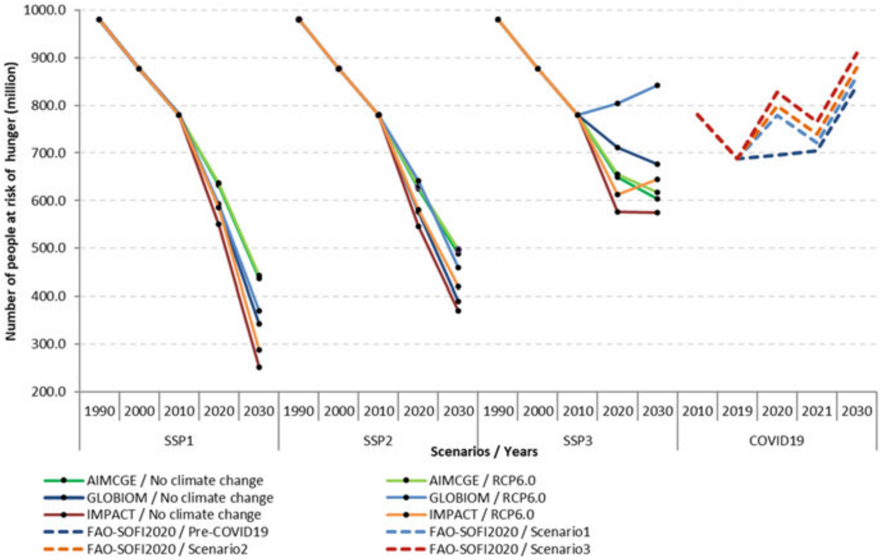


Fig. 1 Hunger levels expected under various socio-economic and climate change scenarios. (Source: Authors' own elaboration based on Hasegawa et al. (2018) and FAO et al. (2020))

change impacts and socio-economic developments of the future. Model-based foresight exercises highlight how food and agricultural systems could evolve in an inherently uncertain future. These foresight exercises provide alternative scenarios on food security in which challenges are addressed to varying degrees, building on historical trends of factors that determine the performance of socio-economic and environmental systems. According to the bio-economic model-based assessments of AIM/CGE, GLOBIOM and IMPACT, under various climatic and socio-economic development scenarios the world will be home to between 251 to 842 million undernourished people in 2030 (Fig. 1; Hasegawa et al. 2018). If population growth were to be largely controlled, high economic growth rates (SSP1) were maintained and climate change effects were neglected (dark green, blue and brown lines in the first bunch of the lines), the number of undernourished people would be reduced to between 251 to 437 million. Yet, when climate change (RCP6.0) is considered in the modelling assessments the number of undernourished people is expected to be between 288 and 443 million (light green, blue and orange lines in the first bunch of the lines). Under the worst scenario, with high population growth, economic stagnation, high-income inequality (SSP3), and a climate change impact (RCP6.0), the number of undernourished people is expected to be between 617 and 842 million (light green, blue and orange lines in the third bunch of the lines). All three modelling assessments indicate similar trends of hunger reduction under various socio-economic and environmental changes. Yet, the magnitude of the reduction differs across the modelling assessments.

The worst scenarios of the projected number of undernourished people in 2030 lie close to the projection presented in the recent report of the state of food security and nutrition in the world without considering the impact of the COVID-19 pandemic, i.e. about 840 million (Fig. 1; FAO et al. 2020). The pandemic is expected to further accelerate the projected increase in the number of people facing hunger, at least in the immediate future. As the global economy contracts due to containment measures of COVID-19, it is anticipated that hunger will also increase globally, hampering the progress of global efforts geared towards achieving the SDG 2 targets. A 4.9 to 10% decline in global GDP growth is estimated to lead to an additional 100 to 194 million people into hunger globally in 2020 and 2021. In the worst-case scenario, the pandemic could potentially increase the number of undernourished people to 909 million by 2030 (FAO et al. 2020).

In the MACC analysis, the reference scenarios of hunger trends presented above serve in determining the number of the undernourished people that would need to be lifted out of hunger to achieve target 2.1 of SDG 2 by 2030 and hence the investments required to reach the target. In this study, the projection that consider the impact of COVID-19 is used as the reference scenario for the population at risk of hunger in 2030, since it is the recent authoritative foresight study on hunger that considers the impact of the pandemic on hunger.

The cost and hunger reduction potential of the various investment options considered in this study are also analyzed relative to a “business as usual” or reference scenario of investments, wherein the costs of investments are assumed to remain frozen or grow following historical trends. The costs in the reference scenario include all investments required to achieve the projected level of implementation of the intervention options by 2030, including the capital, operational, and programme costs where applicable. For instance, the IMPACT model-based projection, from the study by Rosegrant et al. (2017), is used as a reference scenario for the interventions such as agricultural R&D, water resource management, and infrastructure. Rosegrant et al. (2017) used IFPRI’s IMPACT model together with a global computable general equilibrium model (GLOBE) and several linked post-solution models to evaluate investment requirements, land-use changes, greenhouse gas (GHG) emissions, biodiversity, water quality, and micronutrient availability and dietary diversity under the business as usual scenario. In addition to the climate change assumptions, Rosegrant et al. (2017) consider investment in agricultural R&D, water resource management, and infrastructure under the business as usual scenario. The projections of these investments under the business as usual scenarios are based on historical trends and expert opinions of long-term developments in the agricultural sector. Investments in water resource management are modelled endogenously combining the IMPACT model with a suite of water models. Similarly, all investment options considered in this study are compared to a reference scenario to identify the incremental cost of implementing the investments.

4.3 Opportunities of Investments in Policies and Programs for Hunger Reduction

For estimating hunger reduction potential, 22 interventions were selected based on the framework described in Sect. 3. Details of these interventions and overview of data and approaches used in calculating their hunger reduction potential and implementation costs are presented briefly in Table 2 to make all of the assumptions transparent. This would address the common critique, inherent in MACC, of a lack of transparency. Twelve of the twenty-two interventions are related to interventions for enhancing crop yields at farm levels through improved technologies, extension services, crop protection measures, soil fertility management and irrigation development. Five of the interventions are related to improved ICT, infrastructure and trade that improve food distribution efficiency. Three of the interventions consider supporting marginal groups of society increasing access on food. The last two interventions serve to reducing child malnutrition through enhanced child and maternal care. The details of the calculations to estimate the hunger reduction potential and costs of the interventions are presented further in the Supplementary Material of the original publication.

4.4 Investments to Reduce Hunger: Marginal Cost Curve Results

After ranking the considered interventions in accordance with their average cost per undernourished, a MACC of hunger reduction potential was elaborated (Fig. 2). Specific parameters of MACC such as the width (number of people lifted out of hunger) and length (annual cost per individual lifted out of hunger) of each bar (intervention) and additional indicators such as cumulative costs and cumulative hunger reduction potentials are provided in Table 3. According to the estimation, overall, the measures included in the MACC have the potential to lift over a billion people out of hunger over ten years between 2020 and 2030. To meet the G7 commitment of lifting 500 million people out of hunger by 2030, an average annual investment ranging between about US$ 11 to 14 billion will be required.[6] This would be achieved through a mix of least-cost intervention options –agricultural R&D efficiency enhancement, agricultural extension services, agricultural R&D, ICT – agricultural information services, small-scale irrigation expansion in Africa, female literacy improvements, and scaling up existing social protection. Following the 2030 hunger projection by FAO et al. (2020) and taking the preliminary estimates on the impact of COVID-19 on hunger (based on the less pessimistic

[6] As can be seen from Fig. 2, the per capita cost estimate of lifting 500 million people out of hunger is within range of the prior estimates by Torero and von Braun (2015) and Laborde et al. (2016) that vary between US$ 30 to 38 per person lifted out of hunger.

Table 2 Investment options for hunger reduction and investment scenarios assumptions

	Interventions	Sources	Modelling Framework	Calculations and assumptions
1	Agricultural R&D	Rosegrant et al. 2017	IMPACT 3 modelling suite	This option considers the hunger reduction potential of increased investments in the CGIAR plus increased complementary investments in national agricultural research systems (NARS), where US$ 1.97 billion and US$ 0.99 billion per year are invested by the CGIAR and NARS respectively.
2	Agricultural R&D efficiency enhancement	Rosegrant et al. 2017	IMPACT 3 modelling suite	This option considers the hunger reduction potential of higher CGIAR agricultural R&D efficiency so that the yield impact of investments is 30% higher. Agricultural R&D efficiency enhancement scenario is assumed to cost 30% of the annual average incremental investment in agricultural R&D with a total of US$ 0.89 billion.
3	Agricultural extension services	FAO et al. 2019; Ragasa & Mazunda 2018; Ecker & Qaim 2011; Blum and Szonyi 2014; World Bank 2020a	Econometric model	Hunger reduction potential of increased investment in extension service is estimated for 38 low and lower-middle-income countries using the methodological note for calculating PoU (FAO et al. 2019) and the impact of extension services on Dietary Energy Supply (DES). The DES is estimated based on Ragasa and Mazunda's study (2018) that shows 36% increase in value of farm production due to the extension services, and Ecker and Qaim (2011) that indicates the elasticity of DES to income to be 0.66. Based on Blum and Szonyi (2014), the implementation cost is assumed to be 1% of the 38 low and lower-middle-income countries GDP in 2019 (based on WDI in 2019 (World Bank 2020a)).
4	Irrigation expansion – Large-scale irrigation expansion	Rosegrant et al. 2017	IMPACT 3 modelling suite	This option reflects the hunger reduction potential of large-scale irrigation expansion in developing countries by 2030, with projected irrigated area expansion of 20 million hectares by transforming rainfed areas.

5	Irrigation efficiency enhancement	Rosegrant et al. 2017	IMPACT 3 modelling suite	This measure considers the hunger reduction potential of a 15 percentage increase in basin efficiency by 2030 due to increased water infrastructure investment and water management improvement in food production units.
6	Irrigation expansion – Small scale irrigation expansion in Africa	FAO 2020; You et al. 2011; Passarelli et al. 2018; Ecker & Qaim 2011	Econometric model	Hunger reduction potential of increased investment in small-scale irrigation expansion in Africa is estimated using the methodological note for calculating PoU (FAO 2020) and the impact of the expansion on DES. The DES is estimated based on Passarelli et al. (2018) that finds 2.5 times increase in agricultural income, and Ecker and Qaim (2011) that indicate an elasticity of DES to income of 0.66. The total annual cost of the expansion is assumed to be US$ 3.8 billion per year based on the estimate by You et al. (2011).
7	Soil-water management	Rosegrant et al. 2017	IMPACT 3 modelling suite	This measure considers the hunger reduction potential of water availability enhancement technologies such as no-till agriculture and water harvesting with an investment of about US$ 4.6 billion annually.
8	Crop protection – insects	Rosegrant et al. 2014	Decision Support System for Agrotechnology Transfer (DSSAT) crop model and IMPACT 2 modelling suite	This measure simulates hunger reduction potential of investments that promote the adoption of crop protection technologies for insects. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 50 per ha cost.
9	Crop protection – diseases	Rosegrant et al. 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger reduction potential of investments that promote the adoption of crop protection technologies for diseases. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 40 per ha cost.
10	Crop protection – weeds	Rosegrant et al. 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger reduction potential of investments that promote the adoption of crop protection technologies for weeds. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 60 per ha cost.

(continued)

Table 2 (continued)

	Interventions	Sources	Modelling Framework	Calculations and assumptions
11	Nitrogen-use efficiency	Rosegrant et al. 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger reduction potential of investments that promote the adoption of agricultural management practices and improved crop varieties to enhance crop nitrogen-use efficiency. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 500 per ha cost.
12	Integrated soil fertility management	Rosegrant et al. 2014	DSSAT model and IMPACT 2 modelling suite	This measure simulates hunger reduction potential of investments that promote the adoption of integrated soil fertility management. To calculate the cost, we assume the technology is implemented on 175 Mha with US$ 100 per ha cost.
13	ICT – Agricultural information services	Hoddinott et al. 2013; FAO et al. 2019	Econometric model and cost-benefit analysis	Hunger reduction potential of improved access to market information through ICT is estimated by extending Hoddinott et al. (2013); poverty reduction assessments in six countries were extrapolated to cover 69 low and lower-middle income countries. The estimated poverty reduction levels are then converted into the corresponding hunger reduction levels using an estimated equivalence coefficient of 0.68 (FAO et al. 2019).
14	Infrastructure (Road, Rail, Electricity)	Rosegrant et al. 2017	IMPACT 3 modelling suite	This option simulates the hunger reduction potential of a mix of infrastructure improvements in developing countries, focusing primarily on improvements to transportation infrastructure (road building, road maintenance, and railroads) and increased rural electrification.
15	Food loss reduction along the value chain	Rosegrant et al. 2015	IMPACT 2 modelling suite	The hunger reduction potential of increased investments in post-harvest reduction is estimated assuming a scenario where a 10% reduction in the post-harvest loss is maintained globally by 2030 through increased investments in infrastructure.

16	International trade – Completing the Doha Development Agenda (DDA)	Anderson 2018; FAO et al. 2019	Cost-benefit analysis	Hunger reduction potential of enhancing international trade is estimated converting Anderson's (2018) poverty reduction estimate of about 160 million using an estimated equivalence coefficient of 0.68 (FAO et al. 2019). Following Anderson (2018), 5% of the estimated annual benefit in 2025 is assumed to be the adjustment cost of the trade reform for the period of ten years, amounting to an annual total investment of US$ 30 billion.
17	Intra-African trade – African continental Free Trade Area (AfCFTA) agreement	World Bank 2020b; FAO et al. 2019; Anderson 2018	Global dynamic CGE model and cost-benefit analysis	Hunger reduction potential of AfCFTA is estimated converting World Bank's (2020b) poverty reduction estimate of 30 million by 2035. The poverty reduction by 2030 is first calculated using linear interpolation and converted into hunger reduction using an estimated equivalence coefficient of 0.68 (FAO et al. 2019). To estimate the implementation cost of AfCFTA, we follow Anderson (2018) in assuming 5% of the economic gains from the continental free trade agreement estimated to be US$ 450 billion by 2035 in the study by World Bank (2020b) over a ten-year period. Then, the adjustment cost of the trade reform is then assumed to be US$ 2.25 billion per year.
18	Social protection – Scaling up existing programmes	FAO et al. 2020; Hidrobo et al. 2018; reviewed papers in Table A2	Cost-effectiveness analysis	Based on a review of cost-effectiveness studies of social protection programmes across different countries, the minimum per dollar cash transfer cost of per capita is identified at US$ 35.7 and used to calculate the annual per capita cost of scaling existing programmes. Based on the review of the current coverage of social protection programmes, we estimated that about 103.1 million people could be targeted.
19	Social protection – Establishing new programmes	FAO et al. 2020; Hidrobo et al. 2018; reviewed papers in Table A2	Cost-effectiveness analysis	Based on a review of cost-effectiveness studies of social protection programmes across different countries, the maximum per dollar cash transfer cost per capita is identified at US$ 88.9 and used to calculate the annual per capita cost of establishing new programmes. Based on the review of the current coverage of social protection programmes, we estimated that about 103.1 million people could be targeted.

(continued)

Table 2 (continued)

	Interventions	Sources	Modelling Framework	Calculations and assumptions
20	COVID-19 – Social protection	FAO et al. 2020; Hidrobo et al. 2018; reviewed papers in Table A2	Econometric model estimates-based simulation and cost-effectiveness analysis	Following the less pessimistic COVID-19 impact scenario estimated by FAO et al. (2020) and based on the reviews of cost-effectiveness studies of social protection programmes across different countries, the maximum per dollar cash transfer cost per capita is identified at US$ 88.9. This is further used to calculate the annual per capita cost of social protection coverage for individuals that would fall into hunger due to COVID-19. Based on the less pessimistic scenario of COVID-19 impact on hunger estimated by FAO et al. (2020), we estimated that about 137.9 million people could be targeted.
21	Nutrition program	Shekar et al. 2017	Lives Saved Tool (LiST) for nutritional outcomes	This option considers increased investment in scaling up 7 nutrition-specific interventions to 90% coverage in 37 countries that account for 90% of the stunted children globally to reduce stunting among children below five years of age. The estimated stunting reduction levels are then converted into the corresponding hunger reduction levels using an estimated equivalence coefficient of 0.997.
22	Female literacy improvement	Smith & Haddad 2015; Shekar et al. 2017; World Bank 2020a	Econometric model and cost-effectiveness analysis	Stunting reduction potential of investment in women's education is estimated using Smith and Haddad's (2015) elasticity of stunting to female secondary school enrolment (−0.166) for 37 countries that account for 90% of the stunted children globally. It is also assumed that the female secondary enrolment rate between 2011 and 2015 is maintained over the next ten years, which is about 6.66 million additional female students enrolled at a per capita cost of US$ 130. The estimated stunting reduction levels are then converted into the corresponding hunger reduction using an estimated equivalence coefficient of 0.997.

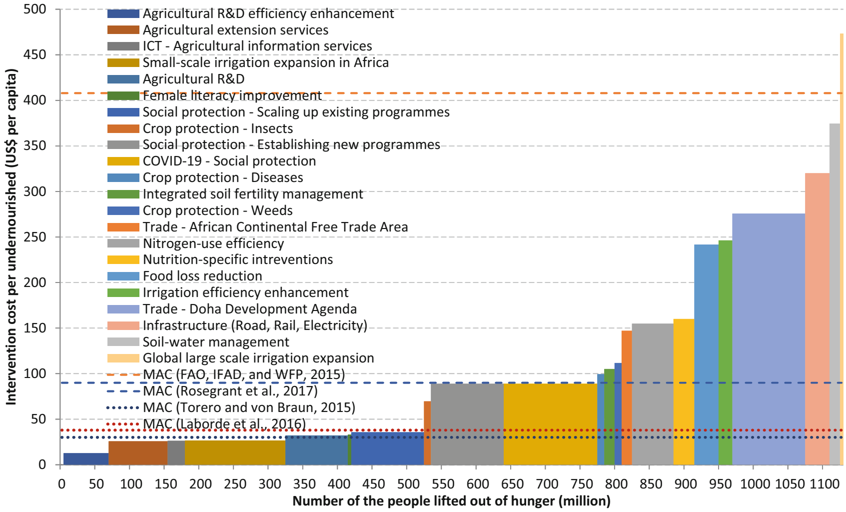


Fig. 2 Marginal cost curve of the suggested interventions to eradicate hunger
Note: The MACC for hunger shows the cost of each hunger reduction measure such that each bar represents a single intervention where the width shows the number of individuals lifted out of hunger, the height its associated annual per capita cost, and the area its associated total annual cost. The total width of the MACC reflects the total hunger reduction possible from all interventions, while the sum of the areas of all of the bars represents the total annual cost of reducing hunger through the implementation of all interventions considered. The positions of the bars along the MACC reflect the order of each intervention by their cost-effectiveness based on the annual per capita costs. When moving along the MACC from left to right, the cost-effectiveness of the interventions worsens as each next intervention becomes more expensive than the preceding. It is important to note that this figure is subject to considerable uncertainty given various assumptions made in the calculation, missed synergies and potential overlap between interventions and impact of extreme events not considered when estimating the costs

scenario) into consideration, the global goal of ending hunger by 2030 may require an investment of about US$ 39 to 50 billion to lift about 840 to 909 million people out of hunger.

As illustrated in Fig. 2, investing in agricultural R&D efficiency enhancement, agricultural extension services, ‘ICT – Agricultural information systems’, are low cost options that have a relatively large hunger reduction potential. Scaling up existing social protection programmes and establishing new programmes to serve food insecure households can reduce the number of people at risk of hunger by about 206.2 million at an annual per capita cost of about US$ 35.7 and US$ 88.9 per undernourished. To address the potential increase in the number of people at risk of hunger estimated in 2020 and 2021 of about 137.9 million, an additional US$ 12.3 billion will need to be spent in social protection. While investing in women’s education also provides a least-cost option to reduce hunger, investment in

Table 3 Hunger reduction potential of interventions and cost of implementation from 2020 to 2030

Least-cost Rank	Interventions	Number of people lifted out of hunger (Million)	Cumulative number of people lifted out of hunger (Million)	Annual cost (US $ Million)	Cumulative amount of annual cost (US$ Million)	Annual cost per individual lifted out of hunger (US $)	Total cost per person lifted out of hunger (US$) over 2020–2030
1	Agricultural R&D efficiency enhancement	69.9	69.9	888	888	12.7	98
2	Agricultural extension services	81.5	151.4	2096	2984	25.7	199
3	ICT – Agricultural information services	26.6	178.0	698	3682	26.2	114
4	Small-scale irrigation expansion in Africa	142.3	320.3	3790	7472	26.6	206
5	Agricultural R&D	92.0	412.3	2960	10,432	32.2	249
6	Female literacy improvement	2.6	414.9	87	10,518	33.1	261
7	Social protection – Scaling up existing programmes	103.1	518.0	3677	14,195	35.7	154
8	Crop protection – Insects	10.1	528.0	700	14,895	69.7	536
9	Social protection – Establishing new programmes	103.1	631.1	9158	24,053	88.9	385
10	COVID-19 – Social protection	137.9	769.0	12,255	36,308	88.9	165
11	Crop protection – Diseases	8.8	777.8	875	37,183	99.4	768

12	Integrated soil fertility management	16.6	794.4	1750	38,933	105.1	814
13	Crop protection – Weeds	9.4	803.8	1050	39,983	111.7	863
14	Trade – African Continental Free Trade Area (AfCFTA)	15.3	819.1	2250	42,233	147.1	1136
15	Nitrogen-use efficiency	56.5	875.6	8750	50,983	154.9	1196
16	Nutrition-specific interventions	30.9	906.6	4950	55,933	160.0	1237
17	Food loss reduction	36.0	942.6	8580	64,513	241.7	1841
18	Irrigation efficiency enhancement	18.6	961.2	4590	69,103	246.3	1906
19	Trade – Doha Development Agenda	108.8	1070.0	30,000	99,103	275.7	2129
20	Infrastructure (Road, Rail, Electricity)	33.8	1103.8	10,810	109,913	320.0	2470
21	Soil-water management	12.2	1116.0	4580	114,493	374.5	2899
22	Irrigation expansion – Global large-scale irrigation expansion	7.6	1123.6	3520	118,013	473.4	3577

Note: Number of people lifted out of hunger and annual cost of each intervention are compiled and computed based on the studies and assumptions presented in Table 2. For each intervention, the number of people lifted out of hunger by the proposed investments is calculated as the difference between the projected number of hungry people in the business as usual 2030 scenario and the projected number of hungry people in the 2030 investment scenario. The annual cost per individual lifted out of hunger is then calculated as the annual cost divided by the number of people lifted out of hunger. The cumulative figures for the number of people lifted out of hunger and annual costs across the interventions reflect the total hunger reduction possible from all interventions and the total annual investments required. Total cost per person lifted out of hunger is calculated as total net discounted cost over the ten-year period (with the exception of COVID-19 social protection, ICT and scaling new and existing social protection programmes where the time frame is 2–5 years respectively, i.e. 2020–2021 and 2020–2024). The discount rate is assumed to be 5%, following Hoddinott, et al. (2013). The total cost per person lifted out of hunger is then calculated as the total net discounted cost divided by the number of people lifted out of hunger nutrition-specific investments can significantly reduce hunger by about 30 million at a total incremental average cost of about US$ 5 billion per year.

Investments in ‘African Continental Free Trade Area (AfCFTA) agreement’, ‘Food loss and waste reduction’, ‘Irrigation efficiency enhancement’, improvements in international trade (completion of the DDA), ‘Infrastructure’, ‘Soil-water management’, and ‘Large-scale irrigation expansion’ can considerably decrease undernourishment by about 232.2 million. These hunger reduction measures are relatively expensive investment options that require a longer time for implementation and hence would need to be frontloaded earlier in the decade to have a large effect soon before 2030.

It is also important to note that the marginal cost curve elements include many investments that contribute to long-term development and sustainability, beyond 2030 and not restricted to hunger reduction. For instance, investments in agricultural R&D and research efficiency, irrigation expansion and water use efficiency, soil water management and infrastructure all have a long-term impact going further to 2050 and also have much broader development impacts beyond the reduction of hunger, like poverty, child malnutrition, and the environment (Rosegrant et al. 2017). The composition of the investments facilitates an increase in resilience for populations affected by hunger today or at risk of hunger in this decade. Since it is beyond the scope of this study, such lagged benefits of investments and their impact on other development outcomes beyond hunger has not been considered in this study and hence the estimates presented might understate the full benefits of these investments.

5 Uncertainties and Caveats of the Assessment

5.1 Uncertainties Associated with Data and Assumptions

The developed MACC of hunger reduction can considerably contribute to debates over the prioritization of efforts and allocation of investments to achieve the global goal of ending hunger. However, it is important to note that the cost assessments and rankings of the interventions are subject to various levels of uncertainties due to various assumptions made in the calculations. Thus, these estimates should be perceived as only the best possible estimations based on available data. Due to the limited availability of data for conducting a proper quantitative analysis of uncertainty, we here present a qualitative analysis of uncertainty (Table 4). This assessment is related to the description of calculation steps presented in Table 2. We further use narrative analysis of potential impacts of various uncertainties on the levels of costs and hunger reduction potential and shape of the MACC.

According to the assessments, despite the very low cost of ‘Agricultural R&D efficiency enhancement’, this cost level is subject to ‘high’ uncertainty and hunger reduction potential is subject to ‘moderate’ uncertainty (Table 4). The cost of ‘Agricultural extension services’ is characterized with ‘low’ uncertainty but its hunger reduction potential is characterized with ‘high’ uncertainty. Most of the

Table 4 Uncertainties of potentials and implementation costs of the hunger reduction interventions

Rank	Interventions	Uncertainties for number of people lifted out of hunger (Million)	Uncertainties for annual cost per individual lifted out of hunger (US$)
1	Agricultural R&D efficiency enhancement	++	+++
2	Agricultural extension services	+	+++
3	ICT – Agricultural information services	++	+
4	Small-scale irrigation expansion in Africa	+	+
5	Agricultural R&D	++	++
6	Female literacy improvement	+	+
7	Social protection – Scaling up existing programmes	++	+
8	Crop protection – Insects	++	+++
9	Social protection – Establishing new programmes	++	+
10	COVID-19 – Social protection	+++	+
11	Crop protection – Diseases	++	+++
12	Integrated soil fertility management	++	+++
13	Crop protection – Weeds	++	+++
14	Trade – African Continental Free Trade Area (AfCFTA)	+	+++
15	Nitrogen-use efficiency	++	+++
16	Nutrition-specific interventions	+	++
17	Food loss reduction	+++	++
18	Irrigation efficiency enhancement	++	++
19	Trade – Doha Development Agenda	+	+++
20	Infrastructure (Road, Rail, Electricity)	+++	++
21	Soil-water management	++	++
22	Irrigation expansion – Global large-scale irrigation expansion	++	++

Note: Levels of uncertainty are defined with "+" for 'low', "++" for 'moderate' and "+++" for 'high'. Evidence-based data estimated through econometric assessment or obtained from reliable statistical sources were considered with 'low' uncertainty. We assume 'moderate' uncertainty if the data was found out from simulation modelling studies or derived through additional calculations considering data with low uncertainty. 'High' uncertainty emerges in case value was obtained through additional calculations based on data with 'moderate uncertainty' or based on pure assumptions remaining interventions except 'Small-scale irrigation in Africa' and 'Female illiteracy improvement' are subject to 'moderate' or 'high' levels of uncertainty.

5.2 Missed Synergies, Overlaps and Other Investment Options

As each intervention in the MACC is considered independently with its marginal costs and hunger reduction effects, beneficial synergies among interventions are not captured. For instance, interventions such as constructing irrigation systems and implementation of ICT in water distribution systems may have additional synergetic benefits. Yet, the presented MACC indicates conservative estimates of mixes of interventions. Consequently, it is possible that the costs are overestimated and hunger reduction impacts are underestimated for such cases.

Some overlap or double counting may also exist between the considered interventions as there are likely a group of people who have already been lifted out of hunger through one policy yet may benefit from the second policy. It may occur for example in places where many people are quite near the threshold of undernourishment. This implies that a certain group of people could be counted multiple times and hunger reduction potential of the interventions might be overestimated. Also, in places where the gap between adequate and actual nourishment is high, a bundle of complementary interventions may be required to lift people out of hunger rather than a single policy (Banerjee et al. 2015; Barrett et al. 2020). Hence, there may be some undercounting in the event of bundled programs which could instead lead to an underestimation of the hunger reduction potential of interventions and overestimation of the costs. However, since the MACC is built based on an aggregated assessment of interventions at the global level, our study does not highlight such details. Further studies should differentiate hunger levels, their exact causes and precise solutions to address this issue. Bottom-up integrated assessment models may capture such synergies and reduce double counting consequently allowing for developing consistent MACCs.

Analyzing the hunger reduction potential and costs of the selected twenty-two options available from the recent studies, it is likely that we omitted other hunger reduction interventions where costs and hunger reduction potentials were either not available or not widely discussed in the literature. As an example, food production and harvesting in marine environments including the production and harvesting of seafood and seagrasses were excluded as the option was not widely assessed at the global level for hunger prevention. Likewise, alternative foods produced from insects and non-traditional food crops were not considered as their health safety and upscaling potential have not been properly examined. With more advances in the sciences, new interventions can come into the scene and they may change the shape of the MACC for hunger reduction.

5.3 The Impact of Extreme Events on the Cost of Hunger Reduction

Investment options reviewed in this study did not explicitly include climate change or the effects of extreme events like conflicts, pandemics and extreme weather events on hunger reduction. Even though it is understood that important drivers of acute food insecurity in 2020 were conflict, economic fallout of COVID-19, and extreme weather events. In 2020 an estimated 99 million people were in acute food insecurity because of conflict situations (Food Security Information Network & Global Network Against Food Crises 2021). This statistic may only be roughly compared with the statistic of undernourishment (768 million) as the two statistics are based on very different concepts.

In 2019, six out of ten people eligible for global humanitarian food assistance were residing in countries with ongoing conflicts (Development Initiatives 2020). Also, the share of children suffering from stunting residing in conflict zones has considerably increased within the last two decades (FAO et al. 2017). Conflicts directly and indirectly impact on food insecurity. For instance directly through resource loss when fields are rendered unusable due to mines, and indirectly through disruption of markets and trade. Barrett (2021) makes the argument that the hunger crises today and of the future are fundamentally humanitarian and conflict resolution issues rather than shortcomings with agri-food systems, and addressing hunger requires targeted humanitarian and conflict resolution efforts instead of agri-food innovations. While it is widely regarded that conflict resolution can have a profound impact on hunger reduction, estimating the cost, such as diplomatic and peace keeping engagements, and impacts on other interventions would be multifaceted and quite complex (Kemmerling et al. 2021), and hence was not considered in this study.

Studies reviewed in our analysis were conducted before the COVID-19 pandemic and did not consider the impacts of such an event or similar pandemics on the goal of hunger reduction and the cost to other interventions. Nonetheless, it is noteworthy that as a pandemic event like COVID-19 impacts all aspects of society and the economy it surely would have a considerable impact on the effort to achieving zero hunger before 2030, given that all the resources needed to achieve this goal would be directed towards the fight against the pandemic. This is especially true for financing, which is mainly from wealthy nations but immediately repurposed and prioritized for healthcare investments and economic stimulus for their citizenry, thus leaving the fight against hunger in peril, howbeit temporarily. The extent and impact of this temporary neglect due to the pandemic are not assessed in this study.

Climate change impacts not only hunger levels but also the costs and potential of the targeted hunger prevention interventions. Rising temperatures and consequent drought increases the value of water and reduce the efficiency of the projects related to irrigation improvement (IPCC 2019). Also, intensified flooding events induced by temperature rise destroys agricultural production systems as well as affect hydraulic infrastructure reducing the resilience capacity to cope with temperature anomalies and systems, exposing the farmers and rural community to hunger. Meanwhile, climate change mitigation efforts are increasingly and deservedly prioritized, but sometimes at the expense of the efforts to reduce hunger. For instance, available land likely to be used for solar power generating projects instead of agriculture, hydroelectric power dams are prioritized regardless of the impact on surrounding farms, and available public funds are allocated to climate change mitigation efforts limiting finance to hunger reduction programmes. In our study, these linkages and the extent of the impact on the interventions were not considered.

5.4 Effects of Scaling on Marginal Costs

As the marginal cost of each intervention is assumed to be fixed per undernourished person lifted out of hunger, the aggregated marginal cost curve appears like a staircase (step) function. Growing marginal cost in the aggregated marginal cost curve is due to the ranking of the individual interventions. In reality, increasing (not fixed) marginal costs of hunger reduction are expected for each intervention. Due to the scaling effects, it is not surprising that the additional cost of reducing the number of undernourished people increases with the number of undernourished people lifted out of hunger. Lifting the first group of people out of hunger requires less investment than the last group of hungry people since the cost of reaching the most vulnerable and hard to reach populations is a lot more than to reach those that are less in need of food assistance and support. Based on our data collected from the literature review of contributions and costs of various interventions, continuous aggregated MACC can be derived by replacing the staircase graph with the polygon graph (See Supplementary Material available in the original publication). The polygon-type graph can be fitted to obtain smoothly growing cost functions that are similar to the ones obtained through modelling. Combining interventions considering their varying marginal costs is an alternative option to assess aggregated MACC yet it may require top-down modelling application (Klepper and Peterson 2006). Such assessment would most likely change the shape of the aggregated MACC, having more people lifted out of hunger at a low price at the beginning but increasing the costs of interventions even further for the remaining groups of people who require food support the most.

5.5 Other Limitations and Some Strengths of the Marginal Cost Curve Approach

MACC can be used to identify promising policies and programmes for investment. This facilitates priority setting by governments and investment stakeholders from the private sector and civil society. An advantage of MACC analysis is also its transparency. However, the concept has several limitations which have been already highlighted in previous studies (Kesicki and Ekins 2012; Bockel et al. 2012; Eory et al. 2018). One of the limitations relates to the fact that the MACC presents the incremental cost of reducing hunger for a single point in time. Hence, it cannot capture intertemporal dynamics and technological inertia. Education and R&D investments for example yield gains after sometime. In a static MACC, lagged effects for such investments are not effectively captured in the MACC.[7] Another aspect is that the MACC concentrates on hunger reduction and thus attributes the entire cost of the interventions only to hunger reduction. This is an overestimation in terms of economic cost-benefit considerations, as most of the interventions considered in this analysis generate various ancillary benefits, including reducing poverty and enhancing health, environmental sustainability, and education. Nevertheless, the MACC can be considered useful for an assessment of various potential interventions to reduce hunger based on a synthesis of studies from different fields based on multiple methodologies.

Additional analysis – for example at regional or perhaps national levels – is also warranted for prioritizing the measures for implementation and setting policies to promote them. Additional studies could focus on extending the analysis by identifying additional cost-effective measures in specific country contexts which can further contribute to hunger reduction. Technical and behavioral challenges to implementing the identified least-cost measures need to be considered in the prioritization process, despite their economic attractiveness.

While most of the parameters used in building the global hunger MACC are compiled from system- and economy-wide model-based studies, the cost and hunger reduction potential of several interventions were assessed based on a specific and large-scale cost-effectiveness studies. A next step, in this respect would be to evaluate the various measures using bottom-up integrated assessment modelling that could capture synergies and trade-offs between the different measures, as well as risks and uncertainties. Theoretically, that would be an advantage, but it remains difficult to embed the level of granularity and programmatic detail in such modelling, as pursued with the 22 interventions considered in the MACC approach here. Yet, additional quantitative sensitivity analysis and interpretation of the different results would be helpful to policymakers to support their decision-making.

[7] However, Rosegrant et al. (2017) capture the lag effects of investments in agricultural R&D in the investment-yield estimation model using a perpetual inventory method, where investments in agricultural R&D contribute to the stock of knowledge over time. The lag structure in the perpetual inventory method used in the study followed a gamma distribution where the impact of R&D investments peaked after ten years from initial investment and then sunk to zero after ten years from its peak.

6 Policy Implications of MACC Analyses

This study has synthesized the findings of various model- and cost-benefit analysis-based studies on food and nutrition security interventions to assess the expected levels of the hunger reduction and the costs of achieving zero hunger by 2030. The most recent 'State of Food Security and Nutrition in the World' report estimated levels of undernourishment by 2030 to be about 630 million without considering the impact of COVID-19, or 660 million when considering the impact of COVID-19 on hunger.

MACC analyses are a basis for policy strategies and policy mobilization. The MACC for hunger reduction developed by synthesizing the outcomes of multiple studies indicates the overall potential of the interventions identify what it takes to end hunger by 2030. Considerable investment is required, but it is a question of political commitment to get the finance mobilized at national and global levels and the actual investments implemented in sound ways. Compared to the hundreds of billions of US$ for economic rescue packages to mitigate COVID-19 in many OECD countries, the investments to end hunger presented in this analysis are rather modest. The results from the MACC indicate that:

- Achieving target 2.1 of SDG 2 need not be prohibitively expensive, provided that a mix of least-cost measures with large hunger reduction potential are prioritized.
- Investments with long-term effects should be frontloaded in the decade to have a large effect soon before 2030.
- To end hunger by 2030, options that require high up-front investments but also have a high long-term impact need to be in the investment mix.
- Overall, the measures included in this MACC analysis have the potential to lift about a billion people out of hunger over ten years until 2030.

Yet, given the finding that investments to end hunger are rather modest, the troublesome question arises, what political economy forces prevent the required actions? Obviously, the spending priorities of those who could mobilize the resources seem not sufficiently oriented toward overcoming hunger, and the voice and influence of the undernourished seem too weak to enforce the investment action. Attempting to comprehensively answer this question goes beyond the scope of this paper. However, research into assessing the political economy for each of the considered interventions in the MACC might help to identify a set of politically acceptable second-best MACC elements that might differ from the marginal costs.

Acknowledgment This chapter was published in Food Policy, 104, October 2021. The supplementary material is also provided in the online version of this paper.

References

Addams L, Boccaletti G, Kerlin M, Stuchtey M (2009) Charting our water future: economic frameworks to inform decision-making. McKinsey & Company, New York. http://www.2030wrg.org/wp-content/uploads/2014/07/Charting-Our-Water-Future-Final.pdf

Anderson K (2018) Benefits and costs of the trade targets for the post-2015 development agenda. In: Lomborg B (ed) Prioritizing development: a cost benefit analysis of the United Nations' sustainable development goals. Cambridge University Press, pp 192–218. https://doi.org/10.1017/9781108233767.011

Banerjee A, Duflo E, Goldberg N, Karlan D, Osei R, Parienté W et al (2015) A multifaceted program causes lasting progress for the very poor: evidence from six countries. Science *348*(6236):1260799

Barrett C (2021) Overcoming global food security challenges through science and solidarity. Am J Agric Econ 103(2):422–447. https://doi.org/10.1111/ajae.12160

Barrett C, Benton T, Cooper K, Fanzo J, Gandhi R, Herrero M, James S, Kahn M, Mason-D'Croz D, Mathys A et al (2020) Bundling innovations to transform agri-food systems. Nat Sustain 3:974–976

Blum JM, Szonyi J (2014) Investment requirements in extension to achieve zero hunger and adapt to climate change. J Agric Sci Technol A 4:552–562. https://doi.org/10.17265/2161-6256/2014.07.002

Bockel L, Sutter P, Touchemoulin O, Jönsson M (2012) Using marginal abatement cost curves to realize the economic appraisal of climate smart agriculture policy options. FAO. http://www.fao.org/3/a-bq866e.pdf

Cafiero C, Gennari P (2011) The FAO indicator of the prevalence of undernourishment. FAO. http://www.fao.org/fileadmin/templates/ess/ess_test_folder/Workshops_Events/Food_Security_for_All_FEB2011/Background_paper.pdf

Development Initiatives (2020) Global humanitarian assistance report 2020. Development Initiatives, Bristol

Ecker O, Qaim M (2011) Analyzing nutritional impacts of policies: an empirical study for Malawi. World Dev *39*(3):412–428. https://doi.org/10.1016/j.worlddev.2010.08.002

Eory V, Pellerin S, Garcia GC, Lehtonen H, Licite I, Mattila H, Lund-Sørensen T, Muldowney J, Popluga D, Strandmark L, Schulte R (2018) Marginal abatement cost curves for agricultural climate policy: state-of-the art, lessons learnt and future potential. J Clean Prod *182*:705–716. https://doi.org/10.1016/j.jclepro.2018.01.252

Fan S, Headey DD, Laborde Debucquet D, Mason-D'Croz D, Rue C, Sulser TB, Wiebe KD (2018) Quantifying the cost and benefits of ending hunger and undernutrition: examining the differences among alternative approaches (IFPRI Issue Brief). IFPRI. https://doi.org/10.2499/9780896292994

FAO, IFAD, & WFP (2015) Achieving zero hunger: the critical role of investments in social protection and agriculture. FAO, Rome. http://www.fao.org/3/a-i4951e.pdf

FAO, IFAD, UNICEF, WFP, & WHO (2017) The state of food security and nutrition in the world 2017. Building resilience for peace and food security. Transforming food systems for affordable healthy diets. FAO, Rome

FAO, IFAD, UNICEF, WFP, & WHO (2019) The state of food security and nutrition in the world 2019. Safeguarding against economic slowdowns and downturns. FAO, Rome. http://www.fao.org/3/ca5162en/ca5162en.pdf

FAO, IFAD, UNICEF, WFP, & WHO (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. FAO, Rome. https://doi.org/10.4060/ca9692en

FAO, IFAD, UNICEF, WFP, & WHO (2021) The state of food security and nutrition in the world 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. FAO, Rome. https://doi.org/10.4060/cb4474en

FAO (2018) The future of food and agriculture – alternative pathways to 2050. FAO, Rome. http://www.fao.org/3/I8429EN/i8429en.pdf

FAO (2020) FAOSTAT statistical database. FAO, Rome. http://www.fao.org/faostat/en/
Fink G, Peet E, Danaei G, Andrews K, McCoy DC, Sudfeld CR et al (2016) Schooling and wage income losses due to early-childhood growth faltering in developing countries: national, regional, and global estimates. Am J Clin Nutr 104(1):104–112. https://doi.org/10.3945/ajcn.115.123968
Food Security Information Network (FSIN) and Global Network Against Food Crises (2021) Global report on food crises 2021. FSIN, Rome. http://https://www.fsinplatform.org/sites/default/files/resources/files/GRFC2021.pdf
Hasegawa T, Fujimori S, Havlík P, Valin H, Bodirsky BL, Doelman JC, Mason-D'Croz D (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang *8*(8):699–703. https://doi.org/10.1038/s41558-018-0230-x
Headey DD (2013) Developmental drivers of nutritional change: a cross-country analysis. World Dev 42:76–88. https://doi.org/10.1016/j.worlddev.2012.07.002
Headey D, Heidkamp R, Osendarp S, Ruel M, Scott N, Black R et al (2020) Impacts of COVID-19 on childhood malnutrition and nutrition-related mortality. Lancet 396:519–520. https://doi.org/10.1016/S0140-6736(20)31647-0
Hidrobo M, Hoddinott J, Kumar N, Olivier M (2018) Social protection, food security, and asset formation. World Dev 101:88–103. https://doi.org/10.1016/j.worlddev.2017.08.014
HLPE (2014) Food losses and waste in the context of sustainable food systems. A report by the high level panel of experts on food security and nutrition of the committee on world food security. FAO, Rome. http://www.fao.org/3/a-i3901e.pdf
HLPE (2020) Food security and nutrition: building a global narrative towards 2030. A report by the high level panel of experts on food security and nutrition of the committee on world food security. FAO, Rome. http://www.fao.org/3/ca9731en/ca9731en.pdf
Hoddinott J, Maluccio JA, Behrman JR, Flores R, Martorell R (2008) Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. Lancet *371*(9610):411–416. https://doi.org/10.1016/S0140-6736(08)60205-6
Hoddinott J, Rosegrant M, Torero M (2013) Hunger and malnutrition. In: Lomborg B (ed) Global problems, smart solutions: costs and benefits. Cambridge University Press, pp 332–389. https://assets.cambridge.org/97811070/39599/frontmatter/9781107039599_frontmatter.pdf
Horton S, Hoddinott J (2014) Benefits and costs of the food and nutrition targets for the post-2015 development agenda: post-2015 consensus. Food Security and Nutrition Perspective paper. Copenhagen Consensus Center. http://www.copenhagenconsensus.com/sites/default/files/food_security_and_nutrition_perspective_-_horton_hoddinott_0.pdf
Horton S, Steckel RH (2013) Malnutrition: global economic losses attributable to malnutrition 1900–2000 and projections to 2050. In: Lomborg B (ed) How much have global problems cost the world? A scorecard from 1900 to 2050. Cambridge University Press, pp 247–272. https://doi.org/10.1017/CBO9781139225793.010
Intergovernmental Panel on Climate Change (IPCC) (2014) Climate change 2014: mitigation of climate change. Working group iii contribution to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York
Intergovernmental Panel on Climate Change (IPCC) (2019) Special report on climate change and land: summary for policymakers. Geneva
Kemmerling B, Schetter C, Wirkus L (2021) Addressing food crises in violent conflicts: food systems summit brief prepared by research partners of the scientific group for the food systems summit. Center for Development Research, Bonn. https://hdl.handle.net/20.500.11811/9142
Kesicki F (2013) Marginal abatement cost curves: combining energy system modelling and decomposition analysis. Environ Model Assess 18(1):27–37
Kesicki F, Ekins P (2012) Marginal abatement cost curves: a call for caution. Clim Policy 12(2):219–236. https://doi.org/10.1080/14693062.2011.582347
Klepper G, Peterson S (2006) Marginal abatement cost curves in general equilibrium: the influence of world energy prices. Resour Energy Econ 28(1):1–23
Laborde D, Bizikova L, Lallemant T, Smaller C (2016) Ending hunger: what would it cost? International Institute for Sustainable Development (IISD) and IFPRI Briefing Note. IISD, Winnipeg. https://www.iisd.org/publications/ending-hunger-what-would-it-cost

Mason-D'Croz D, Sulser TB, Wiebe K, Rosegrant MW, Lowder SK, Nin-Pratt A et al (2019) Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. World Dev *116*:38–53. https://doi.org/10.1016/j.worlddev.2018.12.006

Passarelli S, Mekonnen D, Bryan E, Ringler C (2018) Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. Food Secur *10*(4):981–997. https://doi.org/10.1007/s12571-018-0812-5

Ragasa C, Mazunda J (2018) The impact of agricultural extension services in the context of a heavily subsidized input system: the case of Malawi. World Dev *105*:25–47. https://doi.org/10.1016/j.worlddev.2017.12.004

Rosegrant MW, Koo J, Cenacchi N, Ringler C, Robertson RD, Fisher M, Cox CM, Garrett K, Perez ND, Sabbagh P (2014) Food security in a world of natural resource scarcity: the role of agricultural technologies. IFPRI. https://www.ifpri.org/publication/food-security-world-natural-resource-scarcity-role-agricultural-technologies

Rosegrant MW, Magalhaes E, Valmonte-Santos R, Mason-D'Croz D (2015) Returns to investment in reducing postharvest food losses and increasing agricultural productivity growth: post-2015 consensus. Food Security and Nutrition Assessment Paper. Copenhagen Consensus Center. http://www.copenhagenconsensus.com/sites/default/files/food_security_nutrition_assessment_-_rosegrant_0.pdf

Rosegrant MW, Sulser TB, Mason-D'Croz D, Cenacchi N, Nin-Pratt A, Dunston S, ... Willaarts B (2017) Quantitative foresight modeling to inform the CGIAR research portfolio (Project Report for USAID). IFPRI. https://www.ifpri.org/publication/foresight-modeling-agricultural-research

Ruel MT, Alderman H, & Maternal and Child Nutrition Study Group (2013) Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? Lancet 382(9891): 536–551. https://doi.org/10.1016/S0140-6736(13)60843-0.

Sachs JD, Schmidt-Traub G, Messner D, Nakicenovic N, Rockström J (2019) Six transformations to achieve the sustainable development goals. Nat Sustain 2:805–814. https://doi.org/10.1038/s41893-019-0352-9

Schmidhuber J, Bruinsma J (2011) Investing towards a world free of hunger: lowering vulnerability and enhancing resilience. In: Prakash A (ed) Safeguarding food security in volatile global markets. FAO, Rome, pp 523–549. http://www.fao.org/3/i2107e/i2107e.pdf

Schneider UA, Mccarl BA, Schmid E (2007) Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agric Syst 94:128–140

Shekar M, Kakietek J, Eberwein JD, Walters D (2017) An investment framework for nutrition: reaching the global targets for stunting, anemia, breastfeeding, and wasting. Directions in Development. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1010-7

Smith LC, Haddad L (2015) Reducing child undernutrition: past drivers and priorities for the post-MDG era. World Dev 68:180–204. https://doi.org/10.1016/j.worlddev.2014.11.014

Torero M, von Braun J (2015 Toward a zero-hunger goal by 2030: some preliminary estimates of what it would cost. Mimeo

UNICEF, WHO, & World Bank (2020) Levels and trends in child malnutrition: key findings of the 2020 edition of the Joint Child Malnutrition Estimates. https://www.who.int/publications/i/item/jme-2020-edition

World Bank (2020a) World Development Indicators [Database]. The World Bank. https://databank.worldbank.org/source/world-development-indicators

World Bank (2020b) The African continental free trade area: economic and distributional effects. The World Bank. http://hdl.handle.net/10986/34139

You L, Ringler C, Wood-Sichra U, Robertson R, Wood S, Zhu T, Nelson G, Guo Z, Sun Y (2011) What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 36:770–782. https://doi.org/10.1016/j.foodpol.2011.09.001

Financing SDG2 and Ending Hunger

Eugenio Díaz-Bonilla

1 Introduction

The adequate functioning of food systems is crucial to achieving multiple Sustainable Development Goals (SDGs) by 2030 (von Braun et al. 2020b). This chapter focuses on financing the transformation of food systems to help achieve crucial components of SDG2,[1] including ending hunger by 2030. Given those objectives, the analysis centers mainly on agricultural production and rural development, as well as on poor and food-insecure consumers, both rural and urban, as part of the more general collection of issues around production and diets in food systems. Even with that focus, the interventions[2] considered have important implications for a variety of other nutritional and environmental objectives.

The chapter compares the additional costs of achieving SDG2, including zero hunger (as estimated by von Braun et al. 2020a and studies referenced therein), with potential financial sources. The estimates of potential funding use the framework in Díaz-Bonilla et al. (2021), which identifies two flows of funds "internal" to food systems (consumer food expenditures, which are the sales/revenues that the agents in the agri-food system use to finance their operations), and four that are "external" to food systems (international development flows, public budgets, banking systems, and capital markets) (Fig. 1).

[1] The focus is on ending hunger (2.1); doubling agricultural productivity and the incomes of small farmers (2.3); and fostering sustainability and resilience within food production (2.4). In the text, references to SDG2 must be understood in this vein.

[2] "Interventions" refer to public sector actions, including policies, programs, investments, expenditures, taxes and subsidies, laws and regulations, and institutional aspects, that seek to address a specific problem.

E. Díaz-Bonilla (✉)
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: E.Diaz-Bonilla@cgiar.org

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_35

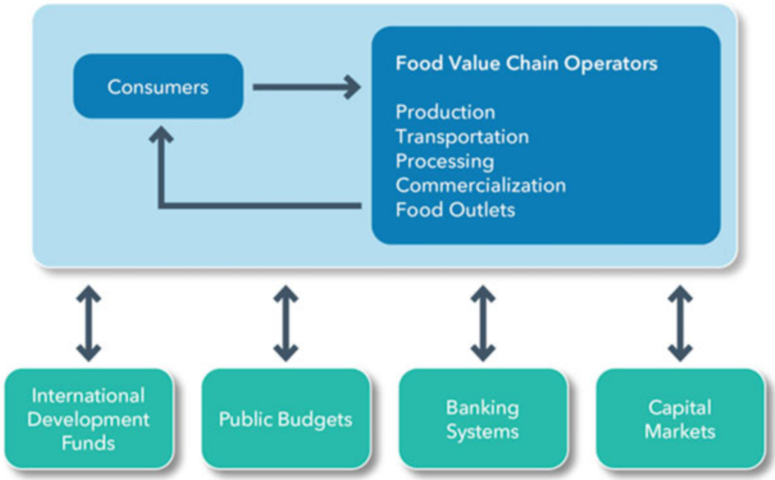


Fig. 1 Flow of funds for food systems. (Source: Díaz-Bonilla et al. (2021))

The main questions analyzed here are: given the estimated costs involved in such a transformation, what are the options for financing the interventions needed, what is their quantitative availability, and how can those potential sources of finance be reallocated and mobilized to achieve SDG2, including ending hunger?

Adequate macroeconomic policies, a supportive business environment, and peace are basic requisites for the operation of food systems. Also, different policy interventions can influence the size and allocation of consumer expenditures[3] and the production outlays of the operators of food value chains (the internal flows) in ways that help achieve different SDGs (see a discussion in Díaz-Bonilla et al. 2021). However, the internal flows are not the focus of this chapter, but rather the availability and mobilization of external flows to food systems, which can augment the internal flows to finance the additional costs of reaching SDG2 and ending hunger.

This chapter is structured as follows. Section 2 focuses on the costs of achieving SDG2, based on the work referenced in von Braun et al. (2020a). Section 3 presents estimates of the current values of the external funds that can complement the internal flows and help finance the additional expenditures and investments needed to achieve the desired objectives. Section 4 compares the costs in Sect. 2 with the availability of funds estimated in Sect. 3 and evaluates different financial alternatives for effectively mobilizing the additional resources needed. The analysis considers the total amount of financial resources available; whether some of them can be reallocated towards the desired objectives; and, if that is not enough, where the additional money may come from, considering overall budget constraints. A conclusion is that, in the aggregate, there are enough financial resources to achieve

[3]Consumer food expenditures are estimated within a range of 8–10 trillion dollars annually (updated from Díaz-Bonilla 2021).

SDG2. However, Sect. 5 argues that it is not only a matter of overall availability of financial resources (which must be further assessed at the level of individual countries as well), but of adequately designing and implementing national programs. Therefore, the section presents the idea of a Zero Hunger Alliance & Fund (based on suggestions advanced by different global leaders[4] and by Action Track One of the United Nations Food Systems Summit, UNFSS) to help developing countries design, finance and implement zero hunger programs. Section 6 summarizes all proposals and Sect. 7 concludes.

2 Costs of Interventions to Achieve SDG2 and End Hunger

The estimates of the costs related to SDG2 and ending hunger are based on the work reported in von Braun et al. (2020a, b), with the background of two other studies, ZEF and FAO (2020) and IFPRI et al. (2020). Those studies consider a variety of interventions to end hunger, increase agricultural incomes, and achieve certain environmental outcomes, mainly related to mitigation and adaptation to climate change. The number of people estimated to avoid hunger depends on the costs and range of the interventions considered (Table 1).

The costs of eliminating hunger are not linear, with each further reduction in the number of people affected becoming more expensive (ZEF and FAO 2020). The largest estimate, of about 163 billion dollars annually, would save about 1050 million people from hunger by 2030.[5] ZEF and FAO (2020) reckons that, without the interventions considered and under intermediate climate scenarios, the number of hungry people in 2030 would be about 900 million. But, as the study clarifies, this projection does not consider the possibility of additional humanitarian, health, or

Table 1 Estimates of ending hunger and other SDG2 goals

Source	People lifted from hunger (million)	Additional cost per year (billion dollars)
IFPRI et al. (2020) (Ceres 2030)	490	33
ZEF and FAO (2020)	870	56
ZEF and FAO (2020)	1050	163

Source: Based on the cited studies

[4]Pope Francis, for instance, advocated a “Global Fund” to end hunger http://www.vatican.va/content/francesco/en/messages/food/documents/papa-francesco_20201016_messaggio-giornata-alimentazione.html

[5]FOLU (2019) estimates the costs of 10 “transitions” needed for the transformation of food systems at 300–350 billion dollars per year until 2030. Those transitions involve several SDGs; but considering only those more directly related to SDG2, the costs would be about 170–190 billion dollars (close to the high estimates in ZEF and FAO 2020).

environmental crises. The matrix of financing in Sect. 4 considers the intermediate estimate of lifting 870 million people from hunger, as well as and in addition to the target of about 1 billion people avoiding hunger (both as a cushion against future crises and because the additional interventions support climate change adaptation and mitigation as well).

3 Possibles Sources of Funding

Each of the following subsections discusses quantitative estimates of the annual current values of the external sources.[6] They will be compared later with the additional costs shown in Table 1.

1. International development flows

International development flows include concessional development assistance and non-concessional lending by bilateral agencies, multilateral development banks (MDBs), and some large private philanthropic funds. Using disbursements[7] in current values (from FAOSTAT), the annual average for the period 2014–2018 has been some 256 billion dollars for all uses/sectors, and 11.1 billion for agriculture,[8] forestry and fishing (AFF), or some 4.3% of all development flows. If development flows to other sectors related to SDG2 (such as water and sanitation) are included, then disbursements in 2018 were estimated to be about 15 billion dollars (ZEF and FAO 2020).

2. Public budgets

Many public policies and expenditures influence the operation of food systems. Considering the interventions related only to SDG2, the analysis centers on two main types of public expenditure: on AFF and on social protection. There is also a brief discussion of additional fiscal expenditures related to the COVID-19 pandemic.

---

[6]Remittances are an important flow of funds. However, they are basically intra-family flows, which may not be possible or desirable to reallocate through public policies.

[7]The values of disbursements are different from the net flows in the case of loans (concessional or not), because repayments of the principal of the previous loans must be deducted.

[8]Agriculture includes Agro-industry, General Environment Protection, Food and Nutrition Assistance, and Rural Development. Some countries report expenditure for the General Government, others only for the Central Government, and some of them report both. Table 2 has been calculated with the larger of the two values reported.

(a) *Agriculture, forestry, and fishing*

Table 2 shows total government outlays (current US dollar average 2014–2019) and outlays on AFF,[9] using FAOSTAT data.[10]

Developing countries,[11] not including China, show total outlays of some 5 trillion dollars, and 125 billion for AFF, which represents about 2.5% of total expenditures. While developing countries spend a larger percentage of their budgets on AFF than developed ones, it is also necessary to consider those expenditures against the size of the agricultural sector, using the Agricultural Orientation Index (AOI; last column of Table 2 with the median values by regions). It is calculated as the percentage of agricultural expenditures over total expenditures divided by the share of agricultural GDP in total GDP. A number smaller (greater) than 1 indicates that the share of government spending on agriculture is less (more) than the share of agriculture in GDP, suggesting that there would be under- (over-) spending in the sector relative to its economic relevance. Clearly, developed countries spend more as a proportion of their agricultural sectors than developing countries (excluding China).

Although the levels of public spending alone do not determine the performance of the agricultural sector, different studies show that the types of expenditure matter, particularly their orientation toward the provision of public goods (see, for instance, Fan, ed. 2008).

Also, as noted, these numbers do not include other public expenditures relevant for agriculture, such as rural infrastructure, or for the food system as a whole. These considerations suggest the need to utilize a broader food-system focus to analyze the level and composition of public expenditures at the country level that are relevant for achieving the desired SDGs.

(b) *Social protection*

Another important type of expenditure related to SDG2 and ending hunger is for programs of social assistance (i.e., those more directly linked to poverty and vulnerability that are financed by general revenues from the government and not

---

[9]Using the distinction made by FAO (2012), they cover public outlays ***in*** agriculture (aimed specifically at enhancing primary production), but not ***for*** agriculture (which are government expenditures in other sectors that can also have a positive impact on the agricultural sector). Further, the classification does not include all of the expenditures that can support the whole food system (Díaz-Bonilla 2015).

[10]The OECD compiles producer support estimates in agricultural products only (not including fisheries and forestry) and for a more limited number of countries than FAOSTAT, but with a very useful disaggregation of interventions that include budgetary and non-budgetary transfers involving consumers (see https://www.oecd.org/switzerland/producerandconsumersupportestimatesdatabase.htm). Suggestions about reallocating or "repurposing" 600–700 billion USD in agricultural "subsidies" are based on those estimates. However, the OECD database shows that not all the transfers are agricultural "subsidies" that can be repurposed.

[11]What is considered a "developed" or "developing" country varies across datasets. Therefore, the numbers presented must be considered approximations for those groups.

Table 2 Government outlays (current dollars, average 2014–2019)

	Total Government Outlays (Billion USD dollars)	Outlays for Agriculture, Forestry, and Fisheries (AFF) (Billion USD dollars)	AFF as Share of Total Government Outlays (%)	AOI median (coefficient)
Africa	483.5	9.6	2.0	0.15
Asia developing	4937.0	365.7	7.4	0.32
(of which China)	2987.0	285.9	9.6	1.19
LAC	1730.9	23.4	1.4	0.32
Oceania	569.1	3.4	0.6	0.19
Northern America & Europe	16966.2	94.2	0.6	0.42
Developing	8013.2	410.9	5.1	0.28
Developing w/o China	5026.2	125.1	2.5	0.28
Developed	19044.8	136.9	0.7	0.41
Total	27058.0	547.8	2.0	0.3

Source: Author, with data from FAOSTAT

by contributions from beneficiaries—known as “non-contributory programs”).[12] Here, we focus on the social assistance programs using data from the World Bank’s ASPIRE database. It is based on household surveys, and therefore it may not capture all governmental programs. Also, the database focuses on developing and emerging countries only. On the other hand, it provides a useful disaggregation of social protection programs and of the distribution of benefits across the population.

Table 3 shows an estimate of the money allocated to those programs in current dollars for the period 2014–2018, using the categories in ASPIRE, except Cash Transfers and Social Pensions (CT+SP), which aggregates the three separate categories of conditional cash transfers, unconditional cash transfers, and social pensions.[13]

For the countries in the ASPIRE database, the median of social assistance expenditures is less than 1.2% of their GDP. Another key characteristic to consider

[12] These are part of the broader category of social protection, which includes programs financed by the beneficiaries (“contributory”). Developing countries spend about 1.1 trillion dollars (916 billion without China) in social protection (annual average 2010–2017; based on IFPRI’s SPEED database using data from the IMF), or about 3.5–4.0% of the GDP.

[13] The ASPIRE database covers 125 countries, 43 from Africa, mostly from sub-Saharan Africa (AFR), 15 from East Asia and the Pacific (EAP) (including China), 29 from Europe and Central Asia (ECA) (including Russia, Hungary, Ukraine), 22 from Latin America and the Caribbean (LAC), 10 from the Middle East and North Africa (MENA), and 6 from South Asia (SAR) (including India).

Table 3 Estimated expenditures for social assistance programs

Billion USD	Total	CT +SP	School feeding	Public works	Food and in-kind	Health fee waivers	Other social assistance	Total excluding health fee waivers
AFR	20.2	12.6	0.9	2.8	1.3	0.5	1.9	19.7
EAP	164.9	47.1	0.8	13.8	9.1	92.3	1.7	72.5
(China)	146.7	39.1	0.0	13.8	5.4	88.4	0.0	58.3
ECA	72.8	59.1	0.3	1.5	0.6	5.8	5.5	66.9
LAC	84.8	44.2	3.9	1.2	2.9	25.9	6.6	58.9
MENA	24.7	10.5	0.0	0.0	9.5	3.7	0.9	21.0
SAR	40.3	4.9	1.5	6.4	24.5	2.2	0.7	38.1
(India)	35.3	1.3	1.4	5.8	24.0	2.2	0.6	33.2
Total	407.7	178.4	7.5	25.7	48.0	130.5	17.3	277.1
Total w/o China	260.9	139.2	7.5	12.0	42.6	42.0	17.3	218.9

Source: ASPIRE and WDI/WB

is the distribution across the population.[14] Social assistance is intended for the poorest segments of a population, and if properly targeted, the largest percentages should go to the poorest quintile, with no benefits accruing to the richest ones. However, in the case of Africa, the poorest quintile receives 11.3% of the benefits (the average for the countries; the median is 8%), while the richest quintile receives 41.5% (average) and 38.9% (median). The East Asia and Pacific region also shows a distribution that is biased toward the rich, with the poorest quintile receiving about 17% (average and median), far less than the richest quintile (average of 33.4% and median of 22%). Other world regions show a better distribution, with the poorest quintile receiving somewhat more than 30% (average and median), but the richest quintile still getting 10–16% of the benefits. These numbers suggest significant problems with the targeting of these programs that are intended to help the poor and hungry.[15] In particular, countries in Africa seem to suffer the dual problem of both lower levels of expenditure overall (a median of about 0.9% of GDP) and ineffective targeting of the poorest groups.

[14] The estimates are from the author using all the annual household surveys for all the countries in the database (several countries have more than one household survey, and the years for each country vary; the average year of the surveys in the database is 2011). Benefit incidence is calculated as the percentage of benefits going to each quintile relative to the total benefits going to the population (Sum of all transfers received by all individuals in the quintile)/Sum of all transfers received by all individuals in the population).

[15] These are data from household surveys, which do not capture the wealthier segments of the population well; therefore, what appears as the richest quintile in the survey may not be so in real life.

(c) *Brief consideration of expenditures related to COVID-19*

The current pandemic is posing further challenges for fiscal accounts. Governments have implemented a variety of policies and investments in health, social protection, and support for employment and production, all of which require the use of a variety of unconventional monetary and fiscal instruments. As reported by the IMF policy tracker for governmental COVID-19 actions, developing and emerging countries made a strong additional fiscal outlay, surpassing 1.2 trillion dollars in 2020 (counting only additional public expenditures as of this writing), with 1.1 trillion dollars spent on non-health measures of social protection and maintenance of employment (excluding China, the respective values are 700 billion dollars and 680 billion dollars). It will be difficult for those levels of expenditure to be sustained in the future, considering the debt already accumulated. These considerations will determine whether developing countries have the flexibility to increase public expenditures for SDGs in the aftermath of the pandemic.

3. Banking system

While, in the previous sections, the focus was on public flows, the transformation of food systems will also require significant private investments from all operators in the food value chains. The internal cash flows from food operations (based on consumers' food purchases) can be expanded by loans from the banking system (which is discussed here) or by operations in capital markets (analyzed in the next subsection).

Table 4, also based on FAOSTAT data, shows the total amount of loans outstanding at a point in time,[16] which was provided by the banking sector to producers in agriculture, forestry, and fisheries (including household producers, co-operatives, and agri-businesses)[17] and for all sectors (the average for 2014–2019, in current dollars).

There are no data on net disbursements (loans minus repayments of principal), but the change in stocks may be an indicator of net flows. For total credit, the yearly average change in stocks for 2015–2019 is about 1.6 trillion dollars globally; but the average for developing countries (excluding China) is only 87 billion dollars. The average annual change in loans for AFF during 2015–2019 is 24 billion dollars worldwide. The estimated flows for AFF in developing countries would be around 14.2 billion dollars, or some 9.5 billion dollars if China is excluded.[18]

Table 4 also shows the percentage of AFF loans as a share of total loans. In the case of developing countries without China, the coefficient is about 4% of total loans. But, as with public expenditures, a more revealing indicator of the importance of lending to the AFF sector is the Agricultural Orientation Index (AOI) (calculated

[16] It should be noted that this is a stock, while the data in the previous sections were flows.

[17] There is no information about loans to other operators in food systems.

[18] The actual annual flow of loans for AFF may be larger, considering that some short-term credit may be extended and liquidated within the year, and thus does not affect stocks from one year to the next.

Table 4 Value of loans outstanding, total and for AFF (Current Dollars; Average 2014–2019)

	Total loans (Billion USD dollars)	Loans to Agriculture, Forestry, and Fishing (Billion USD dollars)	% of AFF over total loans	AOI (median)
Africa	402.5	16.3	4.1	0.2
Asia developing	17043.6	427.9	2.5	0.4
(of which China)	11612.3	180.5	1.6	0.2
LAC	1429.2	28.7	2.0	0.5
Oceania	995.7	93.3	9.4	1.4
Northern America & Europe	20978.8	404.4	1.9	1.1
Developing	18879.3	473.1	2.5	0.3
Developing w/o China	7267.0	292.6	4.0	0.3
Developed	22878.6	531.3	2.3	1.3
Total	41757.9	1010.2	2.4	0.4

Source: Author, based on FAOSTAT

as the percentage of AFF credit in total credit, divided by the percentage of agricultural GDP in total GDP). The last column in Table 4 provides the median AOI for the countries in each region. As in the case of public expenditures, developing countries show far smaller AOIs than developed countries,[19] and values for Africa are lower than for other developing regions.

4. Capital markets

Capital markets at the global and national levels offer another source of external funds. Here, the focus is on socially- and environmentally-oriented investments,[20] a potentially relevant source of funds for the transformation of food systems, considering the global trend toward investments that consider broader objectives along with financial returns.

However, definitions of these new investments are evolving, and therefore data on the actual volume of operations vary. Just as an indicator, Díaz-Bonilla (2021) cites that the issuing of Green Bonds in 2019 was 260 billion USD and, of Social Bonds, some 131 billion USD in 2020.[21]

The largest shares of investments in those categories take place in developed countries, and the amounts oriented towards agriculture and the transformation of

[19] In Oceania, the values are dominated by Australia and New Zealand.

[20] Díaz-Bonilla (2021) also included an estimate of foreign direct investments (FDI) for AFF and Food, Beverage and Tobacco. FDI for agriculture and agro-industries, in the aggregate, is part of the internal flows within food systems, but for individual countries, they can be considered additional financing.

[21] Aimed, respectively, at specific environmental and social objectives. When both objectives are combined, they are called sustainable bonds. There are also other themed bonds, such as "blue bonds" for sustainable fisheries.

food systems are small. For instance, the survey of impact investments in GIIN (2020) shows that only 8.1% of the funds (average 2018–2019) were allocated to food and agriculture.[22]

The challenge is to mobilize these resources for investments in support of the transformation of food systems to achieve SDG2, including ending hunger.

4 Matrix of Financing and Interventions to Shape the Flows of Funds

Table 5 is an indicative matrix of financing that compares the current levels of the different sources discussed in Sect. 3 with the costs identified in Sect. 2. It assumes certain percentage of financing for each group of interventions from the individual flow of funds: for instance, some of them may only be financed by public expenditures, while others could receive credit from the banking system or investments from capital markets.

Table 5 shows the current values of flows of funds in those categories for developing countries calculated in the previous section (excluding China).[23]

Overall, there seem to be enough aggregate resources (except, perhaps, in the case of banking systems for the 1 billion target).[24] The next subsections discuss policy options for each source to ensure that those resources can be mobilized to achieve SDG2 and end hunger. As mentioned, the analysis considers several questions: what the amount of available financial resources is; whether some of them can be reallocated towards the desired objectives; and, if that is not enough, then where the additional money may come from, considering the overall availability of financial resources ("budget constraints").

A general constraint is defined by global aggregate savings: they amount to about 21.6 trillion dollars (average of 2015–2019), but are distributed very unevenly across regions (see details in Díaz-Bonilla 2021). Further, global savings are the counterpart to world investments. Therefore, any proposal to increase investments in certain activities would require adjustments in other investments and/or consumption, with

[22] There are also several bonds issued by MDBs with agri-food components. But that money is then lent to developing countries as part of the international development flows discussed above and should not be (double) counted here.

[23] The estimate for capital markets is a rough approximation, partially combining (to avoid double counting) the value of social bonds issued by developing countries, as surveyed in the Climate Bond Initiative and HSBC (2021) (although they were not necessarily financing aspects of SDG2) and of the results for impact investment flows into agriculture, according to the survey in GIIN (2020).

[24] The financing matrix in Table 5 is just an example; different percentages of financing by sources can be considered that also depend on the instruments to be utilized. For instance, if governments decide to scale up cash transfers that include grants for productive activities and environmental sustainability, then, the additional costs of improved technologies would be financed by the public sector, instead of loans from the banking system.

Table 5 Matrix of incremental costs and financing, and reference flows (USD billions)

	Average annual incremental investment cost	International development flows	Public expenditures: AFF	Public expenditures: social	Public expenditures: infrastructure	Banking system	Capital markets
AgR&D, extension and ICT	6.6	1.3	5.3	0.0	0.0	0.0	0.0
Small scale irrigation Africa	3.8	0.8	1.1	0.0	0.0	1.5	0.4
Crop protection (Insects, Diseases, Weeds), integrated soil fertility management	4.4	0.9	0.9	0.0	0.0	2.2	0.4
Infrastructure: roads, rail, electricity	10.8	2.2	0.0	0.0	8.6	0.0	1.1
Gender programs and nutrition	5.0	1.5	0.0	3.5	0.0	0.0	0.0
Social protection	25.1	5.0	0.0	20.1	0.0	0.0	0.0
TOTAL (870 million lifted from hunger)	55.8	11.7	7.3	23.6	8.6	3.7	1.9
TOTAL (1 billion lifted from hunger plus other interventions)[a]	163.1	16.3	41.8	27.1	8.6	56.6	12.6
CURRENT FLOWS		11–12	86	293	n/a	9.5	9.9

Source: Author, using data from Sect. 3 and ZEF and FAO (2020)
[a]"Other interventions" include: Efficiency enhancement in irrigation; Global large-scale expansion of irrigation; Nitrogen-use efficiency; Food loss reduction; Soil-water management; Optimal crop planting and varieties (Adaptation); Soil Carbon Sequestration (Mitigation)

economy-wide repercussions that must be considered. Also, there may be "budget constraints" at the level of each individual flow of funds that need to be analyzed.

(a) *International development flows*

International development flows for food systems should be increased by about 15 billion dollars above current levels (within the range suggested in IFPRI et al. 2020). Here, it is further suggested that 2 billion dollars of that increase be allocated to support the Zero Hunger Alliance & Fund (outlined below). If total international development flows cannot be increased (because bilateral development aid is limited by budgetary and political factors in donor countries, and net flows of non-concessional loans from MDBs are also constrained by their capital base and restrictive financial policies), this implies a reallocation of funds from other activities. For example, some of the development funds are supporting investments with high green-house gas (GHG) emissions, such as coal-based energy (UNFCCC 2021). At COP26,[25] 25 countries and public finance institutions committed to ending financing abroad of projects with unabated (i.e., without carbon-capture) fossil fuel energy by the end of 2022, and those funds can then be reallocated to ending hunger. Similarly, other funds can be reallocated from activities with lower priority.

Another option currently being discussed is to reallocate a percentage of the new issue of Special Drawing Rights (SDRs) in the IMF to support developing countries (the new allocation has been about 650 billion dollars, of which about 60% went to developed countries).[26] At the time of this writing, there is a discussion at the IMF about options for developed countries to donate or lend part of the SDRs that they do not need to support low-income countries. Here, an additional alternative is suggested to use the SDRs in a way that further multiplies their impact for broader objectives: the allocation of, for example, 2% of SDRs to a fund to guarantee "zero hunger bonds" issued by developing countries (explained later).[27]

In general, international development funds should be used more strategically to leverage and mobilize private funds. In addition, multilateral and bilateral organizations should better coordinate their own operations to avoid the fragmentation of relatively isolated initiatives and competition across international agencies at the national level.

(b) *Public expenditures*

Table 5 estimates that public expenditures for agriculture and rural development and for social assistance would have to be increased by about 6% and 11%, respectively, to eliminate the risk of hunger for about 870 million people. If the objective is lifting

[25] https://unfccc.int/news/end-of-coal-in-sight-at-cop26

[26] A smaller reallocation already happened to the IMF's Poverty Reduction and Growth Trust (PRGT), which provides concessional loans to low-income countries (https://www.imf.org/en/About/FAQ/special-drawing-right).

[27] A larger allocation of 10% of the SDRs has been suggested in Díaz-Bonilla (2021) to guarantee "pandemic recovery bonds."

1 billion people from hunger, along with other climate mitigation and adaptation measures, then public expenditures in agriculture and rural development will need to expand by almost 20% and those in social assistance by about 12%.

These are aggregate numbers. Focusing on individual countries, indicators such as the AOI for agricultural expenditures or the percentage of social assistance expenditures in total GDP show that developing countries in general, and particularly in Africa and Asia (not counting China), devote comparatively fewer resources than other regions to those crucial interventions. Here, it is suggested that individual developing countries should try to increase their AOIs to about 0.5 and social assistance expenditures to at least 2% of the GDP.

Specific public expenditure reviews can help determine the adequacy of both the level and composition of public expenditures dedicated to SDG2, as well as their efficiency, efficacy and equity. Certainly, targeting could be improved in social and agricultural programs, and better instruments can be utilized, such as the evolving type of enhanced social safety net.[28]

Part of the additional resources can come from reallocation of agricultural subsidies with negative impacts on poverty, nutrition, and the environment (see, for instance, Laborde et al. 2020). Using data from OECD, the total amount of expenditures that can be subject to that repurposing in developing countries (excluding China) was estimated at about 52 billion dollars (Díaz-Bonilla 2021).[29]

Other expenditures with negative effects that should be phased down, following the Glasgow Climate Pact document agreed to at COP26 (paragraph 36), are subsidies to fossil fuels, globally estimated at some 800 billion dollars (Parry et al. 2021); the money saved can be reallocated to activities linked to SDG2 and ending hunger.

However, reallocating/repurposing, along with better targeting, even with improved instruments, may not be enough to reach the levels needed to achieve SDG2 and end hunger, and therefore expenditures and revenues may have to be increased.

One way to achieve this is by improving tax administration so as to reduce tax evasion. Also, developing countries should reassess the multiple exemptions to value-added and sales taxes: in several countries, they represent an important loss of revenue, help rich, as well as poor, consumers, and do not address challenges of nutrition or environmental sustainability. Implementing taxes on unhealthy and/or environmentally damaging food products can shift incentives while collecting

[28] Cash transfers in the rural sector have been expanding to include poverty, nutrition, environmental, and productive payments (De La O Campos et al. 2018). Recent work by the World Bank has extended the framework for social inclusion to multidimensional programs that include social safety nets, livelihoods and jobs, and financial inclusion (see Andrews et al. 2021).

[29] The total amount of agricultural subsidies that can be repurposed (average 2014–2018 in current dollars) is less than 240 billion dollars: about 132.5 billion dollars in OECD countries, of which the EU represents 82.5 billion, and 105.8 billion dollars for non-OECD countries, of which China represents 62.1 billion dollars. For developing countries (excluding China, but including OECD members that are developing countries), the value is about 52 billion dollars (Díaz-Bonilla 2021).

additional revenue. Taxes on international trade, including with impacts on fiscal accounts and on production and consumption incentives, should be analyzed considering SDG2 and hunger. Further, more progressive taxation of incomes and wealth will strengthen revenues. Finally, pricing the externalities of fossil fuels should be implemented, not only to shift incentives away from high GHG emissions, but as a source of revenue (Parry et al. 2021).

The Zero Hunger Alliance & Fund, discussed below, can help developing countries conduct the specific fiscal analyses involved in the reallocation, refocusing and scaling up of public expenditures needed to support programs to end hunger, considering the constraints posed by the fiscal response to the pandemic.

Additionally, all countries, but particularly the developed ones that have greater influence on the operation of global financial markets, must be more active at the international and national levels to implement stronger controls on money laundering and tax havens that facilitate illegal financial outflows and tax evasion from developing countries. Also, proposals for a more unified system of taxation of international corporations, with an established formula to allocate the taxable base and a common minimum corporate tax, must be implemented.[30] These initiatives would help many developing countries to increase fiscal revenues that are currently being lost through corruption and tax evasion.

(c) *Banking systems*

Expansion of irrigation and the adoption of improved agricultural practices (needed to reach SDG2 and end hunger) will require financing from the banking system. Estimates in Table 5 suggest that, in the aggregate, credit to the agricultural sector in developing countries (excluding China) will have to increase by some 40% in flows (for the central estimates of 870 million people avoiding hunger). While this is an aggregate estimate, for individual countries, it is suggested that they target an AOI for credit of at least 0.5.

For the banking sector to play this role, the systemic barriers that limit the supply of financial services for agriculture, small farmers, and the poor and vulnerable (women, disadvantaged ethnic groups, and youths) must be addressed. This requires a country-level analysis of the banking system considering the following aspects.[31] First, the adequacy of the overall macroeconomic and regulatory framework. Lending to the agricultural sector is affected by macroeconomic volatility, and by regulations that are designed for the urban sector and for activities with more regular cash flows than agriculture. Second, the origin and use of the funds that are to be intermediated (such as deposits; budget allocations by the government; rediscounts by the monetary authorities; regulatory mandates to lend to the agricultural sector; loans from international organizations; and others). In particular, it is suggested here

[30] Some advances were made in October 2021 at the G20 presidential meeting in Rome (https://www.reuters.com/business/g20-leaders-endorse-global-minimum-corporate-tax-deal-2023-start-2021-10-30/).

[31] What follows is based on Díaz-Bonilla (2015); Díaz-Bonilla et al. (2019).

that an updated version be used of the monetary policies that sustained agri-food development in the 1960s and 1970s, implemented then by what have been called "developmental central banks," and which, with the 2008 global recession and the current pandemic, have been revived mainly in developed countries under the name of quantitative easing (Díaz-Bonilla 2015).[32] Such an approach must be implemented within a consistent monetary program that maintains control of inflation.

Additional funds may also come from reallocation of credit that now supports activities with negative externalities such as deforestation or fossil fuels. In that regard, it would be important to properly implement the "Glasgow Leaders' Declaration on Forests and Land Use" at COP26, and implement the disclosure recommendations concerning climate-related financial risks, as suggested by the Task Force on Climate-Related Financial Disclosures (TCFD) created in 2015 by the Financial Stability Board (FSB).[33]

The third component of the analysis is the types of banking and financial institutions that can intermediate those funds. There is a wide variety of formal and informal banking and financial operators, with their own advantages and disadvantages. Here, it is suggested that the role of public development banks (PDBs) be strengthened. They were dismantled in many developing countries during the 1990s because of concerns about corruption, inefficiency, and fiscal costs. However, several of them, including those with an agricultural orientation, have been reformed to operate with incentives, performance metrics, and controls to avoid the problems of the past, while pursuing developmental objectives. In fact, during the UNFSS, and following the November 2020 "Finance in Common Summit" of PDBs, a coalition of those banks to help finance the transformation of food systems was announced.[34] That coalition can help PDBs address the pervasive market failures in agricultural and climate credit markets that affect small farmers and firms, particularly those operated by women, youths and vulnerable ethnic groups.

The fourth aspect to consider relates to financial instruments. A central one is credit, particularly longer-term operations, which face agricultural-sector-specific problems, such as the dispersion and small scale of customers, and weather and other risks. Innovative insurance schemes, technical assistance, and better weather and market information can mitigate some of those risks. Supply-chain and value-chain lending offer a flexible form of financing that can include small farmers; input and equipment suppliers should also be considered as potential vehicles for lending to small and family farmers. In any case, credit for long-term investment may require funding from public fiscal or monetary sources (as suggested above).

---

[32] The U.S. Federal Reserve operated as a developmental central bank to help the U.S. economy in the 1930s. More recently, with the recent crises, central banks, mainly in developed countries, have revived the use of those dedicated lines of credits to buy both public and private credit instruments.

[33] Established by the G-20 in 2009, to ensure that the financial system is resilient to all forms of risk.

[34] https://foodsystems.community/public-development-banks-coalition/

Beyond the obstacles to credit, there is a dearth of other financial products and services for small farmers, rural populations, and SMEs. This is true both on the financing side (such as leasing, warrants, and the discount of invoices, all of which require the adaptation of regulations and operational mechanisms) and on the payments and savings side (for instance, simplified checking and savings deposits, which are an important risk mitigation tool for rural households). In general, digital technology can reduce transaction costs and generate more information about potential customers, lowering risk for financial institutions.

(d) *Capital markets*

Table 5 suggests that capital market operations will have to increase significantly above current estimated levels to achieve SDG2 and zero hunger, plus other environmental and health objectives. The net-zero deforestation commitments and emissions disclosures already mentioned in the banking section can also help shift incentives and financial flows in capital markets. Additionally, we present two other ideas here.

First, it is necessary to develop a robust pipeline of investable opportunities (including individual projects, impact investment funds, and/or thematic bonds) with the adequate profile of risk/reward to attract investors, and clear, measurable, and monitorable impact objectives, aligned with achieving SDG2 and ending hunger.

An international project preparation/incubation/acceleration facility could be set up to link investable opportunities for small farmers and rural populations in social and environmentally relevant activities with private capital, based on CGIAR technologies and leveraging the presence of its centers in more than 100 developing countries, where they work with a variety of national agricultural research institutes (NARIs) (see the detailed proposal in Díaz-Bonilla et al. 2018).[35]

The facility would identify projects involving small and family farms; aggregate and structure them (as different types of investable vehicles), with adequate rates of return and risk profiles, and with value sizes that compensate investors for the transaction costs and due diligence requirements; provide technical assistance to both small farmers and investors, particularly in relation to sustainable technologies (based on the work of the CGIAR centers and participant NARIs); and define and monitor metrics for the impacts desired. This facility can also support enhanced environmental lending by public and private banks. International development funds, as well as some national public expenditures, can be used more strategically in this facility as blended finance with private sector funds, including for the purpose of de-risking investments.

[35] More recently, there have been other similar ideas regarding the need for an institutional device to link investable opportunities and investors (see, for instance, Millan et al. (2019) and Finance for Biodiversity Initiative (2021)).

A second proposal is to guarantee "zero hunger" bonds to finance related public programs. In particular, as mentioned, it is suggested here that 2% of the new allocation of SDRs of 650 billion dollars be assigned to a fund, which could be set up within the IMF, to guarantee the interest rate payments of zero hunger bonds issued by developing countries as part of the Zero Hunger Alliance described later.

Although the specific design of those bonds will have to be discussed with potential private and institutional investors, some features to consider are the following: they will be a "consol" or perpetual bond;[36] possibly issued in dollars; paying an adjustable rate with a cap (say, 5%, which is close to the average nominal yield since the 1950s); and may be callable, with call protection (for example, until 2050). Other official development aid and private philanthropic funds could be utilized as well to guarantee the interest payments, and thus eliminate country risk for the countries that join the international alliance to eliminate hunger (discussed below).

This alternative will greatly increase the impact of the SDRs: for instance, 13 billion dollars can guarantee an issuance of between 52 and up to 130 billion dollars in zero hunger bonds (under the assumptions in the footnote[37]). The funds raised, in addition to the zero hunger objective, would also help finance sustainable agricultural technologies and other environmental interventions addressing climate change mitigation and adaptation.

Certainly, the financial scheme suggested here can also be utilized for special bonds with other purposes, such as financing pandemic-related expenditures (a "pandemic recovery bond" is discussed in Díaz-Bonilla 2021 and von Braun and Díaz-Bonilla 2021).

5 The Need for Country-Based Institutional Arrangements: A Zero Hunger Alliance & Fund[38]

The quantitative estimates and the financing matrix discussed above suggest that, in the aggregate, there are enough additional financial resources to save anywhere from 870 to 1 billion people from hunger by 2030, effectively achieving zero hunger.

However, the potential sources of financing and whether they are sufficient cannot be judged solely at the aggregate level; they also need to be assessed in each individual country. And even if the domestic resources exist and can be

[36] Alternatively, 100-year bonds can be considered, with payment periods during the last 10 years.

[37] The guarantee fund holds between 2 and 5 years in interest payments at the rate of 5%; the default rates of the interest payments that have to be covered by the guarantee fund are similar to those of the IMF or the World Bank; and the erosion that those payments inflict on the guarantee fund is covered by additional international public money. The multiplier effects changes with different assumptions.

[38] A more detailed explanation is in Díaz-Bonilla (2021).

mobilized, they can only be transformed into solid programs to end hunger and achieve SDG2 if individual countries are willing and capable to do so.

However, institutionally weak governments may not be able to design the programs and coordinate the work of their own Ministries and agencies, as well as the international organizations operating in their countries. They could benefit from the establishment of institutional mechanisms to help developing countries design, finance, and implement their programs. The fiscal constraints imposed by the public responses to the current pandemic reinforce the need for these country-based arrangements.

Therefore, it is suggested that a "Zero Hunger Alliance and Fund" (ZHAF, or "the alliance") be established, with the objective of operating as an international mechanism to assist the developing countries that formally join the alliance in the design, financing, and implementation of their zero hunger plans.

The proposal outlined here builds on the idea of a Zero Hunger Fund, which was suggested by Action Track One of the UNFSS and has considered the experiences of other initiatives.[39] It also expands the scope of the announcement by the UN Secretary-General in his "Chair Summary and Statement of Action on the UN Food Systems Summit" about appointing Resident Coordinators and UN Country Teams to develop and implement national programs, while enjoining the Rome-based agencies (FAO, IFAD, and World Food Program) with the coordination of a UN-based hub to support the follow-up activities to the Food Systems Summit.

The proposed ZHAF would go further than the UN system, as a public-private partnership with the capacity to support, both institutionally and financially, country-owned and country-coordinated programs to end hunger. The ZHAF would have personnel seconded from international organizations (with specific assignments of, say, 3 years) focusing on poverty, food security and nutrition issues. It can work with (and even within) the UN coordinating mechanism suggested by the Secretary-General. It would support participating countries, which, after formally joining the Alliance, should designate a coordinating group of high-level officials with the relevant authority to design national initiatives and mobilize the financial and institutional resources needed to implement them.

The ZHAF will receive $2 billion a year for 5 years from the annual increase of $15 billion in international development funds, while also expecting to mobilize an additional $500 million per year from the private sector, with targeted commitments from at least 50 companies in food and other sectors.

[39] Such as the Global Agriculture and Food Security Program (GAFSP), the Poverty Reduction Strategy Papers or Programs (PRSPs), and GAVI, the Vaccine Alliance (more details are in Díaz-Bonilla 2021).

To expand the financial resources available, it is also suggested that the developing countries joining the ZHAF be allowed to issue the new “zero hunger bonds” guaranteed by the SDRs.

The fund would be used to cover operational costs; hire technical and operational experts to support the countries in defining the programs and mobilizing the human, financial, and institutional resources to carry them out; facilitate the issuance of zero hunger bonds and other financial support; and, eventually, possibly finance some interventions directly.

In addition to helping eliminate hunger by 2030, the ZHAF, through specific policy interventions and investments supported at the national level, would help achieve other crucial nutritional and environmental objectives, which will be monitored and documented.

It is recognized that the establishment of a new global hunger fund is not without risks. Potential public and private sector contributors may suffer “donor fatigue.” Also, some developing countries may not join the alliance, and others may not have the necessary capabilities, even with the support of the ZHAF, to coordinate and sustain the effort to eliminate hunger.

Yet, the institutional arrangement outlined here (and detailed in Díaz-Bonilla 2021) has several important advantages. It has a flexible public-private institutional structure, and it supports participating countries as they implement country-owned, country-coordinated, integral programs. It also focuses on the single and measurable objective of ending hunger by 2030, while, at the same time—given the type of agricultural technologies and environmental interventions supported—it will contribute to crucial objectives related to climate change mitigation and adaptation. The ZHAF would also mobilize a significantly larger volume of funds than those directly allocated to it. And, by relying on personnel from existing organizations, it reduces the risks of creating another permanent international bureaucracy.

Ending hunger is within reach, and the Zero Hunger Alliance & Fund can play a central role in achieving it.

6 Summary of Proposals

Table 6 summarizes the proposals discussed above.

Table 6 Summary of proposals

Topics	Proposals
International development flows	Increase by 15 billion dollars annually the international development funds dedicated to agricultural and rural development, food and nutrition security, and environmental aspects of food systems. Reallocate development funds currently supporting fossil fuels and other environmentally damaging activities
	Allocate yearly 2 billion dollars of the additional 15 billion dollars to the Zero Hunger Alliance & Fund
	Allocate 2% of the future issue of Special Drawing Rights (SDRs) of 650 billion dollars to offer guarantees for a new “zero hunger bond” to help finance the economic, social, and environmental interventions needed to achieve SDG2 and end hunger. These instruments can be perpetual or very long-termed bonds, with an adjustable but capped coupon
Public budgets	Implement public expenditure and tax reviews in developing countries to increase and reallocate inefficient agricultural expenditures and fossil fuel subsidies and scale up, better target, and redesign social safety nets using new and evolving cash transfers that combine poverty, productive, nutritional, environmental, and financial inclusion components
	Increase the Agricultural Orientation Index (AOI) of expenditures for agriculture, forestry, and fisheries (for example, to not less than 0.5) and social protection expenditures as a percentage of GDP (for example, to at least 2%)
	Revenues in developing countries should be strengthened through better tax administration and the revision of sales, income, wealth, and trade taxes, and by implementation of international initiatives to control corruption, tax evasion, and other practices that erode those countries’ tax bases. Pricing fossil fuel externalities should also be implemented
Banking systems	Reactivate the tools of the “developmental central banks,” using rediscounts to offer credit to small farmers, rural populations, and SMEs in food value chains (within a consistent monetary program that maintains control of inflation)
	Revitalize and modernize public development and agricultural banks (with incentives, performance metrics, and controls to avoid the problems of the past in this type of institution) to increase credit (supported by central bank discounts) and offer other financial services to small farmers, rural populations, and SMEs in food systems, with particular consideration for women, vulnerable ethnic minorities, and youths
	Increase the AOI of agricultural credit to at least 0.5
	Implement the zero deforestation and emissions disclosures discussed as part of COP26 and the work of the Task Force on Climate-Related Financial Disclosures (TCFD)
Capital markets	Create a project preparation/incubation/acceleration facility to structure productive opportunities for small farmers into investable opportunities for impact investors, using economic, social, and environmentally sound technologies with the support of One CGIAR and national agricultural research institutes (NARIs) and partners in more than 100 developing countries

(continued)

Table 6 (continued)

Topics	Proposals
	Support countries that participate in the Zero Hunger Alliance & Fund with the design, guarantee (using 2% of the new allocation of SDRs and other public funds) and launch of a new type of social and environmental bond, called a "zero hunger bond"
	Implement the zero deforestation and emissions disclosures discussed as part of COP26 and the work of the Task Force on Climate-Related Financial Disclosures (TCFD)
Zero Hunger Alliance & Fund	Create a public-private international institution, with a dedicated fund, to organize country-based alliances to eliminate hunger by 2030. This institution can work within the UN coordinating mechanism suggested by the UN Secretary-General to follow up on the UNFSS

Source: Author

7 Conclusion

This chapter analyzed the costs and potential financial mechanisms for achieving SDG2, including the end of hunger, and made a series of specific proposals for mobilizing the resources to achieve those objectives. The proposals include the creation of a Zero Hunger Alliance & Fund, in support of country-owned and country-coordinated integral programs to end hunger by 2030. It is hoped that this chapter has shown that it is feasible to achieve the SDG2 and end hunger in an improved global food system, if we decide together to do it.

Acknowledgements The author acknowledges the detailed and very useful comments from Joachim von Braun, Johan Swinnen and Rob Vos. Those comments significantly improved the different versions of this document. However, they are not responsible for any of the remaining errors and omissions. This chapter is an abridged and updated version of Díaz-Bonilla (2021).

References

Andrews C, de Montesquiou A, Sánchez IA, Dutta PV, Paul BV, Samaranayake S, Heisey J, Clay T, Chaudhary S (2021) The state of economic inclusion report 2021: the potential to scale. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1598-0

Climate Bond Initiative and HSBC (2021) Sovereign green, social, and sustainability bond survey. The ultimate power to transform the market

De La O Campos AP, Villani C, Davis B, Takagi M (2018) Ending extreme poverty in rural areas – sustaining livelihoods to leave no one behind. FAO, Rome. 84 pp. http://www.fao.org/3/CA1908EN/ca1908en.pdf

Díaz-Bonilla E (2015) Macroeconomics, agriculture, and food security: a guide to policy analysis in developing countries. International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/9780896298590

Díaz-Bonilla E (2021) Using the new IMF Special Drawing Rights for larger purposes: guaranteeing 'pandemic recovery bonds'. https://www.ifpri.org/blog/using-new-imf-special-drawing-rights-larger-purposes-guaranteeing-%E2%80%98pandemic-recovery-bonds%E2%80%99

Díaz-Bonilla E, Loboguerrero AM, Verchot L, Viglizzo E, Mirzabaev A (2018) "Financiamiento de 'Un futuro alimentario sostenible'." T20 Task Force 3 on Food Security and Sustainable Development. https://t20argentina.org/wp-content/uploads/2018/06/TF3-3.5-Task-Force-3-FINAL-v4-EDB-revised-after-peer-review.pdf

Díaz-Bonilla E, Fernández-Arias E, Piñeiro V, Prato B, Arias J (2019) Foro de análisis financiamiento e inclusión financiera para el desarrollo agropecuario, rural y de sistemas alimentarios en América Latina y el Caribe: Documento resumen, LAC working paper 5. International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/p15738coll2.133448

Díaz-Bonilla E, Swinnen J, Vos R (2021) Financing the transformation to healthy, sustainable, and equitable food systems. In: 2021 global food policy report: transforming food systems after COVID-19. IFPRI, Washington, DC

Fan S (ed) (2008) Public expenditures, growth, and poverty in developing countries: lessons from developing countries. Johns Hopkins University Press, Baltimore

FAO (2012) The state of food and agriculture 2012; investing in agriculture for a better future. FAO, Rome. http://www.fao.org/3/i3028e/i3028e00.htm

Finance for Biodiversity Initiative (2021) Greening sovereign debt: building a nature and climate sovereign bond facility. F4B. https://www.financeforbiodiversity.org/contact/

FOLU (2019) Growing better: ten critical transitions to transform food and land use. The global consultation report of the food and land use coalition (FOLU)

GIIN (2020) Annual impact investor survey 2020, 10th edn. The Global Impact Investing Network. https://thegiin.org/research/publication/impinv-survey-2020/

International Food Policy Research Institute (IFPRI), International Institute for Sustainable Development (IISD), Cornell University (2020) Ceres2030: sustainable solutions to end hunger; ending hunger, increasing incomes, and protecting the climate: what would it cost?

Laborde D, Mamun A, Martin W, Piñeiro V, Vos R (2020) Modeling the impacts of agricultural support policies on emissions from agriculture. IFPRI discussion paper, no. 1954. International Food Policy Research Institute. https://tinyurl.com/y4cvmv5v (Also available as World Bank working paper: http://hdl.handle.net/10986/34453)

Millan A, Limketkai B, Guarnaschelli S (2019) Financing the transformation of food systems under a changing climate. CCAFS report. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen. https://cgspace.cgiar.org/handle/10568/101132

Parry I, Black S, Vernon N (2021) Still not getting energy prices right: a global and country update of fossil fuel subsidies. IMF working paper. September 2021 WP/21/236. Fiscal Affairs Department. IMF

UNFCCC Standing Committee on Finance (2021) Fourth (2020) Biennial assessment and overview of climate finance flows. https://unfccc.int/sites/default/files/resource/54307_1%20-%20UNFCCC%20BA%202020%20-%20Report%20-%20V4.pdf

von Braun J, Díaz-Bonilla E (2021) Letter: perpetual bonds can help states fight hunger. Financial Times. First available online on 06 June 2021. https://www.ft.com/content/6c0fae16-0662-42b5-a2b5-90b4b6facc78

von Braun J, Chichaibelu BB, Cullen MT, Laborde D, Smaller C (2020a) Ending hunger by 2030 – policy actions and costs. Policy brief 12 Oct 2020

von Braun J, Afsana K, Fresco L, Hassan M, Torero M (2020b) Food systems – definition, concept and application for the UN food systems summit. A paper from the Scientific Group of the UN Food Systems Summit. Draft 20 Dec 2020 (for discussion)

ZEF (Center for Development Research, University of Bonn) and FAO (2020) Investment costs and policy action opportunities for reaching a world without hunger (SDG 2). Bonn/Rome. https://www.zef.de/fileadmin/downloads/ZEF_FAO_SDG2.pdf

Trade and Sustainable Food Systems

Andrea Zimmermann and George Rapsomanikis

1 Introduction

Trade is an integral part of our food systems. It connects people at all stages of agricultural and food value chains, promotes food security, is inherent to economic growth, and interacts with society and the environment. Since 1995, agricultural and food trade has more than doubled in value, quantity, calories, and land used for export (FAO 2020b; Qiang et al. 2020; Traverso and Schiavo 2020). Today, about one-third of agricultural and food exports in the world are traded within global value chains that encompass at least three countries (Fig. 1; FAO 2020b).

Agricultural and food trade links the food systems of countries and plays a crucial role in providing consumers worldwide with sufficient, safe and nutritious food, while generating income and employment for farmers, workers and traders in agriculture and the food industry.

Trade is closely related to economic development. Developed countries make up more than 60% of agricultural and food trade. Emerging economies, such as Brazil and China, have been increasing their market shares since the early-2000s and play an increasingly important role in global agricultural and food markets (FAO 2018a, b).

At the same time, and as the interdependence among nations strengthens, the role of trade in society and income distribution becomes more important (FAO 2020b). This, together with the emergence of new players in global markets, has induced lively debates on what economic, environmental and social outcomes trade and global markets generate. These debates have been intensified and broadened through significant concerns about inequality, growing environmental consciousness,

A. Zimmermann (✉) · G. Rapsomanikis
Commodity Markets and Development Team, Markets and Trade Division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
e-mail: Andrea.Zimmermann@fao.org

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_36

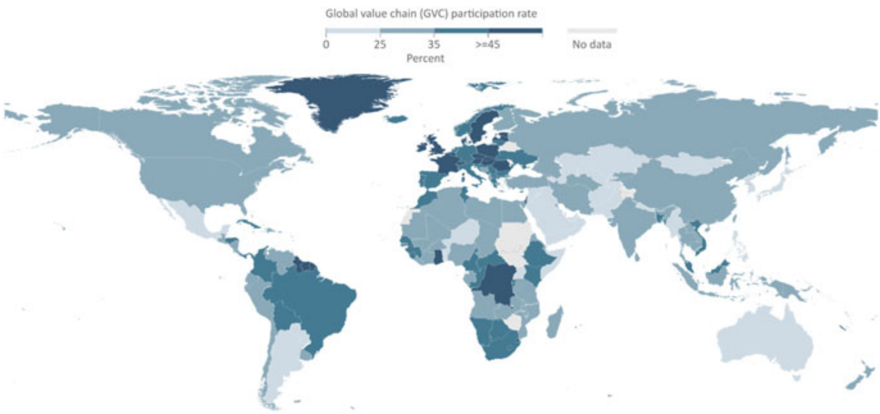


Fig. 1 Participation in global value chains in food and agriculture. (Source: Based on analysis from Dellink et al. (2020); adapted from FAO (2020b))

changing lifestyles and diets that have been attributed to globalization and the related concerns about health risks associated with increasing shares of overweight and obese people (FAO 2016, 2018b, 2020b).

The COVID-19 pandemic has fueled fears about the functioning of global agricultural and food trade, and the discussion about reshoring tendencies in manufacturing and services and shortening global value chains has also reached food and agriculture.

However, agricultural production strongly depends on specific natural resource endowments and environmental conditions, such as soil characteristics, altitude, water availability and climate. These are distributed unevenly across the world and, together with differences in technology, shape trade flows. This distinguishes agricultural and food trade from trade in manufacturing and services. In fact, since the Neolithic period, agricultural and food trade has evolved in line with the comparative advantage derived from these immutable characteristics (see, for example, Smith et al. 2015).

At the same time, the demand for food is most rapidly increasing in regions where population and income growth are strongest, but which may not always be the most productive. These developments may reinforce the role of trade in ensuring food security and providing nutritious and healthy diets for all.

This chapter highlights the role of agricultural and food trade in moving food globally from surplus to deficit regions, thus ensuring food security and serving a fundamental food system function. It further addresses the interlinkages among trade and economic development, the environment and societal shifts in food consumption. Ultimately, the chapter illustrates the role that trade can play in balancing different aspects of sustainability from a global perspective and points out the scope for further research and novel policy approaches.

2 Trade, Food Security and Nutrition

Trade in food and agriculture can help balance food supply and demand globally by moving food from surplus to deficit areas. Higher food imports can increase the *availability* of calories and nutrients in a country. Through increased food supply, food prices would fall, thus improving *access* for net consumers. At the same time, decreasing food prices induced by import competition can also affect incomes and livelihoods of domestic farmers and food processors who are net producers. However, for a country, increased trade openness may also allow for better access to other countries' markets and promote exports of agricultural products to these markets, thereby creating and expanding employment opportunities and raising workers' incomes (Dithmer and Abdulai 2017; FAO 2016).

By moving food from surplus to deficit areas at times of shortages, which might, for example, be caused by natural disasters or seasonal growing patterns, trade can also contribute to more stable food supplies and prices, and thus to the *stability* dimension of food security. The exchange of foods that are produced under specific climate, soil and other natural conditions can contribute to the diversity of diets (Remans et al. 2014) and improved food *utilization* (FAO 2016, 2018b).

Although the theoretical pathways of how trade can affect food security and nutrition are well established, the linkages between agricultural and food trade and food security and nutrition are complex, and some of the impacts can offset each other. This makes the identification of the effects in empirical assessments difficult. In fact, there has so far been only little empirical evidence on these relationships (FAO 2018b; Mary 2019).

A relatively new strand of literature contrasts trade openness with direct nutritional outcomes such as undernourishment. At the global level, it was shown that agricultural trade openness has, on average, a positive net impact on food security measured as dietary energy supply adequacy. It also increased dietary diversity measured as the share of calories from non-staple foods and protein consumption (Dithmer and Abdulai 2017). However, the exact mechanisms and impacts can vary by context and stage of development (FAO 2016). For example, in a sample of 52 developing countries, food trade openness was associated with an increase in the prevalence of undernourishment. In fact, it was found that food supply increased as a result of increased trade openness, but, in net food-importing countries, the negative effect on agricultural producers and the food sector caused by import competition prevailed. This result could point to efficiency constraints in net importing countries with large agricultural sectors (Mary 2019).

Besides trade openness, the ease with which trade takes place also matters. For example, poor trade facilitation, with high bureaucratic requirements and lengthy export and import times, can negatively affect various dimensions of food security, as shown in a study of 45 African countries observed between 2006 and 2015 (Bonuedi et al. 2020).

Among the most-researched relations within the area of agricultural trade and food security are the linkages between trade and price volatility. Price volatility, which is described by episodes of large and unexpected price changes, can intensify and contribute to risks to food security (Kalkuhl et al. 2016). In particular, the food price crisis of 2007/08 has triggered a plethora of studies on its causes. While a whole set of macroeconomic and sector-specific drivers for the price surges has been identified (Tadesse et al. 2014), it is now well established that trade restrictions that were imposed by many countries in response to rising food prices exacerbated food price volatility.

Trade-restricting measures, such as high import tariffs and export bans, reduce the volume traded in international markets, and thus constrain the exchange mechanism between surplus and deficit areas. This makes markets more vulnerable to shocks and increases price volatility at times of crisis (Anderson 2012). To insulate themselves from sudden food price surges, countries tend to impose new or heighten existing export restrictions and/or lower import barriers so that the domestic price does not rise as high as the world market price (Rapsomanikis 2011), with the effect that world markets become even thinner, market uncertainty increases and international food prices become more volatile (Anderson and Nelgen 2012; Anderson et al. 2013; Martin and Anderson 2012).

Export restrictions, especially when applied by major exporters, can significantly harm their trading partners, in particular, net food-importing developing countries. For example, export restrictions implemented by various countries between 2006 and 2011 increased international price volatility for wheat and rice. In fact, the contribution of export restrictions to price volatility appeared to be on the same order of magnitude as that from key macroeconomic variables (Rude and An 2015).

At the same time, export restrictions also affect domestic markets (FAO 2016). For example, export restrictions on wheat applied by major wheat exporters during the 2007/08 food price crisis not only harmed their trading partners, but also reduced prices for domestic producers and increased domestic market instability. The negative market effects discouraged private investors and prevented the countries that imposed the export restrictions from achieving their production potential (Götz et al. 2013).

Dietary diversity is important for the adequate provision of nutrients and human health. As natural conditions do not allow for the production of all foods everywhere, trade is an important means to help diversify diets. A number of studies investigate the relationship between trade and dietary diversity.

Since the beginning of the 1960s, trade in crops has expanded and diversified. This process has been identified as the main driver of globally diversifying supply of vegetable products (Aguiar et al. 2020). In fact, the diversity of foods produced is a strong predictor of food supply diversity only in low-income countries, which are less integrated in international trade. In middle- and high-income countries, food supply diversity was shown to be independent of production diversity, and other factors, including international trade, contributed more to the diversity of a country's supply (Remans et al. 2014).

Although lower-income countries are often not well integrated in global markets, a study found that they still tend to improve their nutrient supply through trade, in particular, the supply of energy, protein, zinc, calcium, vitamin B12 and vitamin A

(Wood et al. 2018). However, in another study, it was found that, while trade distributes substantial volumes of nutrients, its role in bridging the nutrient adequacy gap[1] was only marginal in low- and lower-middle-income countries. International trade helped close the nutrient gap in most high- and upper-middle-income countries, even where domestic production ensured only a very low nutrient adequacy (Geyik et al. 2021).

Taken together, the evidence shows that trade is indispensable to ensure food security in all its dimensions. Without trade, the availability and accessibility of foods and nutrients would be more unevenly distributed, any form of domestic production disruptions would cause serious concern for food security, and diets would be less diverse.

However, increased competition through rising imports may be challenging for farmers in developing countries that are characterized by low efficiency and productivity constraints associated with poor physical infrastructure, weak institutions and low skills.

3 Trade, Growth and Inequality

The global trade regime – as reflected by the WTO rules and a multitude of trade agreements – has contributed to increasing trade significantly since the last decades of the twentieth century. Population growth and urbanization, rising incomes and improvements in transport and communication technology have colluded with lower policy-induced trade barriers to fuel trade (FAO 2020b).

Most economists would agree that openness to international trade promotes economic growth (Irwin 2019). Trade results in efficiency gains, as resources are allocated in line with comparative advantage, which is shaped by differences in technology and relative factor endowments. In agriculture, where differences in land and water endowments and climate are significant across countries, gains from openness and market integration can be large (Martin 2018). These gains can add to the rate of growth of the economy, but are difficult to estimate.

Isolating the impacts of trade openness, whether it comes from a reduction in trade costs or trade policy reforms, is challenging, given the myriad factors that affect economic growth. In addition, focusing the analysis on single sectors, such as food and agriculture, can be complex. Using structural models to test counterfactual scenarios is the analysts' preferred method for untangling the role of trade and trade policy in economic growth. For example, a study looking at the effect of market integration across US counties between 1880 and 1997 suggests that such gains are

[1]The nutrient adequacy gap describes the difference between nutrient requirements and actual availability, referring to six essential nutrients (protein, iron, zinc, vitamin A, vitamin B12 and folate) (Geyik et al. 2021).

substantial as agricultural production is allocated according to comparative advantage (Costinot and Donaldson 2016).

In addition to the effect of efficiency gains, trade facilitates technology and knowledge spillovers across countries which promotes growth by improving the production process, increasing product quality and innovating new products (Grossman and Helpman 1991). Indeed, since 1995, the growth in food and agricultural trade has taken place together with increases in agricultural productivity per capita, particularly in emerging and developing economies (FAO 2018a).

This conventional wisdom concerning the effects of trade openness on growth and productivity is being questioned by many practitioners. Gains from trade are asymmetrically distributed. Trade openness affects the prices of goods and those of production factors, including labor, and thus can result in winners and losers. In agriculture, a major concern relates to the ability of smallholder farmers from developing countries to compete effectively in open markets.

A handful of studies focus on the impact of trade openness on agricultural productivity, with the underlying hypothesis being that trade facilitates the diffusion of technology and knowledge spillovers. Focusing on how agricultural productivity in 44 countries – both developed and developing – converges at higher levels, one study finds that openness to trade increases labor productivity growth rates in agriculture within an analytical framework that also takes into account the costs of technology diffusion and adaptation (Gutierrez 2002).

Additional evidence suggests that trade openness can have a short-run negative impact on agriculture's efficiency (Hart et al. 2015). However, in the long run, it is found to increase efficiency in agriculture, reflecting the ability of the sector to adapt to global markets and increased competition through technology adoption, but also through the withdrawal of inefficient farms from the sector. In Chile – a country that liberalized trade in the 1990s after a period of import-substitution policies – an analysis of 70,000 farms suggests that trade openness is positively related to farm yields (Fleming and Abler 2013).

Downstream, a study of more than 20,000 food firms in Italy and France suggests that import penetration in both final food products and intermediate inputs systematically contributes to firm-level productivity growth (Olper et al. 2017). Participation in agricultural and food global value chains, either through imports of inputs or exports of intermediate products, is also found to promote agricultural labor productivity (FAO 2020b; Montalbano and Nenci 2020). The main mechanism for this lies in how value chains unbundle the production process, allowing farms and firms to leverage their comparative advantage in global markets and facilitating the transmission of improved technology, leading to better farm practices and improved labor productivity.

These linkages between trade openness and technology are unwrapped by a micro-level data study of the impact of trade in agricultural inputs on the productivity of 1.1 million fields across 65 countries. Since the 1980s, trade openness in agricultural inputs has been found to result in significant shifts from traditional farm technologies to modern ones, thus having distributional implications for productivity and welfare across the world (Farrokhi and Pellegrina 2020).

In addition to the efficiency gains from better resource allocation in agriculture and the dynamic effects on agricultural productivity through the transmission of technology and knowledge, trade openness in food and agriculture can generate significant effects on the broader economy by facilitating structural transformation. Trade in food, especially imports, can help meet domestic food requirements and allows for labor to be allocated to non-agricultural sectors, thus promoting economic growth and development (Tombe 2015). Analyzing the process of structural transformation in the UK in the nineteenth century and, more recently, in South Korea, a study finds that agricultural imports played a crucial role in the transformation process of both economies (Teignier 2018).

Trade openness, either by intensifying competition or through fueling the structural transformation process, can promote growth, but can also affect income distribution and inequality. A recent analysis of the impacts of eliminating tariffs on agricultural products across low- and middle-income countries pointed to increases in both income and inequality (Artuc et al. 2019). The results suggest that, on average, liberalizing agricultural trade would increase household incomes. At the same time, eliminating import tariffs was found to have highly heterogeneous impacts across countries, and, within countries, across households. In most countries, the top 20% of the richest households would gain more from liberalization than the bottom 20%, thus exacerbating inequality.

In the context of food systems, trade openness highlights the trade-offs between promoting economic efficiency and generating positive social outcomes. Integrating smallholder farmers in global markets is challenging. Policies that promote trade openness often tend to underplay market failures, and complementary actions to address inequality are necessary. Inclusive business models, such as contract farming, can address the constraints that farmers in developing countries face in entering markets and global value chains (FAO 2020b). However, a range of public policies and investments, such as carefully designed input subsidies targeted at smallholder farmers, skill upgrades and education, the removal of labor market rigidities, and improvements in infrastructure and regulation, can complement the market mechanism and promote a fair structural transformation.

4 Trade, Environment and Climate Change

Agriculture builds one complex with the environment. Natural resources and climate are inputs to agricultural production, and a part of the human impact on the environment is transmitted through this production process.

While expected changes in climatic and environmental conditions over the coming decades will affect food security and nutrition, short-term shocks, such as natural hazards, pests, diseases and extreme weather events, already lead to harvest losses and supply chain disruptions. In regions with limited access to international markets and where food production and consumption are tightly coupled, these shocks can more readily translate into local shortages of (specific) foods (Davis et al. 2021).

At the same time, changes in trade flows are associated with changes in agricultural production, which can influence greenhouse gas (GHG) emissions, land and water use and biodiversity through positive and negative externalities. Because of the spatial heterogeneity of resource availability, resource productivity, and farming practices, the environmental impact of producing food is localized and highly dependent on its origin. Depending on whether the environmental impact of agricultural production is greater or lesser in the exporting region than in alternative production sites, agricultural and food trade can therefore either increase or reduce the aggregate impact of agriculture on the environment globally (Dalin and Rodríguez-Iturbe 2016).

By contributing to a better allocation of production across countries, trade can improve the utilization of natural resources in agriculture at the global level, which, in the aggregate, can be beneficial to the environment (Roux et al. 2021). Without trade, some countries would have to produce a wider range and larger quantities of foods, even if their natural endowment was not compatible with such an expansion, placing additional pressure on their ecosystems.

For example, increased agricultural production in net food-importing countries in the Middle East and North Africa would likely be at the expense of further water depletion in an already water-scarce region (Biewald et al. 2014).

However, greater import demand and demand for specific products in some regions of the world can also lead to the depletion of natural resources and/or increased pollution in exporting countries.

In particular, if comparative advantage is derived from differences in environmental regulation, production might shift to countries with relatively laxer regulation, leading to worse environmental outcomes in the aggregate (Grossman and Krueger 1991).

Moreover, trade can induce technological change, including through the transfer of technology and best practices between trading partners, and lead to increased productivity and more efficient resource use (Grossman and Krueger 1991). For example, greater agricultural output per hectare may release some agricultural land from production (land sparing), which thus becomes available for natural habitats and species, contributing to wildlife biodiversity (Phalan et al. 2011).

In order to analyze the impact of trade on resource use and pollution, a growing literature expresses trade flows in terms of the resource inputs and emission content they carry (virtual resource trade, carbon/land/water footprint). In fact, while trade was not found to be a major topic in ecosystem research based on a survey of ecological journals published in 2017 (Pace and Gephart 2017), the literature on interactions between trade and the environment has been rapidly expanding since then. The analysis of impacts of agricultural trade on the environment mainly centers on climate change and the use of water and land, also covering deforestation (Balogh and Jámbor 2020).

4.1 Climate Change

Agricultural trade can play a role in both adjusting to the effects of climate change (adaptation) and reducing GHG emissions from agriculture (mitigation).

4.1.1 Trade as Adaptation Mechanism

Climate change may lead to significant trade disruptions in the short term (through extreme weather events) and to long-term changes in trade patterns through the altering of countries' comparative advantages. Trade could help countries adapt to short-term supply disruptions and long-term changes in comparative advantage triggered by climate change (FAO 2018a).

As climate change is expected to have an uneven effect across regions, trade can be an important avenue for ensuring food security. In studies on climate change impacts on agriculture in the time period 2050 to 2100, low-latitude regions such as the Near East, North Africa, sub-Saharan Africa and South Asia are often projected to be adversely affected, whereas high-latitude regions such as North America, parts of South America (e.g., Chile), Central Asia and Eastern Europe are expected to experience largely positive impacts on agricultural production (FAO 2018a; Reilly 1995; Wheeler and von Braun 2013).

Under deteriorating conditions for agricultural production due to climate change, food imports by relatively more adversely affected (often developing) countries will have to come from those countries (often developed) that are relatively less adversely affected.

In fact, most studies integrating biophysical and economic models project a stronger role for trade as a result of climate change at the global level (Ahammad et al. 2015; Baldos and Hertel 2015; FAO 2018a; Havlík et al. 2015; Janssens et al. 2020; von Lampe et al. 2014, 2014; Nelson et al. 2014; OECD 2015; Schmidhuber and Tubiello 2007; Fig. 2).

However, the adaptive role of trade in ensuring food security could be constrained by trade restrictions and structural barriers to adjustment.

While a substantial role in mitigating adverse effects from climate change in agriculture would be played by endogenous production adjustments, such as shifts in production patterns, in line with evolving comparative advantage (Costinot et al. 2016; Gouel and Laborde 2021), freer trade could indeed offset part of the welfare losses from climate change (Costinot et al. 2016; Gouel and Laborde 2021; Stevanović et al. 2016; Wiebe et al. 2015). Open markets could also contribute towards food security, especially in adversely affected regions that are already characterized by a high prevalence of undernourishment (Baldos and Hertel 2015; Janssens et al. 2020).

The aggregate patterns of climate change effects at the global and regional levels can mask differences in the distribution of gains and losses within countries and regions. Through the balancing mechanism of international trade, agricultural and

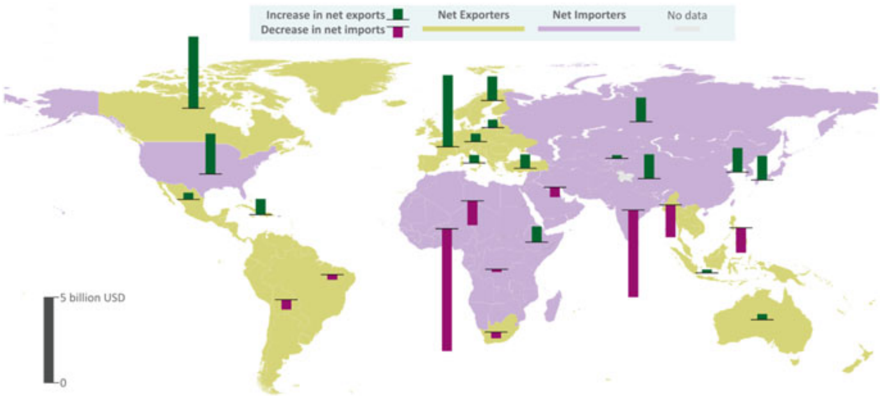


Fig. 2 Projected changes in agricultural net trade in 2050: climate change scenario relative to a no-climate change baseline (in billion USD, 2011 constant prices). (Source: Based on analysis from Cui et al. (2018); adapted from FAO (2018a))

food prices in adversely affected regions would be relatively lower under free trade, compared to a scenario in which trade is restricted. This would benefit net food consumers, while agricultural producers could lose out. At the same time, farmers in less affected or even benefiting regions could gain from relatively higher prices under free trade, while consumers would face welfare losses (Stevanović et al. 2016).

As labor productivity in agriculture would be more affected by higher average temperatures than that in other sectors of the economy, affected countries could adapt to climate change by importing food and shifting labor towards non-agricultural sectors. However, under limited market integration, subsistence food requirements in many developing countries could even drive specialization towards, rather than away from, agriculture, thus exacerbating losses from climate change (Nath 2020).

4.1.2 Trade in Climate Change Mitigation

Foresight analyses suggest that, between 2012 and 2050, agricultural production will have to increase by 50% to provide food for a growing and progressively wealthier population (FAO 2018c). Such increases in production could also result in increases in global GHG emissions, unless food systems become 'emissions efficient' and produce lower emissions per unit of output. And, as trade expands to contribute to climate change adaptation, increased transport will also add to emissions (FAO 2018a; Pendrill et al. 2019; Schmitz et al. 2012, 2015). The ultimate impact on global emissions depends on whether imports are sourced from systems that operate at lower emission efficiency or from ones that operate at higher emission efficiency (Table 1).

Table 1 Impacts of emissions leakage through trade

Relative emissions efficiency (between imports that displace domestic products)	Impact on global emissions	Result of emissions leakage
Imports are produced in systems with **lower emissions efficiency** (higher emissions per unit of output)	**Increase** in global emissions	**Emissions misallocation**
Imports are produced in systems with **higher emissions efficiency** (lower emissions per unit of output)	**Decrease** in global emissions	**Emissions reallocation**

Source: FAO (2018a)

Several policy incentives can help improve emission efficiency and lower GHG emissions. For example, taxing GHG emissions is a way to 'internalize' their full cost to the society and can provide incentives to farmers to adopt technologies and practices that promote climate change mitigation (FAO 2018a).

However, mitigation policies implemented through a uniform global carbon price would curb emissions, but also reduce agricultural production, raise agricultural commodity prices, and impact food security. Underlining the trade-offs among food security, nutrition and emission reduction targets, especially for developing countries, the most significant reduction in consumption as a result of global carbon taxes has been projected for livestock products in sub-Saharan Africa (FAO 2018a; Havlík et al. 2015).

If, instead, carbon taxes were imposed unilaterally, countries that try to internalize the cost of GHGs may inadvertently confer a competitive advantage on others that do not impose a similar measure. This would imply the risk of increasing production and exports from countries without mitigation policies, resulting in emissions leakage. In this case, the impact of this leakage on global emissions may be positive (emissions reallocation) or negative (emissions misallocation), depending on the relative emission efficiency of domestic production vis-à-vis imports (Table 1). Specific trade policies can contribute towards addressing the trade-off between food security and emission reduction targets. To even out disparities between domestic and international levels of carbon taxes, border measures, such as border tax adjustments based on food products' carbon footprints, could be implemented (FAO 2018a).

Instead of, or in addition to, taxing GHG emissions, the labeling of final products with respect to GHGs emitted during their production can be a way of shaping consumer preferences towards lower-emitting production practices.

Common to all of these policies is the fact that they would require an accurate and complete assessment of the costs incurred to the society by the GHGs emitted during agricultural and food production, or, as is usually done in practice, a reliable estimate of the direct emissions involved in the production process of different foods, namely, the carbon footprint.

However, the consistent accounting of GHG emissions in agriculture already implies several challenges, including methodological issues and excessive data requirements. Carbon footprints need to be quantified encompassing the emissions generated in the production and supply of inputs used by farmers, direct and indirect emissions generated in agricultural production processes, and subsequent emissions associated with the transportation, processing, storage, and delivery of products to consumers (FAO 2018a; Rosenzweig et al. 2020). In particular, agricultural production involves many different sources of emissions that need to be covered. Moreover, these sources of emissions are often diffuse, difficult to monitor and varied by location (Escobar et al. 2020). For example, fertilizer use is a major source of nitrous oxide emissions, but measuring the emissions from a given area of land is complicated, since it depends on factors other than the amount of fertilizer applied, many of which are site-specific (e.g., management practices, soil types, and weather) (FAO 2018a).

In addition to overcoming technical challenges in determining carbon footprints in agriculture and possible trade-offs with food security through certain mitigation policies, the carbon-accounting mechanisms would also need to be agreed upon internationally to avoid any trade disputes (FAO 2018a).

Alternative policy approaches to reducing GHG emissions from agriculture center on domestic measures that incentivize climate-smart agricultural practices. These can be indirectly related to trade by altering traded volumes and market signals (FAO 2018a).

4.2 Land, Water, Biodiversity

Besides GHG emissions, agricultural production can affect natural resources, such as land and water, and biodiversity. Through trade, these external effects can occur in countries far away from the final point of consumption. In the case of water, these externalities are mainly positive (Dalin and Rodríguez-Iturbe 2016). By importing products and services from countries with abundant water resources, water-deficient countries can alleviate the pressure on their own water supplies (Deng et al. 2021; Pastor et al. 2019).

With increasing agricultural trade, the total land use embodied in said trade also more than doubled (almost tripled) between 1986 and 2016. As in the case of water, countries with absolute or relative abundance of land, such as the United States, Brazil and Argentina, are net exporters of 'virtual' agricultural land. Countries with relatively less land per capita, such as Japan, the Netherlands and mainland China, are among the net importers of 'virtual' land. Countries with relatively little arable land but high yields, such as European and some Asian countries, tend to export high-value agricultural products, such as fruits, vegetables and animal-based foods (Qiang et al. 2020).

However, due to trade-offs with other resource uses, trade may not always allocate production to the regions with the most efficient land use (Roux et al.

2021). For example, a globally optimal allocation of water use might imply an expansion of land use into natural areas and forests (Pastor et al. 2019).

By specializing agricultural production away from certain products that are increasingly imported, land use changes can also occur in importing countries. For example, increased nitrogen pollution was observed in countries that shifted from domestic soybean production to increased soybean imports. In these cases, farmland that was originally used for cultivating soybeans, which can fix nitrogen and require significantly less fertilizer, was converted to grow crops such as wheat, corn, rice and vegetables, which are more prone to overfertilization (Sun et al. 2018).

Land use also affects biodiversity. On the one hand, some farming systems can be beneficial to biodiversity, and many ecosystems depend directly on agricultural land use (Henle et al. 2008; Tscharntke et al. 2012). On the other hand, the conversion of natural habitats to farmland can lead to the displacement or eradication of wildlife (Rockström et al. 2009), and biodiversity in existing agricultural systems can be affected by an overuse of agrochemicals and certain forms of land management.

By distinguishing between biodiversity loss from agricultural land used for exports and that from land used for domestic consumption, increasing import demand from developed countries is sometimes found to be the main driver for biodiversity loss in exporting countries (Chaudhary and Brooks 2019; Chaudhary and Kastner 2016; Lenzen et al. 2012; Moran and Kanemoto 2017). However, more systematic research covering multiple disciplines, various dimensions/indicators of biodiversity and counterfactuals is needed to provide comprehensive assessments of biodiversity footprints (Baylis et al. 2021; de Chazal and Rounsevell 2009; Marquardt et al. 2019; Ortiz et al. 2021).

Overall, the evidence on the effects of extreme weather events, natural hazards, pests and diseases on food systems is concentrated on the main staple crops (maize, rice and wheat) and relatively few types of shocks (Davis et al. 2021). Similarly, the analysis of the impact of trade on the environment also tends to focus on aggregated trade or on trade in staple food crops. Only very recently have studies considered the impacts of a broader range of specific products, such as trade in cash crops (Sporchia et al. 2021).

Ensuring food security and satisfying dietary needs for a growing number of people, especially in already food-deficient regions, may not be possible without exploiting the relative comparative advantage in other regions of the world.

5 Globalization of Food: Trade, Social and Health Impacts

Improvements in productivity and the expansion of international trade have increased the availability of food, reduced food prices and contributed to overall declining rates of undernutrition in the world. At the same time, together with higher incomes and a more sedentary lifestyle, trade has also been associated with increasing rates of overweight and obesity worldwide (FAO 2018b, 2020b).

The liberalization of trade and investment has sometimes been identified as being among the key mechanisms through which globalization impacts health (Cowling et al. 2018; Mary and Stoler 2021). Overall, the empirical literature appears to point to a broad association among trade liberalization, improved dietary quality and reduced undernutrition (Cuevas García-Dorado et al. 2019).

However, subject to context and method of analysis, the body of empirical work investigating the relationship among globalization, trade in food and agriculture and health outcomes finds mixed results (Cowling et al. 2018; Cuevas García-Dorado et al. 2019; Mary and Stoler 2021).

Some studies explore the relationship between globalization indices and average body mass index (BMI: kg/m^2) in specific countries. In low-income countries, increasing mean BMIs can indicate a reduction in undernutrition, while high mean BMIs can also indicate a greater prevalence of overweight in a country.

Economic globalization, measured as an index of trade and foreign direct investment (FDI) flows and restrictions,[2] was found to be positively related to increases in mean BMI (Vogli et al. 2014). The relationship between economic freedom[3] and BMI was found to be very weak overall. Only in the case of men living in developing countries was an increase in economic freedom associated with slightly higher BMIs (Lawson et al. 2016).

Several studies consider indicators different from BMI, such as the prevalence of obesity and/or overweight. The economic integration (or economic globalization; see above) between countries is often shown to have no or a decreasing effect on the prevalence of overweight (Costa-Font and Mas 2016; Goryakin et al. 2015; de Soysa and de Soysa 2018).

Globalization can also manifest in shifts in socio-cultural norms, which, in turn, affect consumer preferences, diets and nutritional outcomes. A closer social integration, measured as an index of personal international contacts, international information flows and cultural proximity (Dreher 2006), is sometimes found to be positively associated with obesity (Costa-Font and Mas 2016; Goryakin et al. 2015).

However, socio-cultural aspects of globalization and access to information and communication technology were found to reduce the share of overweight and obese

[2]Several studies distinguish among the impacts of economic, political and social globalization based on the KOF index (Dreher 2006). According to this index, economic integration refers to actual trade and FDI flows and restrictions. Political integration is composed of a country's international engagement with other countries and international organizations, and social integration measures personal international contacts, international information flows and cultural proximity.

[3]Economic freedom was measured with the Economic Freedom of the World index. The index assesses the degree to which policies and institutions of countries are supportive of economic freedom. It measures economic freedom in five broad areas: size of government; legal systems and property rights; sound money; freedom to trade internationally; and regulation (Gwartney et al. 2013).

young people aged between 15 and 19, suggesting that increased international interconnectivity in this age group might help spread knowledge about healthier eating and lifestyle habits (Knutson and de Soysa 2019).

Recent studies also explore the relationship between (general) trade openness and obesity rates. For example, an increase in trade openness was associated with increasing overweight and obesity rates in Brazil (Miljkovic et al. 2018) and at the global level (An et al. 2019). This relationship appeared to be stronger in developing countries with high economic growth rates, while no relationship between trade openness and obesity prevalence was identified among high-income countries (An et al. 2019).

In a study on the effects of social globalization and trade openness on average BMI and different indicators of diet quality, increasing social globalization was associated with higher mean BMI, animal protein and sugar supply. These results seem to be driven by specific components of social globalization such as information flows through television and the internet. Trade openness did not reveal any effect on dietary outcomes or health (Oberlander et al. 2017).

A critical review of methodological approaches used in quantitative analyses of the impacts of global trade and investment on non-communicable diseases and risk factors encourages future studies, *inter alia*, to clearly define the exposure of interest and, in particular, not conflate trade and investment, explore the mechanisms of broader relationships that might steer the results, adjust for reverse causality; increase the use of individual-level data, and consider sector-specific, rather than economy-wide, trade and investment indicators (Cowling et al. 2018).

Empirical evidence on the interlinkages between trade in food and agriculture and nutritional outcomes remains scarce, and, so far, only a few studies have explored these linkages more systematically (FAO 2020b). Agricultural and food trade constitutes an important means to ensure dietary diversity. However, as trade improves the availability and accessibility of both foods necessary for a healthy diet and foods high in fat, sugar, salt and calories, the effects on nutritional outcomes can be mixed (FAO 2018b, 2020b; Krivonos and Kuhn 2019).

In fact, trade has helped overcome the constraints that the uneven distribution of natural resource endowments poses on the supply of foods and nutrients across countries. A study suggests that trade resulted in food and nutrients being more equally distributed in 2010 than in 1970 (Bell et al. 2021).

Agricultural trade openness has also been associated with increasing overweight and obesity prevalence in developing countries (Mary and Stoler 2021); rising imports of sugar and processed foods were found to be correlated with slightly higher average BMIs (Lin et al. 2018); and the exposure to food imports from the United States of America was found to explain part of the rise in obesity prevalence among Mexican women between 1988 and 2012 (Giuntella et al. 2020).

6 The Trade Policy Environment

International trade negotiations in the General Agreement on Tariffs and Trade (GATT), and subsequently under the WTO, have contributed to opening global markets, and barriers to agricultural and food trade have declined since the Uruguay Round of the GATT and the WTO Agreement on Agriculture in 1995.

Since the beginning of the 1990s, the number of regional trade agreements that have been notified to the WTO has also risen, from fewer than 25 in 1990 to more than 350 being in force in 2021. European countries are currently the main partners in regional trade agreements, followed by countries in East Asia (WTO 2021).

Considerable attention has been paid to prospects for development from the African Continental Free Trade Area (AfCFTA). The AfCFTA has been signed by 54 and ratified by 36 of the 55 African Union (AU) Member States, and entered into force in May 2019, with trade commencing in January 2021 (FAO and AUC 2021). The AfCFTA is expected to significantly increase intra-African trade of agricultural and food products, with estimates ranging between a 20% and 30% increase in 2040 compared to a scenario without the AfCFTA (United Nations Economic Commission for Africa 2018; United Nations Economic Commission for Africa and Trade-Mark East Africa 2020).

In contrast to multilateral trade agreements, regional trade agreements grant concessions only to a few trade partners, discriminating against others. The proliferation of regional trade agreements is sometimes seen as “building blocks” towards multilateral trade liberalization, but could also hinder further integration (Bhagwati 1991, 1993). This discussion is of particular relevance in the agricultural sector (Sheldon et al. 2018), for which the depth of many regional trade agreements, and thus their actual potential to impact members’ trade, has also been called into question (Grant 2013).

More recently, the use of environmental provisions in trade agreements has increased considerably, a trend that is particularly strong in agreements between industrialized and developing countries (Morin et al. 2018). Moreover, the consideration of nutritional objectives in trade agreements has also emerged (Thow and Nisbett 2019), with the discussion in multilateral fora focusing on issues related to nutrition labeling (Thow et al. 2018).

While the strong focus on environmental and nutrition aspects in trade policy is relatively new, non-tariff measures, especially food safety standards and their international harmonization, continue to be a major point of discussion in agricultural trade (FAO 2020a; Santeramo and Lamonaca 2019; Wieck 2018).

These discussions on environmental provisions and nutritional issues in the context of trade trace the multiple trade-offs among economic, environmental and social objectives within food systems. They also highlight that, in general, the market mechanism cannot guarantee the provision of a range of social and environmental benefits that are central to sustainable development. Food and agricultural trade may result in negative environmental outcomes or may fail to address social objectives, such as reducing inequality.

In food and agriculture, trade policy measures address a broad array of mainly economic objectives. For example, tariffs are commonly used to protect local producers from international competition and can contribute towards maintaining a level of farm income that keeps pace with income in other economic sectors. Tariffs are also used to reduce import dependence and promote self-sufficiency in staple foods. Export restrictions can lower the domestic price of food and contribute towards food security in the short term. Both tariffs and export taxes provide an important source of government revenue. Other measures, such as non-tariff barriers, aim at improving the safety and quality of food. All of these policy instruments should address their objectives as sustainably as possible, but can also entail positive or negative external effects to society and the environment.

Within a food systems approach to trade, policy formulation based on tariffs or export restrictions to address environmental and social objectives, such as the preservation of biodiversity, better nutrition or equity, might be very costly and insufficient to achieve all sustainability targets.

Externalities or non-economic objectives, such as those considered in this chapter, are best addressed by policies that act directly on the relevant margin, for example, using domestic policy instruments such as taxes and subsidies, rather than the introduction of trade distortions. Formulating policies at the margin implies a 'targeting principle' that allows for ranking different policy instruments in line with their effectiveness in addressing externalities or non-economic objectives (Bhagwati and Ramaswami 1963; Dixit 1985; Rodrik 1987). Trade policies may not be the best and most efficient way to address externalities and achieve environmental objectives. For example, a domestic carbon tax acts on the margin, providing incentives to farmers to reduce emissions and adopt climate-smart farming technologies.

In some cases, policy objectives can be independent of each other. For example, the prevalence of overweight and obesity can be addressed by taxes on the sugar or fat content of food or raising awareness of healthy diets, rather than trade policies.

Political economy considerations suggest that trade policies can also be endogenous in the sense that they have been created by pressure groups, such as producer organizations, exerting influence on the policy-making process. In this case, the 'targeting principle' may not apply. For this reason, it is important to understand the process by which policies are formulated and consider context-specific policy approaches, instead of broad principles (Rodrik 1987).

While open markets and free trade are conducive to global food security and promote economic growth, liberalization processes can create winners and losers, and thus should be framed and supported by complementary policies that address market failures, externalities and system-inherent distortions. For example, addressing inequality can be achieved by redistributing gains from liberalization and facilitating mobility across sectors.

In order to effectively design such policies, a better understanding of their simultaneous impacts on all parts of the food system will be necessary. Evolving food system research will require both strong disciplinary approaches and analytical tools integrating several dimensions and multi-level perspectives (Baylis et al. 2021;

van Ittersum et al. 2008). It will also require effective communication of the "plurality and conditionality of complex, dynamic systems research" (Zurek et al. 2018) to non-expert audiences and policy-makers.

Key Policy Issues to Be Considered on the Food Systems Summit Agenda

Recognize the role of trade in promoting food security, economic growth and better natural resource use and management

Trade openness contributes towards global food security and better nutrition, a better allocation of food production, and a more efficient and sustainable use of natural resources across countries. For a country, participation in global markets and value chains facilitates the diffusion of technology and knowledge and leads to increased productivity and more efficient resource use. To allow trade to flow smoothly and fulfill these functions, unjustified trade distortions and barriers should be avoided. Enhancing market transparency through improved information, cutting red tape and simplifying trade procedures through digitalization can significantly facilitate trade.

Implement complementary policies to address the trade-offs between economic and social objectives in the context of open markets

Open markets lie at the heart of the development process. In developing countries, a range of public policies and investments can help farmers overcome constraints to market access and create an enabling environment for a prospering economy for all. These include skill upgrades and education, the removal of labor market rigidities, and improvements in infrastructure, institutions and regulation. Social protection mechanisms and the redistribution of economic gains from trade openness to vulnerable population groups can improve inclusion and reduce inequalities.

Strengthen the role of trade in climate change adaptation and mitigation

As climate change is expected to have an uneven effect across regions, trade openness can be an important avenue for ensuring food security in countries that are more adversely affected by global warming and extreme weather shocks. However, the mitigating role of trade is equally important. Internalizing the cost of climate change in the food price across countries can help trade reallocate agricultural production to regions where emissions per unit of output is lowest. This can address the dual challenge of meeting food demand growth in the future and reducing greenhouse gas emissions.

Maximize the gains from trade for all countries

Both regional agreements and multilateral mechanisms can support trade and economic growth. Nevertheless, as food surplus and deficit areas may be located in different world regions and specific products may be most efficiently produced in other parts of the world, gains from agricultural and food trade can be maximized through multilateral mechanisms. Multilateral mechanisms can also help guide an optimal policy mix in addressing trade-offs among economic, health and environmental objectives, such as the harmonization of food safety standards and the development of a common understanding on sustainability certification.

References

Aguiar S, Texeira M, Garibaldi LA, Jobbágy EG (2020) Global changes in crop diversity: trade rather than production enriches supply. Glob Food Sec 26:100385

Ahammad H, Heyhoe E, Nelson G, Sands R, Fujimori S, Hasegawa T, van der Mensbrugghe D, Blanc E, Havlík P, Valin H, Kyle P, d'Croz H, van Meijl H, Schmitz C, Lotze-Campen H, von Lampe M, Tabeau A (2015) The role of international trade under a changing climate: insights from global economic modelling. In: Elbehri A (ed) Climate change and food systems: global assessments and implications for food security and trade. FAO, Rome, pp 293–312

An R, Guan C, Liu J, Chen N, Clarke C (2019) Trade openness and the obesity epidemic: a cross-national study of 175 countries during 1975–2016. Ann Epidemiol 37:31–36

Anderson K (2012) Government trade restrictions and international price volatility. Glob Food Sec 1(2):157–166

Anderson K, Nelgen S (2012) Trade barrier volatility and agricultural price stabilization. World Dev 40(1):36–48

Anderson K, Rausser G, Swinnen J (2013) Political economy of public policies: insights from distortions to agricultural and food markets. J Econ Lit 51(2):423–477

Artuc E, Porto G, Rijkers B (2019) Household impacts of tariffs: data and results from agricultural trade protection. Policy Research Working Papers. The World Bank. 40 pp. Available at https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-9045

Baldos ULC, Hertel TW (2015) The role of international trade in managing food security risks from climate change. Food Security 7(2):275–290

Balogh JM, Jámbor A (2020) The environmental impacts of agricultural trade: a systematic literature review. Sustainability 12(3):1152

Baylis K, Heckelei T, Hertel TW (2021) Agricultural trade and environmental sustainability. Ann Rev Resour Econ 13(1):379–401

Bell W, Lividini K, Masters WA (2021) Global dietary convergence from 1970 to 2010 altered inequality in agriculture, nutrition and health. Nature Food 2(3):156–165

Bhagwati J (1991) The world trading system at risk. Princeton University Press, Princeton, 156 pp

Bhagwati J (1993) Regionalism and multilateralism: an overview. In: de Melo J, Panagariya A (eds) New dimensions in regional integration. Cambridge University Press, pp 22–51

Bhagwati J, Ramaswami VK (1963) Domestic distortions, tariffs and the theory of optimum subsidy. J Polit Econ 71(1):44–50

Biewald A, Rolinski S, Lotze-Campen H, Schmitz C, Dietrich JP (2014) Valuing the impact of trade on local blue water. Ecol Econ 101:43–53

Bonuedi I, Kamasa K, Opoku EEO (2020) Enabling trade across borders and food security in Africa. Food Security 12(5):1121–1140

Chaudhary A, Brooks TM (2019) National consumption and global trade impacts on biodiversity. World Dev 121:178–187

Chaudhary A, Kastner T (2016) Land use biodiversity impacts embodied in international food trade. Glob Environ Chang 38:195–204

de Chazal J, Rounsevell MDA (2009) Land-use and climate change within assessments of biodiversity change: a review. Glob Environ Chang 19(2):306–315

Costa-Font J, Mas N (2016) 'Globesity'? The effects of globalization on obesity and caloric intake. Food Policy 64:121–132

Costinot A, Donaldson D (2016) How large are the gains from economic integration? Theory and evidence from U.S. agriculture, 1880–1997. National Bureau of Economic Research. Available at https://www.nber.org/papers/w22946

Costinot A, Donaldson D, Smith C (2016) Evolving comparative advantage and the impact of climate change in agricultural markets: evidence from 1.7 million fields around the world. J Polit Econ 124(1):205–248

Cowling K, Thow AM, Pollack Porter K (2018) Analyzing the impacts of global trade and investment on non-communicable diseases and risk factors: a critical review of methodological approaches used in quantitative analyses. Glob Health 14(1):53

Cuevas García-Dorado S, Cornselsen L, Smith R, Walls H (2019) Economic globalization, nutrition and health: a review of quantitative evidence. Glob Health 15(1):15

Cui HD, Kuiper M, van Meijl H, Tabeau A (2018) Climate change and global market integration: implications for global economic activities, agricultural commodities and food security. Background Paper for The State of Agricultural Commodity Markets (SOCO) 2018. Rome, FAO. 42 pp. Available at https://www.fao.org/3/CA2332EN/ca2332en.pdf

Dalin C, Rodríguez-Iturbe I (2016) Environmental impacts of food trade via resource use and greenhouse gas emissions. Environ Res Lett 11(3):035012

Davis KF, Downs S, Gephart JA (2021) Towards food supply chain resilience to environmental shocks. Nature Food 2(1):54–65

Dellink R, Dervisholli E, Nenci S (2020) A quantitative analysis of trends in agricultural and food global value chains (GVCs). Background paper for The State of Agricultural Commodity Markets (SOCO) 2020. Rome, FAO. 62 pp. Available at https://doi.org/10.4060/cb0729en

Deng G, Lu F, Wu L, Xu C (2021) Social network analysis of virtual water trade among major countries in the world. Sci Total Environ 753:142043

Dithmer J, Abdulai A (2017) Does trade openness contribute to food security? A dynamic panel analysis. Food Policy 69:218–230

Dixit A (1985) Chapter 6 Tax policy in open economies. In: Auerbach AJ, Feldstein MS (eds) Handbook of public economics. Elsevier, pp 313–374. Available at https://www.sciencedirect.com/science/article/pii/S1573442085800094

Dreher A (2006) Does globalization affect growth? Evidence from a new index of globalization. Appl Econ 38(10):1091–1110

Escobar N, Tizado EJ, Zu Ermgassen EKHJ, Löfgren P, Börner J, Godar J (2020) Spatially-explicit footprints of agricultural commodities: mapping carbon emissions embodied in Brazil's soy exports. Glob Environ Chang 62:102067

FAO (2016) The State of Agricultural Commodity Markets 2015–16. Trade and food security: achieving a better balance between national priorities and the collective good. FAO, Rome, p 89. Available at http://www.fao.org/publications/soco/the-state-of-agricultural-commodity-markets-2015-16/en/

FAO (2018a) The State of Agricultural Commodity Markets 2018. Agricultural trade, climate change and food security. FAO, Rome, p 112. Available at http://www.fao.org/3/I9542EN/i9542en.pdf

FAO (2018b) Trade and nutrition technical note. Trade policy technical note No. 21. FAO, Rome, p 8. Available at http://www.fao.org/3/I8545EN/i8545en.pdf

FAO (2018c) The future of food and agriculture – Alternative pathways to 2050. FAO, Rome, p 224. Available at http://www.fao.org/3/I8429EN/i8429en.pdf

FAO (2020a) Understanding international harmonization of pesticide maximum residue limits with Codex standards: a case study on rice. FAO, Rome, p 108. Available at http://www.fao.org/documents/card/en/c/cb0463en

FAO (2020b) The State of Agricultural Commodity Markets 2020. Agricultural markets and sustainable development: Global value chains, smallholder farmers and digital innovations. FAO, Rome, p 164. https://doi.org/10.4060/cb0665en

FAO & AUC (2021) Framework for boosting intra-African trade in agricultural commodities and services. FAO and AUC, Addis Ababa, p 80. https://doi.org/10.4060/cb3172en

Farrokhi F, Pellegrina HS (2020) Global trade and margins of productivity in agriculture. National Bureau of Economic Research. Available at https://www.nber.org/papers/w27350

Fleming DA, Abler DG (2013) Does agricultural trade affect productivity? Evidence from Chilean farms. Food Policy 41:11–17

Geyik O, Hadjikakou M, Karapinar B, Bryan BA (2021) Does global food trade close the dietary nutrient gap for the world's poorest nations? Glob Food Sec 28:100490

Giuntella O, Rieger M, Rotunno L (2020) Weight gains from trade in foods: evidence from Mexico. J Int Econ 122:103277
Goryakin Y, Lobstein T, James WPT, Suhrcke M (2015) The impact of economic, political and social globalization on overweight and obesity in the 56 low and middle income countries. Soc Sci Med 133:67–76
Götz L, Glauben T, Brümmer B (2013) Wheat export restrictions and domestic market effects in Russia and Ukraine during the food crisis. Food Policy 38:214–226
Gouel C, Laborde D (2021) The crucial role of domestic and international market-mediated adaptation to climate change. J Environ Econ Manag 106:102408
Grant JH (2013) Is the growth of regionalism as significant as the headlines suggest? Lessons from agricultural trade. Agric Econ 44(1):93–109
Grossman GM, Helpman E (1991) Trade, knowledge spillovers, and growth. Eur Econ Rev 35(2): 517–526
Grossman GM, Krueger AB (1991) Environmental impacts of a North American Free Trade Agreement. National Bureau of Economic Research. Available at https://www.nber.org/papers/w3914
Gutierrez L (2002) Why is agricultural labour productivity higher in some countries than others? Agric Econ Rev 3(1):58–72
Gwartney J, Lawson R, Hall J (2013) The economic freedom of the world: 2013 annual report. Fraser Institute
Hart J, Miljkovic D, Shaik S (2015) The impact of trade openness on technical efficiency in the agricultural sector of the European Union. Appl Econ 47(12):1230–1247
Havlík P, Valin H, Gusti M, Schmid, Erwin, Leclère D, Forsell N, Herrero M, Khabarov N, Mosnier A, Cantele M, Obersteiner M (2015) Climate change impacts and mitigation in the developing world. Policy Research Working Paper. World Bank Group, p 56. Available at http://documents.worldbank.org/curated/en/866881467997281798/pdf/WPS7477.pdf
Henle K, Alard D, Clitherow J, Cobb P, Firbank L, Kull T, McCracken D, Moritz RFA, Niemelä J, Rebane M, Wascher D, Watt A, Young J (2008) Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe–A review. Agric Ecosyst Environ 124(1): 60–71
Irwin DA (2019) Does trade reform promote economic growth? A review of recent evidence. National Bureau of Economic Research. Available at https://www.nber.org/papers/w25927
van Ittersum MK, Ewert F, Heckelei T, Wery J, Alkan Olsson J, Andersen E, Bezlepkina I, Brouwer F, Donatelli M, Flichman G, Olsson L, Rizzoli AE, van der Wal T, Wien JE, Wolf J (2008) Integrated assessment of agricultural systems – a component-based framework for the European Union (SEAMLESS). Agric Syst 96(1–3):150–165
Janssens C, Havlík P, Krisztin T, Baker J, Frank S, Hasegawa T, Leclère D, Ohrel S, Ragnauth S, Schmid E, Valin H, Van Lipzig N, Maertens M (2020) Global hunger and climate change adaptation through international trade. Nat Clim Chang 10(9):829–835
Kalkuhl M, von Braun J, Torero M (2016) Volatile and extreme food prices, food security, and policy: an overview. In: Kalkuhl M, von Braun J, Torero M (eds) Food price volatility and its implications for food security and policy. Springer, Cham, pp 3–31. https://doi.org/10.1007/978-3-319-28201-5_1
Knutson A, de Soysa I (2019) Does social globalisation through access to information communication technologies drive obesity among youth? An empirical analysis, 1990–2013. Glob Public Health 14(12):1911–1926
Krivonos E, Kuhn L (2019) Trade and dietary diversity in Eastern Europe and Central Asia. Food Policy 88:101767
von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, Calvin K, Fujimori S, Hasegawa T, Havlik P, Heyhoe E, Kyle P, Lotze-Campen H, Mason d'Croz D, Nelson GC, Sands RD, Schmitz C, Tabeau A, Valin H, van der Mensbrugghe D, van Meijl H (2014) Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agric Econ 45(1):3–20

Lawson RA, Murphy RH, Williamson CR (2016) The relationship between income, economic freedom, and BMI. Public Health 134:18–25

Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L, Geschke A (2012) International trade drives biodiversity threats in developing nations. Nature 486(7401):109

Lin TK, Teymourian Y, Tursini MS (2018) The effect of sugar and processed food imports on the prevalence of overweight and obesity in 172 countries. Glob Health 14(1):35

Marquardt SG, Guindon M, Wilting HC, Steinmann ZJN, Sim S, Kulak M, Huijbregts MAJ (2019) Consumption-based biodiversity footprints – do different indicators yield different results? Ecol Indic 103:461–470

Martin W (2018) A research agenda for international agricultural trade. Appl Econ Perspect Policy 40(1):155–173

Martin W, Anderson K (2012) Export restrictions and price insulation during commodity price booms. Am J Agric Econ 94(2):422–427

Mary S (2019) Hungry for free trade? Food trade and extreme hunger in developing countries. Food Security 11(2):461–477

Mary S, Stoler A (2021) Does agricultural trade liberalization increase obesity in developing countries? Rev Dev Econ

Miljkovic D, de Miranda SHG, Kassouf AL, Oliveira FCR (2018) Determinants of obesity in Brazil: the effects of trade liberalization and socio-economic variables. Appl Econ 50(28): 3076–3088

Montalbano P, Nenci S (2020) The effects of global value chain (GVC) participation on the economic growth of the agricultural and food sectors. Background paper for The State of Agricultural Commodity Markets (SOCO) 2020, FAO, Rome, p 60. Available at http://www.fao.org/documents/card/en/c/cb0714en

Moran D, Kanemoto K (2017) Identifying species threat hotspots from global supply chains. Nature Ecology & Evolution 1(1):0023

Morin J-F, Dür A, Lechner L (2018) Mapping the trade and environment nexus: insights from a new data set. Global Environmental Politics 18(1):122–139

Nath IB (2020) The food problem and the aggregate productivity consequences of climate change. National Bureau of Economic Research. Available at https://www.nber.org/papers/w27297

Nelson GC, Valin H, Sands RD, Havlík P, Ahammad H, Deryng D, Elliott J, Fujimori S, Hasegawa T, Heyhoe E, Kyle P, Lampe MV, Lotze-Campen H, d'Croz DM, van Meijl H, van der Mensbrugghe D, Müller C, Popp A, Robertson R, Robinson S, Schmid E, Schmitz C, Tabeau A, Willenbockel D (2014) Climate change effects on agriculture: economic responses to biophysical shocks. Proc Natl Acad Sci 111(9):3274–3279

Oberlander L, Disdier A-C, Etilé F (2017) Globalisation and national trends in nutrition and health: a grouped fixed-effects approach to intercountry heterogeneity. Health Econ 26(9):1146–1161

OECD (2015) The economic consequences of climate change. OECD Publishing, Paris, p 140. https://doi.org/10.1787/9789264235410-en)

Olper A, Curzi D, Raimondi V (2017) Imported intermediate inputs and firms' productivity growth: evidence from the food industry. J Agric Econ 68(1):280–300

Ortiz AMD, Outhwaite CL, Dalin C, Newbold T (2021) A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. One Earth 4(1):88–101

Pace ML, Gephart JA (2017) Trade: a driver of present and future ecosystems. Ecosystems 20(1): 44–53

Pastor AV, Palazzo A, Havlik P, Biemans H, Wada Y, Obersteiner M, Kabat P, Ludwig F (2019) The global nexus of food–trade–water sustaining environmental flows by 2050. Nature Sustainability 2(6):499–507

Pendrill F, Persson UM, Godar J, Kastner T, Moran D, Schmidt S, Wood R (2019) Agricultural and forestry trade drives large share of tropical deforestation emissions. Glob Environ Chang 56:1–10

Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333(6047):1289–1291

Qiang W, Niu S, Liu A, Kastner T, Bie Q, Wang X, Cheng S (2020) Trends in global virtual land trade in relation to agricultural products. Land Use Policy 92:104439

Rapsomanikis G (2011) Price transmission and volatility spillovers in food markets. In: Prakash A (ed) Safeguarding food security in volatile global markets. Rome, FAO, pp 144–163

Reilly J (1995) Climate change and global agriculture: recent findings and issues. Am J Agric Econ 77(3):727–733

Remans R, Wood SA, Saha N, Anderman TL, DeFries RS (2014) Measuring nutritional diversity of national food supplies. Glob Food Sec 3(3):174–182

Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. Nature 461(7263):472–475

Rodrik D (1987) Policy targeting with endogenous distortions: theory of optimum subsidy revisited. Q J Econ 102(4):903–911

Rosenzweig C, Mbow C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, Liwenga ET, Pradhan P, Rivera-Ferre MG, Sapkota T, Tubiello FN, Xu Y, Mencos Contreras E, Portugal-Pereira J (2020) Climate change responses benefit from a global food system approach. Nature Food 1(2):94–97

Roux N, Kastner T, Erb K-H, Haberl H (2021) Does agricultural trade reduce pressure on land ecosystems? Decomposing drivers of the embodied human appropriation of net primary production. Ecol Econ 181:106915

Rude J, An H (2015) Explaining grain and oilseed price volatility: the role of export restrictions. Food Policy 57:83–92

Santeramo FG, Lamonaca E (2019) The effects of non-tariff measures on agri-food trade: a review and meta-analysis of empirical evidence. J Agric Econ 70(3):595–617

Schmidhuber J, Tubiello FN (2007) Global food security under climate change. Proc Natl Acad Sci 104(50):19703–19708

Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich JP, Bodirsky B, Krause M, Weindl I (2012) Trading more food: implications for land use, greenhouse gas emissions, and the food system. Glob Environ Chang 22(1):189–209

Schmitz C, Kreidenweis U, Lotze-Campen H, Popp A, Krause M, Dietrich JP, Müller C (2015) Agricultural trade and tropical deforestation: interactions and related policy options. Reg Environ Chang 15(8):1757–1772

Sheldon IM, Chow DCK, McGuire W (2018) Trade liberalization and constraints on moves to protectionism: multilateralism vs. regionalism. Am J Agric Econ 100(5):1375–1390

Smith O, Momber G, Bates R, Garwood P, Fitch S, Pallen M, Gaffney V, Allaby RG (2015) Sedimentary DNA from a submerged site reveals wheat in the British Isles 8000 years ago. Science 347(6225):998–1001

de Soysa I, de Soysa AK (2018) Do globalization and free markets drive obesity among children and youth? An empirical analysis, 1990–2013. International Interactions 44(1):88–106

Sporchia F, Taherzadeh O, Caro D (2021) Stimulating environmental degradation: a global study of resource use in cocoa, coffee, tea and tobacco supply chains. Current Research in Environmental Sustainability 3:100029

Stevanović M, Popp A, Lotze-Campen H, Dietrich JP, Müller C, Bonsch M, Schmitz C, Bodirsky BL, Humpenöder F, Weindl I (2016) The impact of high-end climate change on agricultural welfare. Sci Adv 2(8):e1501452

Sun J, Mooney H, Wu W, Tang H, Tong Y, Xu Z, Huang B, Cheng Y, Yang X, Wei D, Zhang F, Liu J (2018) Importing food damages domestic environment: evidence from global soybean trade. Proc Natl Acad Sci 115(21):5415–5419

Tadesse G, Algieri B, Kalkuhl M, von Braun J (2014) Drivers and triggers of international food price spikes and volatility. Food Policy 47:117–128

Teignier M (2018) The role of trade in structural transformation. J Dev Econ 130:45–65

Thow AM, Jones A, Hawkes C, Ali I, Labonté R (2018) Nutrition labelling is a trade policy issue: lessons from an analysis of specific trade concerns at the World Trade Organization. Health Promot Int 33(4):561–571

Thow AM, Nisbett N (2019) Trade, nutrition, and sustainable food systems. Lancet 394(10200): 716–718

Tombe T (2015) The missing food problem: trade, agriculture, and international productivity differences. Am Econ J Macroecon 7(3):226–258

Traverso S, Schiavo S (2020) Fair trade or trade fair? International food trade and cross-border macronutrient flows. World Dev 132:104976

Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A (2012) Global food security, biodiversity conservation and the future of agricultural intensification. Biol Conserv 151(1):53–59

United Nations Economic Commission for Africa (2018) An empirical assessment of the African Continental Free Trade Area modalities on goods. United Nations Economic Commission for Africa, Addis Ababa, p 5. Available at https://repository.uneca.org/handle/10855/41828

United Nations Economic Commission for Africa & TradeMark East Africa (2020) Creating a unified regional market. Towards the implementation of the African Continental Free Trade Area in East Africa. United Nations Economic Commission for Africa and TradeMark East Africa, Kigali, p 144. Available at https://archive.uneca.org/sites/default/files/PublicationFiles/tmea_afcfta_report_5_june_2020.pdf

Vogli RD, Kouvonen A, Elovainio M, Marmot M (2014) Economic globalization, inequality and body mass index: a cross-national analysis of 127 countries. Crit Public Health 24(1):7–21

Wheeler T, von Braun J (2013) Climate change impacts on global food security. Science 341(6145): 508–513

Wieck C (2018) International trade rules for food safety and food quality. In: Meilke K, Josling T (eds) Handbook of international food and agricultural policies. World Scientific, pp 277–308. Available at https://www.worldscientific.com/doi/abs/10.1142/9789813226487_0011

Wiebe K, Lotze-Campen H, Sands R, Tabeau A, van der Mensbrugghe D, Biewald A, Bodirsky B, Islam S, Kavallari A, Mason-D'Croz D, Müller C, Popp A, Robertson R, Robinson S, van Meijl H, Willenbockel D (2015) Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ Res Lett 10(8):085010

Wood S, Smith M, Fanzo J, Remans R, DeFries R (2018) Trade and the equitability of global food nutrient distribution. Nature Sustainability 1:34–37

WTO (2021) WTO|Regional Trade Agreements gateway [online]. [Cited 15 April 2021]. https://www.wto.org/english/tratop_e/region_e/region_e.htm

Zurek M, Hebinck A, Leip A, Vervoort J, Kuiper M, Garrone M, Havlík P, Heckelei T, Hornborg S, Ingram J, Kuijsten A, Shutes L, Geleijnse JM, Terluin I, Van't Veer P, Wijnands J, Zimmermann A, Achterbosch T (2018) Assessing sustainable food and nutrition security of the EU food system — An integrated approach. Sustainability 10(11):4271

Part VI
Regional Perspectives

Policy Options for Food System Transformation in Africa and the Role of Science, Technology and Innovation

Ousmane Badiane, Sheryl L. Hendriks, Katrin Glatzel, Fadi Abdelradi, Assefa Admassie, John Asafu Adjaye, Miltone Ayieko, Endashaw Bekele, Thameur Chaibi, Mohamed Hag Ali Hassan, Mame Samba Mbaye, Fatima Ezzahra Mengoub, Douglas W. Miano, John H. Muyonga, Tolulope Olofinbiyi, Racha Ramadan, and Simbarashe Sibanda

1 Introduction

Over the past decade, Africa's food systems have begun to transform, sparked by economic recovery, rising incomes, an expanding middle class, a growing population, rapid urbanization, globalization, and digitalization, among other factors. These key drivers are inducing fundamental changes in the dietary preferences and habits of consumers and the corresponding demand for food, with responses from the

O. Badiane (✉)
Akademiya2063, Kigali, Rwanda
e-mail: obadiane@akademiya2063.org

S. L. Hendriks
Department of Agricultural Economics, Extension and Rural Development, University of Pretoria, Pretoria, South Africa

K. Glatzel
Department of Policy Innovation, Akademiya2063, Dakar, Senegal

F. Abdelradi
Faculty of Agriculture, University of Cairo, Giza, Egypt

A. Admassie
School of Economics, Addis Ababa University, Ababa, Ethiopia

J. A. Adjaye
The African Center for Economic Transformation (ACET), Accra, Ghana

M. Ayieko
Tegemeo Institute of Agricultural Policy and Development, Egerton University, Njoro, Kenya

E. Bekele
Addis Ababa University, Ababa, Ethiopia

T. Chaibi
National Research Institute of Rural Engineering, Water and Forests (INRGREF), Tunis, Tunisia

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_37

components of food systems, including food production, distribution and allocation (Tschirley et al. 2019). Yet, the shifts are coupled with a variety of challenges, including climate change, environmental degradation, low adoption of new technologies, and a growing energy deficit, amidst ongoing, rising resource-scarcity and limited financial resources, as well as socio-economic shocks, migration and youth unemployment. Covid-19 has added an additional strain on African food systems. Now is the opportunity to take stock, re-think and advance African food systems, to make them more sustainable, nutritious, resilient, and inclusive.

The UNFSS and COP26 have provided important moments for shaping the future of the region's food systems and ensuring that the much-needed agriculture-led growth and development agenda can simultaneously deliver on improving nutrition and health, saving lives, and protecting the environment. This includes addressing the usual elements of undernutrition and widespread micronutrient deficiencies and the growing problem of overweight and obesity that is increasing across the continent.

The chapter begins with a discussion of the context within which African food systems have developed and are now transforming, their key drivers, and the challenges and opportunities for this transformation. It concludes with STI and policy actions that are required to accelerate the transformation of food systems across the continent. The discussions are informed by literature and perspectives coming out of leading think tanks and universities in Africa.

M. H. A. Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), Trieste, Italy

M. S. Mbaye
Université Cheikh Anta Diop de Dakar (UCAD), Dakar, Senegal

F. E. Mengoub
Policy Center for the New South, Rabat, Morocco

D. W. Miano
Department of Plant Science and Crop Protection, University of Nairobi, Nairobi, Kenya

J. H. Muyonga
School of Food Technology, Nutrition & Bioengineering, Makerere University, Kampala, Uganda

T. Olofinbiyi
Akademiya2063, Nairobi, Kenya

R. Ramadan
Faculty of Economics and Political Science, Cairo University, Giza, Egypt

S. Sibanda
The Food, Agriculture and Natural Resources Policy Analysis Network (FANRPAN), Pretoria, South Africa

2 The Context of African Food Systems

African food systems are diverse, and draw on several traditional and modern technologies. Agriculture (including crop production, animal husbandry, fisheries and forestry, and processing) can stimulate economic growth and enhance economic transformation in Africa through raising rural incomes, creating jobs, and increasing government revenue (Baumüller et al. 2021). Increasing producers' and processors' incomes can positively affect poverty reduction and food security and nutrition (Baumüller et al. 2021). The emergence of processing sectors across the continent offers great potential to transform food systems, generate much-needed employment opportunities and positively impact nutrition. Furthermore, the African Continental Free Trade Area (AfCFTA) offers many additional opportunities for the development of food systems, including diverse livelihoods across the food system and the provision of safe and nutritious food to all on the continent using Africa's own resources and reducing the reliance on imports and development assistance.

Africa will require radical actions to reduce undernutrition, correct micronutrient deficiencies and simultaneously stem the tide of increasing overweight and obesity. Africa had the highest regional undernourishment rate in 2019 (19.1%, or more than 250 million undernourished people), more than twice the world average and growing faster than any other region (FAO et al. 2020). The proportion of undernourished people has risen by 1.5% since 2014 and is projected to rise to 25.7% by 2030 (FAO et al. 2020). More than 675 million people in Africa were food insecure (as measured by the Food Insecurity Experience Scale of FIES) in 2019 (FAO et al. 2020). Recent economic slowdowns and downturns partly explain the increase in hunger in several parts of Africa South of the Sahara (SSA) (FAO et al. 2020). The Covid-19 pandemic and other more localized shocks have worsened the situation, increasing the vulnerability of resource-poor food producers, particularly in already fragile regions.

The Covid-19 pandemic has disrupted food systems and livelihoods in Africa and threatens the significant gains over the past few decades in African development. The pandemic has led to transport restrictions and quarantine measures that restrict farmers' access to input and output markets and services, including human and animal health services (MaMo 2020). While data suggest that Africa has largely been spared the pandemic's scourge (Maeda and Nkengasong 2021), the long-term impacts have yet to unfold.

Food system transformation is required to ensure adequate incomes for producers and enable access to affordable, healthy diets[1] while managing increasing food demand from growing and rapidly urbanizing populations. Hence, the need to refocus the broader agricultural development agenda in Africa, in particular, under CAADP, to adopt a food systems lens. As food systems require cross-sectoral

[1] A healthy diet is health-promoting and disease-preventing. It provides adequate nutrients (without excess) and health-promoting substances from nutritious foods and avoids the consumption of health-harming substances (Neufeld et al. 2021a, b).

coordination beyond what was needed for CAADP, institutional innovation is also needed for Africa to rise to the vision of the AUC Agenda 2063 and the Food Systems Summit's aspirations.

2.1 Drivers and Opportunities

The main drivers of food system transformation in Africa include sustained economic recovery and rising incomes, rapid urbanization, steady population growth, deepening globalization, and digitalization. Each of these drivers and how they contribute to the transformation of food systems across Africa are reviewed below.

(a) **Sustained, broad economic recovery and rising incomes**

The strong economic recovery observed across the African continent—with considerable growth acceleration since the early 2000s—is striking. Between 2000 and 2014, real per capita GDP has increased by over one-third on average, with faster growth of up to 100% or more in some countries. Furthermore, GDP per capita is projected to double by 2050. This positive growth trajectory has contributed to reductions in poverty and the emergence of a sizable, dynamic middle class. Rising incomes, accompanied by a growing middle class, are shaping the composition of consumer diets, driving an increasing demand for animal-source foods, such as dairy, eggs and meat. Between 2000 and 2010, per capita consumption of eggs, meat and milk in Africa grew by 24, 25 and 47%, respectively. By 2050, it is projected that per capita consumption of meat and milk will reach 26 kg and 64 kg per year, while close to 70% of total meat and milk consumption is expected to come from urban areas (MaMo 2020). Despite improvements in the quality of diets, hunger and malnutrition levels in Africa have remained high. While income growth is important for food security and nutrition, it is crucial to ensure that the food demands of high-income consumers are not catered to at the expense of the availability of more affordable foods for low-income consumers.

(b) **Population growth and distribution**

Countries in SSA are expected to account for over half of the world's population growth between 2019 and 2050. Further, by the end of the century, the continent is projected to add more than 1 billion people. With higher food demand, Africa is experiencing a widening food import gap, putting pressure on food production systems and scarce foreign exchange resources. Moreover, Africa's youth population is growing faster than other age groups, providing an opportunity for a demographic dividend with potentially positive effects on food system transformation and economic growth. Meeting the nutritional and employment needs of a growing young population will be key to reaping the demographic dividend. A rapid increase in rural density across the continent, particularly in peri-urban centers, is contributing to the transformation of agriculture and the diversification of rural economies—thereby influencing the structure of farming (Allen 2015). In some countries, the number of medium- and large-scale farms is increasing, and in others, they already account for a sizable and rising portion of total farmland. Agribusinesses and downstream food systems are thus responding to population growth and urbanization in dynamic ways.

(c) **Urbanization**

Urbanization across Africa has reached the levels of other regions in the world and has continued to grow at a rate of nearly 4% per annum. While there were only two African cities with more than a million inhabitants in 1950, this increased to 50 in 2010 and is expected to nearly double by 2025 (Conway et al. 2019). An important feature of Africa's urbanization, with significant implications for food system transformation, is that it is being driven by the emergence of many small cities or rural towns.

Africa's total urban food market is projected to reach US$ 150 billion by 2030, with potential opportunities for smallholder farmers to capture as much as US$30 billion (AUC/NEPAD 2008). Urbanization in Africa is driving increased demand for processed, ready-to-cook, or ready-to-eat foods, such as couscous, millet flour, garri (cassava flakes), and ultra-processed foods. By 2040, the share of processed foods is expected to increase five to tenfold compared to 2010 and will account for nearly 75% of the demand for staple foods (Conway et al. 2019). However, urbanization and the associated changes in consumer lifestyle and diets can increase overweight and obesity (Ziraba et al. 2009). There is a widespread increase in the consumption of refined or highly processed foods, as well as of sugar, salt, fats, and oils. At the same time, growing attention to public health and diets presents opportunities to decrease the prevalence of obesity and diet-related chronic and non-communicable diseases, such as diabetes and heart diseases.

(d) **Globalization, the large-scale food industry, and trade**

Globalization and the growth of the large-scale food industry, including the rapid development of supermarkets, are driving changes in the supply and demand of food. Moreover, trade policies and processes that facilitate or mitigate the expansion of trade are contributing to the globalization of food trade and increasing the demand for food quality and safety standards. These drivers are closely linked with urbanization, rising incomes, and a growing middle class, as changing environments and preferences interact to influence dietary patterns. Domestically, the need to feed Africa's growing cities is reshaping farmers' access to markets, starting with those closest to towns and moving outward into remote areas. The rise of secondary cities is expanding market access and extending value chains into previously hard-to-reach areas. To harness the benefits afforded by greater domestic, regional and international trade, it is necessary to raise the productivity of smallholder famers, improve the quality of their produce and boost competitiveness of domestic processing sectors.

2.2 Threats and Challenges

While a new optimism has emerged about the potential of food system transformation, African food systems continue to face several challenges, including low levels of investment in agriculture, climate change, environmental degradation, limited adoption levels of yield-increasing technologies, slow adoption of biotechnology, and an energy deficit.

(a) **Climate change and environmental degradation**

Climate change is a major risk to food system transformation. It presents significant challenges to African agriculture and threatens recent progress in increasing productivity and reducing poverty and hunger. The combination of rising temperatures and changing precipitation patterns is projected to result in a broad range of impacts, including increases in the frequency of weather volatility and extreme weather events, rising sea levels, changes in the incidence of agricultural pests and diseases, adverse effects on crop productivity, and a general decline in the production of several key crops in the coming decades (Pereira 2017). By 2050, climate change is expected to leave more than 38 million more people at risk of hunger in SSA than would otherwise be the case, particularly in Eastern Africa. In addition, more than 4 million children under five years of age are projected to face malnutrition (Wiebe et al. 2017).

Even though the intensification and homogenization of food systems have contributed to increases in per capita agricultural outputs, they have resulted in major degradation of soils and a loss of biodiversity around the world, including in Africa. Several studies show not only the significant impacts of degradation on agricultural production in SSA (hence, threats to future food security), but also the need for solutions that are tailored specifically to local agro-ecological conditions and farming systems (Bindraban et al. 2012). Ensuring food security and safeguarding biodiversity should not be seen as incompatible goals, but rather as synergetic, given the interdependence between agriculture and biodiversity, as well as the important role that each plays in preserving the other.

(b) **Limited adoption of improved production technologies**

The expanded use of modern inputs, such as improved seeds, irrigation, and mechanization, have significant potential to accelerate food system transformation, but the intensity of input use in Africa still lags behind that of other regions (Sheahan and Barrett 2017). Africa has the least mechanized food systems in the world: farmers have ten times fewer mechanized tools per farm area than farmers in other developing regions, and access has not grown as quickly as in other regions. However, some countries have experienced more dynamic growth in mechanization, by emphasizing equipment rental or service hiring markets, improving access to credit, promoting domestic manufacturing, and improving the environment for public-private partnerships to thrive (MaMo 2019b). Mechanization in African food systems needs rethinking and fresh strategies. Its success will not only be about technology, but also organizational innovations, such as reliable services and cooperation arrangements for and with farmers. Opportunities for mechanization must be harnessed at each stage of the agricultural value chain and, when done right, can and should be employment-enhancing, not labor-replacing (MaMo 2018).

(c) **Slow adoption of biotechnology**

Biotechnology, including improved seed varieties, has not been widely embraced across Africa. Investment in technical expertise and the development of institutional infrastructure for harnessing biotechnology and fostering adoption, particularly among smallholders, are a priority. Through crop biotechnology and genomics, scientists are designing and developing crops with higher yields, additional nutrients, and enhanced tastes. The power of modern agricultural biotechnology and genomics in transforming African food systems into a force of economic growth, creating wealth in the rural space and beyond, feeding a growing African population and conserving resources for future generations, cannot be ignored.

(d) **Energy deficit**

Currently, Africa faces the highest costs of electricity provision in the world, and large shares of the population, particularly in rural areas, remain unconnected to energy grids (Badiane et al. 2020). Recent figures show that 580 million people in Africa still lacked access to electricity in 2019 (Ringler and Brent 2020). Policies that explore promising off/mini-grid solutions that can meet the needs of smallholder farmers, agro-industries and households in remote areas should be explored, coupled with fiscal incentives, including reduced import duties. Expanding access to alternative sources of energy, such as solar, wind and biogas, can help boost food security across the continent by stimulating sustainable agricultural development and improving water security, thereby accelerating rural and economic growth (Ringler and Brent 2020). One promising example is cluster-based approaches to agricultural electrification through "farm blocks" that are equipped with basic infrastructure and complemented by industrial cluster zones for agricultural processing (MaMo 2019b).

3 Transforming Food Systems in Africa Through STI and Policy Innovations

Adopting an integrated approach to transforming food systems could provide multiple opportunities for the development of African economies and societies. With her rich diversity of production systems, significant biodiversity and strong cultural association with traditional diets that are, for the most part, nutritious and healthy, the development of Africa's food systems has the potential to build healthier, more sustainable and more equitable systems.

Any change in food systems will lead to a multiplicity of changes affecting nutrition, health, welfare and the environment. The health implications, welfare outcomes (such as through livelihood outcomes, wages and incomes) and dietary patterns' environmental footprints are strongly dependent on how foods are produced and processed. STI can help support food system development in ways that protect resources, provide livelihood opportunities and improve incomes across the system, while delivering more nutritious and healthy diets.

Policies and practices that promote adaptation to rapidly changing climate conditions are urgently required. A key intervention is the adoption of improved agricultural technologies for sustainable intensification (Wiebe et al. 2017). Widespread adoption of climate-smart practices, such as integrated soil fertility management, drought- and heat-tolerant crop varieties, integrated crop-livestock management, and conservation agriculture, should also be encouraged (Nkonya and Koo 2017; Conway et al. 2019). While these climate-smart agriculture practices show promise in terms of higher productivity and improvements to food security, their adoption by smallholder farmers in SSA is constrained by limited access to inputs and information, markets, and risk-management tools. Major investments in research and technology, coupled with institutional and physical infrastructure, are therefore needed.

Digitalization has significant potential to improve efficiency, equity, and environmental sustainability in food systems across Africa. The use of digital and data-driven technologies at each segment of agriculture value chains can guide and support decisions on production methods, value chain optimization, and storage methods so as to avoid food waste and loss. For many farmers, access to output and input markets has increased as a digital revolution is allowing markets to connect faster.

The private sector is already playing a major role in accelerating the development of promising technologies and solutions in the food and agriculture sector. Innovation funds, often in the form of grants, are now being used to create platforms for innovative activity by providing incentives to improve collaboration and the quality of services offered. Placing digitalization at the center of food system transformation strategies and policies will be key to harnessing its cross-cutting innovative power. Moreover, data derived from digitalization efforts offer opportunities to design better-informed policies for food system transformation at scale.

It should be noted that the biotechnology revolution arose from the convergence of advancements in the biological, physical, engineering, and social sciences. In terms of food systems, what converges is the technical reinforcement of these advancements in terms of product optimization and formulation and the mutual benefit of different disciplines. Food systems approaches will bring about new innovations from transdisciplinary perspectives to solve unique problems.

3.1 Improving Production Efficiency and Restoring and Sustainably Managing Natural Resources

Within the context of a growing demand for food (including animal-sourced foods), improving the efficiency of production systems is necessary, given constraints on land and resource availability and the relatively small land plots in most of Africa (Lowder et al. 2016). At the same time, it is also an environmental imperative.

Restoring soil fertility is a major priority for agricultural transformation in Africa. Continuous cropping and unsustainable cultivation practices driven by shrinking farm sizes and increasing food demand threaten future food supply in Africa (Jayne et al. 2014), limiting the potential benefit from yield gains offered by plant genetic improvement (Tittonell and Giller 2013). Appropriate soil improvement practices and informed production choices are essential to prevent further degradation. A holistic and integrated strategy is needed that focuses on raising organic matter and improving moisture retention (Kihara et al. 2016). The soil microbiome affects how plants react to environmental stresses such as high salinity and low water availability and diseases. The isolation of microbial strains and modern high-throughput sequencing technologies are being used to catalogue microbial species associated with plants in different soils, including arid and saline soils (Wild 2016). The development of next-generation crop varieties should simultaneously select beneficial characteristics in both the plant and the microbiome to improve soil fertility and crop yields (Gopal and Gupta 2016). Research is also needed to develop protective seed coatings to protect plants from soil-borne pests and pathogens while also providing micro bio-fertilizers (Rocha et al. 2019).

Sustainably managing water use for food production, food processing and industrialization, as well as safe drinking water, sanitation and hygiene, is critical for successful food system transformation. The demand for these resources competes for the available water that can be eased through use of appropriate technology and policies. Urbanization will place increased pressure on water demand and compete with water for food production, while urbanization and industrialization also pose threats to overall water quality.

Irrigation use remains low in Africa. Yet, evidence shows that average yields on irrigated areas are 90% higher than in nearby rainfed areas. Investment and innovation will be necessary for low-cost yet efficient irrigation options to mitigate the impact of water scarcity and expand the availability of diverse foods year-round. Hydroponic production, with recirculation of water and nutrients in a closed system, can reduce water consumption (Al Shrouf 2017), while drip irrigation delivers just the right amount of water, at a specific time, to a precise spot where the water will be best absorbed by the plant, producing “more crop per drop.” Promoting the use of renewable energies in water desalination for agriculture use could offer competitive cost options for the delivery of modern energy and increase the use of non-conventional water resources to guarantee long-term food security and socio-economic stability.

Many energy-generation systems also depend on water sources for hydroelectric power, the cooling of power plants and hydraulic fracturing. Several countries with large-scale irrigation programs source water from aquifers, threatening long-term sustainability, and possibly leading to conflict over water in the future. Competition for water needs to be eased using appropriate technology and policies to protect and manage water resources (including river basins and lakes). Water-harvesting and storage are necessary to support crop and livestock production. More innovation is required in recycling wastewater to increase the overall availability of water. The desalination of seawater offers one option to increase the availability of water for human consumption and agricultural production. However, this technology is still expensive and results in waste (high salt concentrations) that poses additional environmental problems (Ahmadi et al. 2020).

Livestock is an important element of millions of people's livelihoods in Africa's pastoralist, mixed crop-livestock farming and commercial systems, offering multiple opportunities for income and employment. Increases in demand for animal products in African countries outpace supply. Meeting this demand will require substantial increases in production while reducing the environmental footprint of livestock production. Livestock (including poultry, swine, sheep, goats, cattle and rabbits) are good sources of high-quality animal protein with rich amino acid profiles (NASAC 2018). They also provide much-needed nutrient-dense foods, vital to overcoming the high rates of child malnutrition in Africa.

However, globally, livestock accounts for 14.5% of all greenhouse gas emissions (cattle for 60% of these), with emissions linked to food digestion and feed production dominating emissions from ruminants (Gerber et al. 2013), and about a third of the freshwater footprint for agriculture (Mekonnen and Hoekstra 2012). Although Africa's livestock sector is still primarily extensive (rather than intensive, industrialized production), this may change as the demand for animal-sourced foods increases with shifting urbanization and changes in income in middle-income countries. Climate change could affect future grazing capacities, lead to more migration of animal herds, and increase zoonotic disease incidence (MaMo Panel 2020).

Livestock genetic improvement programs, interventions to increase carbon sequestration in grasslands and improved management of grazing lands could significantly increase productivity and reduce greenhouse gas emissions (Gerber et al. 2013; Henderson et al. 2015). The use of high-quality forage grasses and legumes offers a wide array of benefits, including higher livestock and crop productivity, restoration of degraded land through the accumulation of organic matter in soils, and improvement of soil fertility through the fixation of atmospheric nitrogen, the inhibition of nitrification in the soil and a year-round supply of feedstock (Rao et al. 2015). Indigenous feed resources can be incorporated into feeds to promote sustainability. The available genetic variability of forage plants is still largely untapped and underutilized (Sandhu et al. 2015). Drought-tolerant *Brachiaria* grasses originated primarily in natural grasslands in Africa, yet they have only recently been re-introduced for commercial cultivation in African countries at a significant scale. It has been estimated that cows reared in *Brachiaria* pastures could increase productivity by up to 40% in Kenya and Rwanda compared to native grasslands, with spillover benefits further down the value chain (Maina et al. 2020).

Emerging challenges in animal health include improving resistance to disease and combating the misuse of antibiotics in animal production systems (Kimera et al. 2020). An example of such pests is the trypanosome parasites. Trypanosomiasis greatly restricts cattle rearing in 32 countries of SSA, leading to losses due to lost animals and animal products of between US$1 billion and US$6 billion annually (Yaro et al. 2016). The development of conventional vaccines against the parasite has been thwarted by trypanosomes' ability to continuously change the antigenic properties of their surface coat and evade attack by the host's immune system (Radwanska et al. 2008). The discovery of innate resistance to trypanosomiasis in some African wild animals linked to the presence of a protein in their blood that kills trypanosomes, called APOL1, has opened new avenues of research (Del Pilar Molina-Portela et al. 2005), offering opportunities to develop effective vaccines.

Fish is an important source of food and nutrients, as well as livelihoods, in Africa. Fish provides 19% of animal protein in African diets (Chan et al. 2019). Africa is a net importer of fish (Chan et al. 2019). A threefold increase in production is needed to meet expected demands in fish (Chan et al. 2019). Aquaculture, an emerging sector on the continent, holds great potential for rapidly increasing the amount of available protein. Aquaculture production in Africa expanded at an average annual rate of 11.7% between 2000 and 2012 (nearly twice the global average rate of 6.2% (FAO 2014). Given the spatial and environmental constraints, this will require improvements in efficiency, husbandry and increased investment in domestication and development of new species for commercial production, alongside the genetic improvement of existing commercial stocks. Initiatives to genetically improve fish for aquaculture have so far been quite limited. Of the 400 species cultured, 90 are domesticated, and, of these, only 18 (5%) have been the subject of significant genetic improvement programs (Teletchea and Fontaine 2014). Genetic improvement can also reduce the environmental footprint of aquaculture.

3.2 Optimizing the Utilization of Indigenous Crops, Livestock, Fish and Underutilized Foods

Africa has over 2000 plant species that include domesticated and semi-domesticated native grains, roots, fruits and vegetables. These are considered to be "lost" species for rediscovery and exploitation in modern food systems, owing to their natural health and nutritional benefits and a variety of adaptive and resilient properties (National Research Council 1996). Many indigenous crops have multiple edible parts such as leaves, fruit, seeds and roots. Many indigenous African livestock, fish and plant breeds are resilient to many risks and adverse growing conditions (Mabhaudhi et al. 2019). But they tend to be viewed as famine foods, foraged and turned to by the poor in adverse situations. Yet, many of these foods are described as 'superfoods.' Optimal utilization of nutritious indigenous and traditional foods holds the potential for diversifying Africa's food systems, especially if more of these can be domesticated and produced in larger quantities. There is an urgent need to create pride in and demand for these foods and investment in research and technology development across the food system to integrate these resources into the daily food basket of African communities.

Although not widely adopted in Africa, biotechnology (techniques for improving plants, animals, and microorganisms) offers many opportunities to improve productivity, overcome abiotic (such as drought) and biotic stresses (diseases and pests), and save time and effort for farmers in Africa. For example, genetically modified crop varieties are labor-saving and reduce agricultural production's drudgery—especially for women, who are often saddled with more labor-intensive tasks such as weeding (Gouse et al. 2016). For instance, African farmers can benefit significantly from the adoption of Bt cotton. However, the share of farmers that stand to gain from the introduction of Bt cotton technology will be largely influenced by whether governments and technology innovators support appropriate incentives and address institutional and socio-economic barriers. Knowledge flows to and from farmers will play a critical role in the proper deployment of biotechnology (Falck-Zepeda et al. 2007). Furthermore, building the technical expertise in Africa to harness and safely deploy biotechnology for communities and the environment will be important.

Biotechnology can support food security in the face of major challenges such as declining per capita availability of arable land; lower productivity of crops, livestock and fisheries; heavy production losses due to biotic (insects, pests, weeds) and abiotic (salinity, drought, alkalinity) stresses; significant postharvest crop damage; and the declining availability of water. Biotechnology techniques that could be applied include tissue culture; marker-assisted selection, which entails the development of genetic markers to fast-track selection of natural traits in plant breeding; the "omics" (sciences such as genomics, proteomics and transcriptomics); the development of diagnostics; genetic modification; and a newer set of tools collectively referred to as the new plant breeding technologies (NASAC 2018).

3.3 Innovation in the Storage, Processing and Packaging of Foods

Transformation of the food system in Africa demands that we harness STI to promote product diversification with nutritious foods; processing to extend shelf life and make healthy foods easier to prepare; improved storage and preservation to retain nutritional value and ensure food safety; and innovations to extend seasonal availability and reduce postharvest losses (including aflatoxin) and food waste (Hendriks et al. 2021).

The emergence of the food processing sector is accompanied by a lengthening of agricultural value chains. From traditionally short chains limited to home-based processing and confined predominantly to rural areas, the changing value chains now primarily supply small towns and large urban centers with a range of branded, ready-to-cook or -eat foods (Conway et al. 2019). Urban-based value chains are fueled by the introduction of new processes for producing and distributing traditional foods outside of the household setting through specialized enterprises (Hawkes et al. 2017). This offers new employment opportunities in processing, distribution, packaging, and marketing across food value chains, as well as increased incomes for farmers. Strengthening the links between producers and processors is important to facilitate firm growth and benefit smallholder farmers.

Postharvest handling and technologies offer opportunities to reduce food losses and waste, particularly in the context of Africa, where cold chains and refrigeration are largely non-existent (MaMo 2019b) and seasonality leads to gluts and shortages of perishable goods. Many of these losses can be prevented through proper training and better handling of goods, the adoption of appropriate tools or technologies, sound policies and marketing-related improvements (Stathers et al. 2020). More investment is also needed in developing and making available solar driers and agro-processing equipment such as shellers and de-pulpers.

Food processing has the potential to contribute to the reduction of postharvest losses, enhancement of food safety and quality, creation of diversity, and stabilization of the food supply, reducing the prevalence of seasonal hunger and improving market access. Food processing can generate jobs and increase the retention of organic waste in farming areas. Even simple processing methods can transform perishable crops into a range of convenient, storable, value-added products, which meet the needs of expanding markets (Muyonga 2014).

Processing foods may smooth supplies, but can create deleterious health consequences (overweight, obesity and non-communicable diseases), depending on their ingredients (trans fats, high sugar and sugar alternatives, and excessive preservatives and other additives) (Pot et al. 2017). On the other hand, processing can also be used to create products that address specific nutrition needs. By blending staples and foods with complementary nutritional value and applying suitable processing procedures, it is possible to develop nutrient- and energy-enhanced foods to supplement prevailing nutritionally inadequate diets, particularly important for infants and young children.

Food safety is critical to the advancement of food systems. Poverty exacerbates the problem, since it leads to overdependence on one foodstuff and may lead to the consumption of contaminated foods because of the lack of alternatives (Shephard and Gelderblom 2014). Evidence on foodborne disease (FBD) in low- and middle-income countries (LMICs) is still limited, but important studies in recent years have broadened our understanding. Most of the known burden of FBD disease in low- and middle-income countries comes from biological hazards, primarily from fresh, perishable foods sold in informal markets (Grace 2015). Testing is often expensive and constrains the approval, distribution and export of foods. The lack of suitable regulations to prevent food contamination, or their poor enforcement when regulations exist (often applied to export goods, but not the domestic market), combined with the low levels of capacity for detecting food toxins, are serious concerns. Rapid and cheap out-of-laboratory analytical techniques designed for field conditions can offer solutions to these problems (Shephard and Gelderblom 2014). Examples are fluorescence spectrophotometry for quantifying mycotoxin levels in grains and raw groundnuts and the Lab-on-Mobile-Device (LMD) platform that can accurately detect mycotoxins using strip tests (Dobrovolny 2013).

More research and development is needed towards packaging solutions to extend the shelf-life of food, thereby reducing enzymatic activity and the growth of microorganisms and preventing moisture loss and decay. Thermal processing has been widely employed in the food industry for food safety assurance and extending product shelf-life by inhibiting or deactivating microorganisms (Caminiti et al. 2011; Stoica et al. 2013). Other technologies that could have significant benefits for food safety in Africa include non-thermal inactivation technologies such as electromagnetic fields, pulsed electric fields, high-voltage discharge, pulsed light, ionizing radiation, microwaves and cold plasma (NASAC 2018). Hybrid technologies and combinations of these methods have not yet been applied to the indigenous food industry, but could hold promise for transforming African food systems.

3.4 Improving Human Nutrition and Health

Making more nutritious food options available to a wide range of consumers is another pathway to influencing nutritional outcomes. This can include public and private sector investment in research and innovation of technologies and processes that improve foods' nutritional value. Recent advances in gene sequencing technologies enable investigation of the complex gut biome at both the genetic and functional (transcriptomic, proteomic and metabolic) levels and can map microbiome variability between species, individuals and populations, providing new insights into the importance of the gut microbiome in human health (Brunkwall and Orho-Melander 2017). Together with studies of traditional diets that include a wide range of herbal, medicinal and fermented products from Africa's wealth of indigenous foods, these offer opportunities for understanding how foods and the gut biome interact to protect human health and immunity.

Food fortification initiatives such as salt iodization, adding vitamin A to cooking oil and multivitamin mixes to maize flour, as well as the bio-fortification of crops such as the varieties of vitamin-A-enriched orange-flesh sweet potato, offer options for reaching a high proportion of the population. More research is needed into which African crops could benefit from breeding programs for bio-fortification to diversify the food basket and preserve the genetic diversity of nutritious traditional crops. Breeding, processing and additives such as prebiotics and probiotics offer the potential for enhancing the bioavailability of nutrients for absorption and metabolism (Markowiak and Śliżewska 2017) or decreasing the concentration of antinutrient compounds that may inhibit the absorption of nutrients (for example, phytates and oxalates) (Popova and Mihaylova 2019).

3.5 Addressing Equity and Vulnerability at the Community and Ecosystem Levels

Several socio-economic, cultural and demographic factors continue to drive inequalities among and within societies and limit the potential for some to benefit from actions aimed at improving livelihoods. This is coupled with political factors and decisions that are essential causes of inequality and power imbalances, severely constraining the ability of food system transformation to deliver sustained poverty reduction and sustainable, equitable livelihoods in Africa (Neufeld et al. 2021a, b). These existing inequities are further exacerbated by conflict, protracted crises and climate change, while the ongoing Covid-19 pandemic has dramatically exposed countries' pinch points and societies' vulnerabilities (Bron et al. 2021; MaMo Panel 2021). To ensure that food system transformation in Africa is not only sustainable, but also equitable, the structures that continue to enable and exacerbate inequities need to be urgently addressed.

One effective solution is to boost the opportunities and capacities of the most vulnerable, through redistributing resources more equitably (e.g., land, incomes, social protection), ensuring quality education, enabling progressive, and not regressive, taxation, and facilitating better targeted state infrastructure investments, among other approaches (Neufeld et al. 2021a, b). This must go hand in hand with decision-making that is more equitable and accountable to those who are most negatively affected by current food systems and their outcomes. Progress in advancing equitable livelihoods must hence be made in several key areas. According to Neufeld et al., this includes solutions that (i) are rights-based; (ii) ensure long-term investment for structural changes; (iii) directly inform local and national policy and programs; and (iv) enhance the development and equitable deployment of contextually relevant innovation and technology that better build on and learn from indigenous knowledge.

3.6 A Data Revolution for Improved Preparedness and Accountability Systems

The complex nature of food systems demands transdisciplinary collaboration and inter-sectoral governance. ICT can enhance learning among stakeholders, as well as between disciplines, to support innovation and the emergence of practical technologies that arise from transdisciplinary collaboration.

Evidence-based policies and planning require extensive and up-to-date data. There is an urgent need to strengthen national and regional institutional capacities for knowledge, data generation, and management that support evidence-based planning, implementation, and monitoring and evaluation (Bahiigwa et al. 2016). ICT innovations also offer multiple opportunities for improving food systems that could support the establishment of "big data" systems, analysis and reporting of cross-sectoral data, and monitoring and evaluation of implementation. Therefore, more significant investment is needed in more and better data, and inclusive annual national and subnational reporting mechanisms need to be developed and implemented to assess progress on commitments for food security and nutrition outcomes and actions in a timely way (Hendriks et al. 2021).

Collecting, managing and reporting data requires extensive information systems. "Big data" systems offer opportunities to analyze vast datasets that reveal patterns, trends and associations, especially in multi-sectoral applications such as those seen in the SGDs and national performance and monitoring situations related to food systems through innovative approaches and algorithms. Some applications include fraud and risk detection and logistic planning in programs and price comparisons, as well as predictive and proactive health disease and health management systems (NASAC 2018).

Public awareness of the problems, hazards and solutions is essential. Cloud computing allows for crowdsourcing and the active participation of citizens in mutual accountability systems and the provision of highly disaggregated geo-referenced data that can play an important role in monitoring contexts such as climate change, disease patterns and early warning systems. Communication science offers opportunities for exploring how to deploy digital media and improve communication systems to share knowledge at all levels. The role of ICT in the rapid identification of pests and diseases and the mapping of their locations and spread are important tools for managing and mitigating the inherent risks they create (Christaki 2015) and for increasing the awareness and preparedness of farmers, especially as much of the African food chain is informal. Investment in qualified staff within government, extension, and supporting research institutes is crucial, with a particular need for investment in young researchers and entrepreneurs.

Comprehensive soil mapping is necessary to address the deficiencies through appropriate soil improvement practices and the cultivation of the most suitable crops for each area. Overlaying these with weather and crop suitability maps can provide hands-on information to farmers through mobile technology. Mobile technology could be used to improve early warning systems and the dissemination of knowledge. One example is the Participatory Integrated Climate Services for Agriculture, which can help farmers make informed decisions based on accurate, location-specific, climate and weather information combined with locally relevant crop, livestock and livelihood options and participatory tools (Dayamba et al. 2018).

Satellite Earth Observations, such as Africa Agriculture Watch, are novel opportunities born out of the ICT revolution that, combined with in-situ data, provide a source of consistent and reliable information to benefit the water, energy, and food sectors. Such observations are necessary to begin understanding the complex feedback processes between the natural environment and human activities (FAO 2014).

ICT can solve many of the current constraints around access to information, data analysis, predictions and early warning. Innovations in mobile technology can overcome many trade- and market-related information challenges, link farmers to markets and provide mutual communication among producers, consumers and researchers. ICT applications and advances in digital banking offer opportunities for solving some of these constraints.

Hence, the digitalization of the agriculture sector needs to be placed at the core of national agricultural growth and food system transformation agendas to harness its cross-cutting innovative strength. By developing national digital agriculture strategies along with required public investments, governments can set out solid long-term visions for the design, development, and use of new technologies along the food system value chain.

Digital innovation hubs create the innovation ecosystem that is needed to spur the digital transformation of Africa's food systems, while providing opportunities and support for young people in the development of locally suitable technologies and digital solutions. More investment and support need to be provided to create more innovation hubs across the continent that are dedicated to developing solutions focused on food system transformation.

Finally, to ensure that digital applications and services meet quality standards, research centers can play an active role in the evaluation and impact assessment of specific technologies and e-services in rural areas. This would allow governments and the private sector to bring to scale those programs and interventions that are proven impactful and beneficial to rural communities. Quality control and standard-setting of new technologies, digital tools, and services require the attention of business associations and governments.

3.7 Leveraging African Research and Science and Improving Education and Training

Food system transformation is a relatively new concept. As such, investment in research and development for the transformation of food systems in Africa needs to be significantly increased. One option is to develop an African funding base to support supranational research activities. Think tanks and research institutions need to be considered public goods that foster continued dialogue and supply of innovative approaches and solutions to the challenges that the food systems face. Crucially, African research institutions need to be equipped to support governments in developing their own evidence-based policy priorities and science, technology, and innovations for food system transformation, coupled with scalable solutions. This ought to occur in tandem with continued exchange and constructive dialogue with other regions in the world to improve public policy. The need for permanent dialogue and exchanges calls for the creation of policy labs that allow for innovation and experimentation and learning from past failures.

3.8 Capacity Strengthening of Institutions and Mutual Accountability

Governments must be held accountable for their commitments to invest in integrated approaches and food system transformation. Mutual accountability country processes, including the Biennial Reviews and the agriculture Joint Sector Reviews, two major innovations under the CAADP agenda, remain critical for this. Mutual accountability will be crucial for improved policies and better outcomes around food system transformation and will ensure that policies respond to the needs of all stakeholders, including the vulnerable and marginalized.

To deliver on the ambitions and targets set out under the African Union Agenda 2063, CAADP and the SDGs, capacities for implementation, monitoring, and evaluation need to be strengthened. Poor institutional capacity has been identified as one of the major barriers to the successful implementation of the program. Countries will, therefore, need to invest more in building the requisite capacities to transform agriculture and food systems and commit to inclusive, technically rigorous, and comprehensive mutual accountability processes. The biennial review and the joint sector review processes hereby constitute best practice approaches that need to be built upon to encompass all elements of food system transformation.

4 Conclusions

As African governments embrace a food systems approach to policy design and implementation, specific attention needs to be paid to transforming food systems in a way that enhances nutrition outcomes, improves livelihoods and protects and enhances the environment. As this chapter shows, this can be achieved through policies and interventions targeted at food and agriculture trade, infrastructure development, finance, and science and technology for food systems, as well as capacity and skill strengthening. Science, technology and policy innovations offer many promising opportunities for food system transformation in Africa.

The chapter emphasizes the importance of evidence-based policies that understand and harness the synergies and trade-offs among food, health, water, energy and ecosystems, that provide alternative solutions for agricultural extension and advisory services, and that promote organizational innovations at the production, industry and downstream levels of supply chains that are lean, agile, resilient and green. Comprehensive and differentiated policy reforms for integrated food systems across Africa, as well as improvements in governance and management for better outcomes, are critical.

At the same time, modern science can unlock the potential and protect the heritage of Africa's nutritious food sources and ensure sustainable and diverse diets. Changing the path of future food systems in Africa will demand a structural transformation (transitioning from low productivity and labor-intensive economic activities to higher productivity and skill-intensive activities) of food systems and considerable value chain development. The mandate and operations of S&T institutions are necessary to enhance their contribution to the exploitation of S&T for sector transformation.

The context-specific essential STI and policy solutions relevant to transforming food systems in Africa relate to:

(a) Raising production efficiency and restoring and sustainably managing degraded resources
(b) Innovating in the storage, processing and packaging of foods
(c) Improving human nutrition and health
(d) Addressing equity and vulnerability at the community and ecosystem levels
(e) Fostering a data revolution for greater access to information and transparent monitoring and accountability systems
(f) Leveraging African research and science and improving education and training
(g) Strengthening the capacity of institutions and mutual accountability

The Food Systems Summit offers opportunities for stakeholders in African food systems to reflect on the role STI can play in transforming food system outcomes to improve the supply of safe and nutritious food for all while restoring and protecting the degradation of natural resources to ensure sustainability for future generations.

References

Ahmadi E, McLellan B, Mohammadi-Ivatloo B, Tezuka T (2020) The role of renewable energy resources in sustainability of water desalination as a potential freshwater source: an updated review. Sustainability 2020(12):5233. https://doi.org/10.3390/su12135233

Al Shrouf A (2017) Hydroponics, Aeroponic and Aquaponic as compared with conventional farming. Am Sci Res J Eng Technol Sci (ASRJETS) 27(1):246–255

Allen T (2015) Changing demographics pulling up agriculture. GREAT Insights Mag 4(4). https://ecdpm.org/great-insights/territorial-development-2/changing-demographics-pulling-up-agriculture/

AUC/NEPAD (2008) Framework for the improvement of rural infrastructure and trade-related capacities for market access. New Partnership for Africa's Development (NEPAD), Johannesburg

Badiane O, Collins J, Ulimwengu JM (2020) Chapter 2: the past, present and future of agriculture policy in Africa. In: Resnick D, Diao X, Tadesse G (eds) 2020 Annual trends and outlook report: Sustaining Africa's agrifood system transformation: The role of public policies. International Food Policy Research Institute (IFPRI) and AKADEMIYA2063, Washington, DC/Kigali, pp 9–25. https://doi.org/10.2499/9780896293946_02

Bahiigwa G, Benin S, Tafera W (2016) Tracking key CAADP indicators and implementation processes. In: Covic N, Hendriks S (eds) Achieving a nutrition revolution for Africa: the road to healthier diets and optimal nutrition, chapter 12, ReSAKSS Annual Trends and Outlook Report 2016. International Food Policy Research Institute, Washington, DC, pp 170–178

Baumüller K, Admassie A, Hendriks S, Tadesse G, von Braun J (ed) (2021) From Potentials to Reality: Transforming Africa's Food Production - Investment and policy priorities for sufficient, nutritious and sustainable food supplies. Peter Lang Publ. (forthcoming an earlier draft is available at https://www.zef.de/fileadmin/downloads/ZEF_Akademiya2063.pdf)

Bindraban PS, van der Velde M, Ye L, Van den Berg M, Materechera S, Kiba DI, Tamene L, Ragnarsdóttir KV, Jongschaap R, Hoogmoed M, Hoogmoed W (2012) Assessing the impact of soil degradation on food production. Curr Opin Environ Sustain 4(5):478–488

Bron GM, Siebenga JJ, Fresco LO (2021) In the age of pandemics, connection food systems and health: a global one health approach. Food systems summit brief prepared by research Parners of the scientific Group of the Food Systems Summit. 2021

Brunkwall L, Orho-Melander M (2017) The gut microbiome as a target for prevention and treatment of hyperglycaemia in type 2 diabetes: from current human evidence to future possibilities. Diabetologia 60:943–951. https://doi.org/10.1007/s00125-017-4278-3

Caminiti AM et al (2011) Impact of selected combinations of non-thermal processing technologies on the quality of an apple and cranberry juice blend. Food Chem 124:1387–1392

Chan C, Tran N, Pethiyagoda S, Crissman C, Sulser T, Phillips M (2019) Prospects and challenges of fish for food security in Africa. Glob Food Sec 20:17–25

Christaki E (2015) New technologies in predicting, preventing and controlling emerging infectious diseases. Virulence 6(6):558–565. https://doi.org/10.1080/21505594.2015.1040975

Conway G, Badiane O, Glatzel K (2019) Food for all in Africa: sustainable intensification for African farmers. Cornell University Press, Ithaca

Dayamba DS, Ky-Dembele C, Bayala J, Dorward P, Clarkson G, Sanogo, Mamadou LD, Traoré I, Diakité A, Nenkam A, Binam JN, Ouedraogo O, Zougmore R (2018) Assessment of the use of participatory integrated climate Services for Agriculture (PICSA) approach by farmers to manage climate risk in Mali and Senegal. Clim Services 12:27–35. https://doi.org/10.1016/j.cliser.2018.07.003

Del Pilar Molina-Portela M, Lugli EB, Recio-Pinto E, Raper J (2005) Trypanosome lytic factor, a subclass of high-density lipoprotein, forms cation-selective pores in membranes. Mol Biochem Parasitol 144(2):218–226

Dobrovolny M (2013) Smartphone app offers cheap aflatoxin test for farmers. Sci Dev Net news item, 4 November 2013. Accessed from http://www.scidev.net/global/icts/news/smartphone-app-offers-cheap-aflatoxin-test-for-farmers.html, 8 August 2017

Falck-Zepeda J, Horna D, Smale M (2007) The economic impact and the distribution of benefits and risk from the adoption of insect resistant (Bt) Cotton in West Africa. IFPRI Discussion Paper 00718

FAO (Food and Agriculture Organisation) (2014) The state of world fisheries and aquaculture. FAO, Rome

FAO, IFAD, UNICEF, WFP and WHO (2020) The state of Food Security and nutrition in the world 2020. FAO, Rome

Gerber PJ et al (2013) Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO, Rome

Gopal M, Gupta A (2016) Microbiome selection could spur next-generation plant breeding strategies. Front Microbiol 7. https://doi.org/10.3389/fmicb.2016.01971

Gouse M, Sengupta D, Zambrano Z, Zependa JF (2016) Genetically modified maize: less drudgery for her, more maize for him? Evidence from smallholder maize farmers in South Africa. World Dev 83:27–38

Grace D (2015) Food safety in low and middle income countries. Int J Environ Res Public Health 12(9):10490–11050. https://doi.org/10.3390/ijerph120910490

Hawkes C, Harris J, Gillespie S (2017) Chapter 4: Changing diets: Urbanization and the nutrition transition. In: 2017 Global Food Policy Report. International Food Policy Research Institute (IFPRI), Washington, DC, pp 34–41. https://doi.org/10.2499/9780896292529_04

Henderson BB et al (2015) Greenhouse gas mitigation potential of the world's grazing lands: modeling soil carbon and nitrogen fluxes of mitigation practices. Agric Ecosyst Environ 207: 91–100

Hendriks SL, Bekele E, Chaibi T, Hassan M, Miano DW, Muyonga JH (2021) The role of science, technology, and innovation for transforming Food Systems in Africa. Presented at the United Nations Food Systems Summit 2021, Research Partners of the Scientific Group for the Food Systems Summit, NY

Jayne T, Chamberlin J, Headey D (2014) Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food Policy 48:1–17

Kihara J et al (2016) Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agric Ecosyst Environ 229:1–12

Kimera ZI, Mshana SE, Rweyemamu MM et al (2020) Antimicrobial use and resistance in food-producing animals and the environment: an African perspective. Antimicrob Resist Infect Control 9:37. https://doi.org/10.1186/s13756-020-0697-x

Lowder S, Skoet J, Raney T (2016) The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev 87:16–29. https://doi.org/10.1016/j.worlddev.2015.10.041

Mabhaudhi T, Vimbayi V, Chimonyo G, Hlahla S, Massawe F, Mayes S et al (2019) Prospects of orphan crops in climate change. Planta 250:695–708. https://doi.org/10.1007/s00425-019-03129-y

Maeda JM, Nkengasong JN (2021) The puzzle of the COVID-19 pandemic in Africa: perspective. Science 1-Jan-2021. https://doi.org/10.1126/science.abf8832

Maina KW, Ritho CN, Lukuyu BA, Rao EJO (2020) Socio-economic determinants and impact of adopting climate-smart Brachiaria grass among dairy farmers in eastern and Western regions of Kenya. Heliyon 6(6):e04335. https://doi.org/10.1016/j.heliyon.2020.e04335

MaMo Panel (Malabo Montpellier Panel) (2019a) Byte by byte: policy innovation for transforming Africa's food system with digital technologies, Dakar. https://doi.org/10.2499/9780896296848

MaMo Panel (Malabo Montpellier Panel) (2019b) Energized: policy innovations to power the transformation of Africa's agriculture and food system. MaMo Panel, Dakar

MaMo Panel (Malabo Montpellier Panel) (2020) Meat, Milk and more: policy innovations to shepherd inclusive and sustainable livestock systems in Africa. MaMo Panel, Dakar

MaMo Panel (Malabo Montpellier Panel) (2021) Connecting the dots: policy innovations for food systems transformation in Africa. MaMo Panel, Dakar

Markowiak P, Śliżewska K (2017) Effects of probiotics, prebiotics, and Synbiotics on human health. Nutrients 9(9):1021. https://doi.org/10.3390/nu9091021

Mekonnen M, Hoekstra A (2012) A global assessment of the water footprint of farm animal products. Ecosystems 15:401–415. https://doi.org/10.1007/s10021-011-9517-8

Muyonga J (2014) Processing as a driver of agricultural development: the case of Makerere University Food Technology and Business Incubation Centre, Uganda. Accessed from http://knowledge.cta.int/Dossiers/S-T-Policy/Reshaping-tertiary-agricultural-education/Feature-articles/Processing-as-a-driver-of-agricultural-development-the-case-of-Makerere-University-Food-Technology-and-Business-Incubation-Centre-Uganda,17 January 2017

NASAC (Network of Science Academies in Africa) (2018) Opportunities and challenges for research on food and nutrition security and agriculture in Africa. NASAC, Nairobi

National Research Council (1996) Lost crops of Africa: volume I: grains. The National Academies Press, Washington

Neufeld L, Hendriks SL, Hugas M (2021a) Healthy diet: A definition for the United Nations Food systems summit 2021. A paper from the scientific group of the UN Food systems summit. UN, New York

Neufeld L, Huang J, Badiane O, Caron P, Sennerby Forsse L (2021b) Advance equitable livelihoods. A paper from the scientific group of the UN Food systems summit. UN, New York

Nkonya EM, Koo J (2017) Chapter 8: The unholy cross: Profitability and adoption of climate-smart agriculture practices in Africa south of the Sahara. In: De Pinto A, Ulimwengu JM (eds) A thriving agricultural sector in a changing climate: Meeting Malabo Declaration goals through climate-smart agriculture. International Food Policy Research Institute (IFPRI), Washington, DC, pp 103–113. https://doi.org/10.2499/9780896292949_08

Pereira L (2017) Climate change impacts on agriculture across Africa. In: Oxford research Encyclopedia of environmental science. Oxford University Press, New York. https://doi.org/10.1093/acrefore/9780199389414.013.292

Popova A, Mihaylova D (2019) Antinutrients in plant-based foods: a review. Open Biotechnol J 13: 68–76

Pot IJ, Braga B, Bo Q (2017) Ultra-processed Food intake and obesity: what really matters for health-processing or nutrient content? Curr Obes Rep 6(4):420–431. https://doi.org/10.1007/s13679-017-0285-4

Radwanska M et al (2008) Trypanosomiasis-induced B cell apoptosis results in loss of protective anti-parasite antibody responses and abolishment of vaccine-induced memory responses. PLoS Pathog 4(5):e1000078

Rao I et al (2015) Strategic management for forage production and mitigation of environmental effects: development of Brachiaria grasses to inhibit nitrification in soil. In: Evangelista AR, Avila CLS, Casagrande DR, Lara MAS, Bernades TF (eds) Preceedings of the 1st International Conference on Faorages in Warm Climates. Forages in Warm Climates. Prganising Committee of the 1st International Conference on Forages in Warm Climates and University of Lavras, Lavras, pp 85–102

Ringler C, Brent W (2020) Why the G20 needs to focus on energizing food systems in Africa. https://www.ifpri.org/blog/why-g20-needs-focus-energizing-food-systems-africa

Rocha I, Ying M, Souza-Alonso P, Vosatka M, Freitas H, Oliviera O (2019) Seed coating: A tool for delivering beneficial microbes to agricultural crops. Front Plant Sci 10:1357

Sandhu JS et al (2015) Recent trends in breeding of tropical grass and forage species. In: Proceedings of the 23rd International Grassland Congress, New Delhi, pp 20–24

Sheahan M, Barrett CB (2017) Ten striking facts about agricultural input use in sub-Saharan Africa. Food Policy 67:12–25. https://doi.org/10.1016/j.foodpol.2016.09.010

Shephard GS, Gelderblom WCA (2014) Rapid testing and regulating for mycotoxin concerns: a perspective from developing countries. World Mycotoxin J 7(4):431–437

Stathers TH, Mvumi B, English A, Omotilewa O (2020) A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asi. Nat Sustain 3:821–835. https://doi.org/10.1038/s41893-020-00622-1

Stoica ML, Borda D, Alexe P (2013) Non-thermal novel food processing technologies. An overview. J Agroaliment Process Technol 19(2):212–217

Teletchea F, Fontaine P (2014) Levels of domestication in fish: implications for the sustainable future of aquaculture. Fish Fish 15(2):181–195

Tittonell P, Giller K (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res 143(1):76–90

Tschirley D, Haggblade S, Reardon T (2019) Africa's emerging food system transformation. In: Global Center for Food Systems Innovation. White paper. Michigan State University, East Lansing. https://doi.org/10.1016/j.gfs.2019.04.009

Wiebe KD, Sulser TB, Mason-D’Croz D, Rosegrant MW (2017) Chapter 2: The effects of climate change on agriculture and food security in Africa. In: De Pinto A, Ulimwengu JM (eds) A thriving agricultural sector in a changing climate: Meeting Malabo Declaration goals through climate-smart agriculture. International Food Policy Research Institute (IFPRI), Washington, DC, pp 5–21. https://doi.org/10.2499/9780896292949_02

Wild S (2016) Quest to map Africa’s soil microbiome begins. Nature 539(7628):152

Yaro M, Munyard KA, Stear MJ, Groth DM (2016) Combatting African animal trypanosomiasis (AAT) in livestock: the potential role of trypanotolerance. Vet Parasitol 225:43–52

Ziraba AK, Fotso JC, Ochako R (2009) Overweight and obesity in urban Africa: A problem of the rich or the poor? BMC Public Health 9:465. https://doi.org/10.1186/1471-2458-9-465

The Role of Science, Technology and Innovation for Transforming Food Systems in Latin America and the Caribbean

Elizabeth Hodson de Jaramillo, Eduardo J. Trigo, and Rosario Campos

1 Introduction

The transformation of food systems (FS) can produce huge benefits for health, food security and nutrition, sustainable agriculture and nature. Central to this discussion is the understanding that FS are demand-led (IFPRI 2020) and represent the full agri-value chain, which includes growing, harvesting, processing, transporting, marketing, distributing, consuming and disposing of food and food-related items, plus the inputs needed and outputs produced at each of these steps. They integrate nutrition, health, resource use, biodiversity, transformation, jobs and livelihoods, all of which ideally should be covered under the concept of the SDGs. As an economic complex, they provide close to 1.3 billion jobs and account for the livelihoods of over 3.2 billion people around the world. In this sense, transforming FS becomes key, if not the main issue, for making real progress towards all 17 SDGs by 2030 (UN 2020). Science, technology and innovation (STI) offer a wide and expanding range of opportunities for making real progress towards these objectives. This paper looks at the issues involved, with a focus on Latin America and the Caribbean (LAC).

E. Hodson de Jaramillo (✉)
Member of the Colombian Academy of Exact, Physical and Natural Sciences and of the Inter-American Network of Academies of Sciences (IANAS), Pontificia Universidad Javeriana, Bogotá, Colombia
e-mail: ehodson8@outlook.com

E. J. Trigo · R. Campos
IICA Technical Cooperation Directorate, Pilar, Argentina

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_38

2 IAP and IANAS Reports "Opportunities for Future Research and Innovation on Food and Nutrition Security and Agriculture"

The IAP report (2018) emphasizes the urgent need to mobilize financial and human resources to promote the shift towards more efficient and sustainable FS, an effort that demands profound changes in the way that food is produced and consumed, and the resulting waste disposed of. Collaboration between the natural and social sciences is required to find sustainable solutions to FS, as well as an efficient international science advisory mechanism. There is a wide range of scientific opportunities, and making the most of them is a wise public policy decision. Furthermore. all stakeholders must be included along the value chain in an integrated way.

The reports highlight that the transformation of FS requires a coordinated global approach to promoting the application of research to innovation, connections among disciplines and sectors, including cooperation with policies, and enhancement of scientific infrastructure with collaboration among countries, and recognizing the circular economy and the bioeconomy as two strategic areas for FS transformation (Lachman et al. 2020; IANAS 2018). Their main recommendations include: (a) promoting substantive changes towards climate-smart FS, (b) developing incentives for consumers to modify and improve their diets, (c) reducing food waste, (d) developing innovative foods, (e) increasing cooperation between the life sciences and the social sciences, as well as policy research on food, nutrition and agriculture, to translate advances into applied innovation, and (f) fostering international cooperation through advisory mechanisms (IANAS 2018; IAP 2018).

3 Food and Nutrition Aspects, Healthy Diets

In relation to nutritional aspects, the Americas present a picture of sharp contrast. The region has an exceptional abundance of natural resources, displaying considerable wealth in agrobiodiversity, arable land and the availability of water. These constitute major advantages for the future, and make the Americas the largest net food exporter in the world, as well as the largest producer of ecosystem services. The region makes vital contributions to several development objectives, including growth and trade promotion, poverty reduction, food and nutrition security, ecosystem services and climate resilience. Moreover, aquaculture is emerging as a major industry in a number of countries, such as Canada, Chile, Mexico, Peru, Argentina and Ecuador (Morris et al. 2020; IANAS 2018). However, malnutrition, food insecurity, obesity and other related diseases coexist to a greater or lesser degree throughout the region. There has been a rise in hunger, with the number of undernourished people increasing by nine million between 2015 and 2019. Food insecurity in LAC went from 22.9% in 2014 to 31.7% in 2019, due to a sharp increase in

South America, and over 100 million people currently cannot afford a healthy diet (FAO 2020a).

For the transformation to sustainable and healthy diets, the research agenda related to food choices must explore alternative ways of influencing consumer behaviour (IAP 2018). Among the factors that define healthy diets are availability, affordability, and social and cultural issues. LAC's great agrobiodiversity and the potential of nutritious, but underutilized or neglected, indigenous crops represent a great opportunity for transformation towards sustainable systems, more balanced diets, and increased resource efficiency and resilience. High diversity in aquaculture in LAC provides wider opportunities for balanced diets (Hodson de Jaramillo et al. 2019).

4 Science and Technology and Food System Transformation

STI is essential for addressing the multidimensional nature of food security and FS. New and emerging technologies in the field of the biological sciences, information and communication, data sciences, artificial intelligence, and associated digital applications are significantly improving the production and productivity of crops and livestock and the quality of food and biomass. Advances in breeding provide means of developing disease-tolerant and environmentally friendly varieties of plants and animals. STI also contributes to improved resource use and waste reduction, as well as increasing the overall economic organization and competitiveness of FS (Basso and Antle 2020; Saiz-Rubio and Rovira-Más 2020; ECLAC et al. 2019; HLPE 2019; Trigo and Elverdin 2019; Rose and Chilvers 2018). In turn, the emerging concept of the circular bioeconomy – keeping renewable components and materials in the system during successive processes while protecting ecosystems using STI – makes it possible to improve productivity and the sustainable use of biological resources and to reduce waste. This approach allows for the development of new, high value-added bioproducts, such as nutraceuticals, biofortified foods, bio-inputs for agriculture, bioenergy and biomaterials for the cosmetic, pharmaceutical, chemical and other industries (Brandao et al. 2021). It generates a range of new services and attaches greater value to biodiversity, for example, through integrated pest management based on biological pesticides and fertilizers. It contributes to an increase in the efficiency of converting biological resources for food, feed, soil health, and other uses by improving biorefinery processes (Trigo et al. 2021; Lachman et al. 2020; ECLAC et al. 2019).

The current STI scenarios for FS transformation offer very concrete opportunities to contribute to the SDGs, particularly to: SDG 1 (Reduce poverty), SDG 2 (Reduce hunger), 3 (Good health and well-being), 6 (Clean water and sanitation), 7 (Affordable and clean energy), 8 (Decent work and economic growth), 9 (Industry, innovation and infrastructure), 12, (Responsible production and consumption), 13 (Climate action), and 15 (Life on land).

These STI scenarios play a key role in the provision of sustainable agricultural development, climate resilience, the production of healthy nutritious foods, and a guarantee of global food security. New developments in agricultural technology will play a leading role in moving our FS towards more sustainable schemes (Trigo and Elverdin 2019). Biotechnology has evolved more efficient and faster ways of doing research in breeding programs in agriculture that, combined with digital technologies, potentiate agricultural advances to produce more with less, innovations that are, in turn, being proactively reflected throughout the FS (Virginia Tech 2020).

Global agriculture is undergoing major transformations through the convergence of digital, biological and engineering technologies (ECLAC 2021; Basso and Antle 2020; Santos Valle and Kienzle 2020; Rose and Chilvers 2018), to optimize agricultural production processes and input utilization in the so-called Agriculture 4.0. The adoption of the new technological strategies must be prudent and based on transparent, inclusive and participatory social processes, adapted to local conditions, capacities and cultures (ECLAC et al. 2019). To define priorities, the participation of local communities is essential, and should promote a convergence of scientific and traditional knowledge (Herrero et al. 2020). The pace of the innovations can be increased, with the appropriate policies, incentives, regulations and social acceptance (Fanzo et al. 2020).

At the level of specific technologies, the range of possibilities is extremely wide, although two essential concepts stand out: greater precision and efficiency for the purpose of producing more with less in a sustainable context (ECLAC et al. 2019; Trigo and Elverdin 2019):

- Rapid and efficient improvement systems, based on the use of genomic information, generational acceleration, and molecular techniques like gene editing.
- Crop sensors connected to mobile devices that allow for evaluating input (fertilization, water needs) at precise times and scales.
- Crop health monitoring systems and biological and artificial intelligence mechanisms, which will allow for a reduction of chemicals in the control of pests and diseases.
- Virtual strategies for the dissemination of management techniques adjusted by locality/region, to significantly increase the integrated management of crops.
- Livestock biometrics; use of collars and other devices to collect real-time information about the behavior, feeding habits, and general condition of the animals.
- Precision agriculture, which integrates agroecological and productive information with information and communication technologies (ICT), proposing management strategies for optimizing the use of inputs, including improvements in the efficient use of water and the use of sensors for the micro-administration of irrigation.

In addition, there are significant advances in the use of beneficial soil microorganisms in agriculture, and an application of the microbiome that can provide higher and more sustainable levels of productivity improvements, food quality and profitability

(Singh et al. 2020; FAO 2019). Strong international cooperation in microbiome science is essential for achieving efficient microbiome-based innovations (D'hondt et al. 2021).

5 A Perspective from Latin America and the Caribbean

The LAC region is not only a great producer of sustainable biomass; it has also become one of the main actors in international markets due to important developments in its scientific-technological capacities, industrial infrastructure and bioenergy generation. Several significant technology developments provide a platform of great importance for facing future challenges. These not only include traditional and export crops, but also agricultural biotechnology applications, conservation and regenerative agriculture and sustainable livestock production systems (ECLAC et al. 2019; Trigo and Elverdin 2019). In biotechnology applications, the region has been one of the early leaders in the adoption of agricultural biotechnology (GM crops) (www.isaaa.org). There are successful public-private initiatives resulting in close-to-market developments in strategic crops such as soybeans, common beans, potatoes and wheat, and, more recently, in rice, through the application of gene editing technologies (ECLAC et al. 2019; Oliva et al. 2019).

Another development worth mentioning is the emergence of a new generation of young entrepreneurs, developing technologies and start-ups in several countries (e.g., Mexico, Costa Rica, Colombia, Peru, Brazil, Argentina, and Uruguay). These are beginning to have an impact on the regional bioeconomy landscape, and are creating new pathways for scientific effort that benefits the region. A non-comprehensive list includes:

- Protera. A Chilean biostartup developing safe, sustainable, and smart protein-based food ingredients with Artificial Intelligence applied to synthetic biology (https://www.proterabio.com/technology).
- Hemoalgae. A Costa Rican biostartup developing high value-added chemical compounds using microalgae-based production platforms (http://hemoalgae.com/).
- Nutriyé. A Mexican biostartup developing functional beverages using nutraceutics and natural biological compounds and exploring the potential of personalized nutrition (http://www.nutriye.com/).
- Syocin Biotech. An Argentinian startup developing synthetic biology platforms to redesign and produce biomolecules that target plant bacterial pathogens (http://syocin.com/).
- Sciphage. A Colombian startup developing bacteriophage-based solutions for treating bacterial infections in poultry and reducing the use of antibiotics. (https://sciphage.com/).
- Eficagua. A Chilean biostartup developing solutions for optimizing the use of water in agriculture (https://eficagua.cl/).

- Oxcem. A Peruvian biostartup creating microalge-based systems to address air pollution in big cities (https://oxcem.com).
- Scintia. A Mexican biostartup developing innovative tools to make biotechnology and synthetic biology more accessible (https://www.scintia.com/).

In the case of conservationist and regenerative agriculture, reduced tillage practices have been adopted in a wide diversity of production systems (ECLAC et al. 2019). There are also important initiatives directed at highlighting the strategic character of soils, such as IICA's "Living Soils of the Americas," which seeks to connect public and private efforts in the fight against soil degradation and to maintain the health of cultivated land, as well as fostering efficient management and conservation of soils (https://iica.int/en/press/news/rattan-lal-and-iica-launch-living-soils-americas-initiative). As mentioned, crop diversification using local varieties is a strategy for facing climate change, improving nutrition and increasing resilience (ECLAC et al. 2019).

LAC countries are highly vulnerable to climate change because of their socio-economic, geographic and institutional characteristics (ECLAC-UNDR 2021), a very important factor within the agricultural sector. Natural disasters such as flooding, storms and landslides are increasing, and several international agencies (UNEP, WFP, CGIAR) are working to promote climate resilience, reforestation and restoration. For instance, the mandate of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is to identify and address the most important interactions, synergies and trade-offs among climate change, agriculture and food security. Some results are presented in an Inventory of CSA practices in LAC climate-smart villages (Bonilla-Findji et al. 2020). Some studies show that, by implementing integrated soil and water management strategies, smallholder family farms can become resilient to climate change (Roop and St. Martin 2020).

The Caribbean region economies are dependent largely on tourism (ECLAC-UNDR 2021), and almost all of the Caribbean countries are net food importers, despite having arable lands, rich agrobiodiversity and favorable growing conditions. As agricultural production declined in 2018, the Caribbean Community formulated a strategic plan to promote sustainable food production and reduce import dependency through the innovation and modernization of agriculture (https://caricom.org/). The objectives are increased employment, poverty alleviation, reduction in the import bill, food and nutrition security and a reversal of the growing incidence of chronic non-communicable diseases. CARDI will promote the adoption of climate-smart agricultural practices by pursuing effective partnerships, capacity-building opportunities and information generation and dissemination (CARDI 2018).

The expanding aquaculture industry (the farming of aquatic organisms, including fish, mollusks, crustaceans and aquatic plants) can provide more sustainable animal source foods (Gephart et al. 2021) and is contributing to the regional economy through more than 200,000 direct employments and 500,000 indirect ones. In 2018, aquaculture in the Americas produced 3,799,191 tons of animal and 21,984 tons of plant material (FAO 2020b).

Despite these important developments, the overall picture in the region is one of concern, as a majority of the countries in LAC, particularly the smaller ones, are on the sidelines. They reflect a substantial diversity among national agricultural research systems, infrastructure, investments in human capital, financing capabilities and the roles of public and private sectors in S&T. In terms of investments, five countries (Argentina, Brazil, Chile, Colombia and Mexico) account for more than 90% of the regional investment (Stads et al. 2016). The same trend is observed when investment is presented in terms of a percentage of the countries' agricultural GDP. Only six countries and one region – Brazil, Chile, Uruguay, Argentina, Costa Rica, Mexico and the Anglophone Caribbean – invest more than 1% (Stads et al. 2016). These figures are closely associated with the productivity gaps that are becoming increasingly evident between the region and the rest of the world, and between tropical and temperate areas (Nim-Pratt el al. 2015). They are also in marked contrast with other countries with relevant agricultural sectors, such as Canada, where investment in agricultural R&D as a percentage of agricultural GDP amounted to 11.3% (2009), or in Australia, where it exceeded 12.5% (2011) (OECD 2018).

A similar picture is seen with investments in and capacity for the biosciences. At best, most countries are in the early stages of effectively using new technologies, with significant investments concentrated in a small number of the larger countries, so that much of the region's agriculture risks losing the benefits of the new technologies. Close to 90% of total investments and applications in biotechnology in LAC were in Brazil (>50%), Argentina, Mexico, Venezuela, Chile and Colombia (Trigo et al. 2010). These low and concentrated investment levels are also reflected in the availability of human resources, an issue that is perhaps more strategic due to the increasing complexity of the situations to be faced. (Stads et al. 2016).

6 Lessons from COVID-19

The confinements and disruptive effects caused globally by COVID-19 have demonstrated the enormous fragility of our agrifood systems, stressing the need for FS transformation (UN 2020). The pandemic caused disruptions to global food supply, stressing the crucial importance of LAC as a provider of food, and pointed to the need for promoting greater intra-regional economic cooperation, in terms of production, trade and technology (Morris et al. 2020). In this sense, the current crisis is a unique opportunity to change the false claims that economic growth is in conflict with environmental sustainability, and to apply the bioeconomy approach for territorial development with circular systems and greater resilience for the benefit of society and the planet (Trigo et al. 2021; Lachman et al. 2020). In most LAC countries, FS responded well and was able to continue providing food throughout the crisis, with a rapid emergence of alternative distribution and marketing systems, through partnerships and use of the internet (IICA 2021).

However, as in other parts of the world, the pandemic has triggered recession and declines in income, especially for poor people, and due to some disruptions in the food chain, vulnerable groups suffered with respect to food security and nutrition. For example, young people in LAC have had difficulty accessing healthy foods such as fruits and vegetables, compounded by decreased physical activity and an increase in the consumption of sugary drinks, snacks and fast foods (León and Arguello 2021). The use of ICT and e-trade have grown rapidly. Overall, the insights and lessons from the pandemic should help in designing better policies and building more resilient and inclusive FS for the future. (Swinnen and Mcdermott 2020). Looking to the future, a key issue to be confronted will be the fiscal consequences of COVID-19, as many countries are already making significant cuts in their R&D investments, imposing new restrictions on already poorly-financed science and technology systems (IICA 2021).

7 Moving Forward: Strengthening Policy in LAC for Research and Its Uptake

Present STI scenarios offer an extensive and strategic set of opportunities and instruments for FS transformation. However, in most cases, existing institutions and orientations reflect past situations and priorities (Morris et al. 2020), and this is a negative factor for effectively mobilizing resources towards transformative Agenda 2030 objectives. Increasing investment levels is a common requirement for all countries, but beyond that, there is an urgent need for institutional structure and organizational approach that better reflects the new environment. The following paragraphs offer some reflections on specific topics and areas of work to consider for this purpose.

7.1 The Institutional Framework for the Innovation and Transfer of Agricultural Technology

STI alone cannot achieve all of the advances in FNS required for the future. Developments, combined with evidence-based policy, must be implemented in the Americas. There is a need for better integration of STI progress and investment opportunities into national policymaking and communicating its potential to the public (IANAS 2018). R&D institutions should address sustainable whole FS in an integrated way and along interconnected value chains (HLPE 2019). Achieving sustainable FS will require the full support of diverse policies: agricultural, trade and exchange, related to resources such as land and water, education, labor, financing, and all aspects connected to human health and safety, as well as permanent incentives. The goal is to deliver sustainable growth, good jobs, food and nutrition security, and climate-resilient ecosystem services (Morris et al. 2020).

Conventional approaches have resulted in "silo institutional approaches" (Trigo and Elverdin 2019), which is not the most appropriate way to face the complex challenges posed by FS transformation. There is a need to incorporate new actors into the process and facilitate interaction between biological sciences and other areas of knowledge. There is little tradition of cooperation; therefore, advancing integration mechanisms around common objectives is a priority. Reconfiguring the relationship between scientific research and local knowledge systems is essential for creation of the necessary innovative transition pathways adapted to each type of agricultural and FS (HLPE 2019).

7.2 Work and Investment Priorities

In general, R&D priorities have been highly focused on solving production problems, improving resource management, and, above all, maintaining a "short vision" of the agricultural and livestock sector (Stads et al. 2016). The new scenarios demand a broader agenda, going beyond production to integrate issues related to sustainability, the entire supply chain value, quality, nutrition, energy production and industrial use of biomass (HLPE 2019). Agriculture and FS offer opportunities to generate significant numbers of high-quality jobs. It is imperative to direct investment toward sectors that are strategic for the big push, which also have a high potential for job creation (ECLAC 2021). When technology meets a recognized need and is cost-effective for the intended beneficiary, uptake can be rapid (Fanzo et al. 2020). At the same time, experiential learning and knowledge-sharing among practitioners, and the co-production of knowledge among multi-stakeholder networks, should be recognized as effective approaches for generating the type of innovations well adapted to the local context that are needed, and enhancing their rapid adoption (HLPE 2019).

7.3 Dealing with the Distributional Effects of the New Scenarios and Public Policies

Technological change has consequences and effects on the competitiveness of the sector. Innovation must be complemented by policies and actions specifically aimed at ensuring the equitable participation of all sectors involved, particularly those sectors of small-scale family agriculture with restrictions in terms of availability of resources and/or access to infrastructure or services. In this regard, agenda priorities should consider: (i) policies and actions aimed at promoting more equitable access to new technologies (credits, training, development of strategic infrastructures, subsidies to providers of certain technological services, etc.); (ii) the strengthening of national research and development institutions to increase their effectiveness in helping to correct existing market failures affecting equitable access to new technologies.

7.4 Improved International Cooperation Mechanism

The nature of FS calls for an integrated and multi-disciplinary approach that includes aspects related to the use of natural resources and the adoption of new technologies, as well as the issues related to food demand and human behavior. Policies must respond to local conditions, capacities and cultures and consider vulnerable groups, but they must also be coordinated with global trends (Fears et al. 2020). To take advantage of the transformative potential of technology, it is essential to develop national/regional innovation ecosystems, with the support mechanisms and necessary infrastructure to promote the high levels of agricultural innovation required for the future through the promotion of regional and international cooperation (HLPE 2019).

In many countries, there are several limitations to accessing the benefits of new technologies and calls for improved cooperation mechanisms aimed at pooling capacities and technology-sharing. This requires a more complex R&D agenda that gives greater importance to basic research in innovation processes, as well as the generalization (and internationalization) of protection frameworks for the intellectual property of the new technologies. This is particularly the case for smaller tropical countries, where scale is not only affected by the size of their economies, but also because they often have greater agroecological diversity. In this context, when thinking about future strategy, the question of the size of economies and how that is reflected in capabilities, investment and the scale of work of research institutions is an unavoidable issue. Related to this, the construction of solid linkage networks with regional public R&D systems and agricultural extension, and with the private sector, becomes fundamental when it comes to achieving greater efficiencies.

References

Basso B, Antle J (2020) Digital agriculture to design sustainable agricultural systems. Nat Sustain 3(4):254–256

Bonilla-Findji O, Alvarez-Toro P, Martinez-Baron D, Lopez C, Álvarez O, Castellanos A, Martínez JD (2020) Latin America climate-smart villages AR4D sites: 2020 inventory. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen. Available at: https://hdl.handle.net/10568/111398

Brandão AS, Gonçalves A, Santos JMRCA (2021) Circular bioeconomy strategies: from scientific research to commercially viable products. J Clean Prod 295:126407. https://doi.org/10.1016/j.jclepro.2021.126407

CARDI–Caribbean Agricultural Research and Development Institute (2018) Building a productive and resilient regional agriculture sector. Cardi Strategic Plan:2018–2022. Available at: www.cardi.org/wp-content/uploads/downloads/2018/05/CARDI-Strategic-Plan-2018-to-2022-Final.pdf

D'hondt K, Kostic T, McDowell R et al (2021) Microbiome innovations for a sustainable future. Nat Microbiol 6:138–142. https://doi.org/10.1038/s41564-020-00857-w

ECLAC, FAO & IICA (2019) The Outlook for agriculture and rural development in the Americas: a perspective on Latin America and the Caribbean 2019–2020. Available at: https://www.agrirural.org/en

ECLAC-Economic Commission for Latin America and the Caribbean (2021) Building forward better: action to strengthen the 2030 Agenda for Sustainable Development (LC/FDS.4/3/Rev.1), Santiago, 2021. Available at: https://www.cepal.org/sites/default/files/publication/files/46696/S2100124_en.pdf

ECLAC-UNDRR (2021) The coronavirus disease (COVID-19) pandemic: an opportunity for a systemic approach to disaster risk for the Caribbean. Available at: http://www.cepal.org/sites/default/files/publication/files/46732/S2000944_en.pdf

Fanzo J, Covic N, Dobermann A, Henson S, Herrero M, Pingali P, Staal S (2020) A research vision for food systems in the 2020s: defying the status quo. Global. Food Security 26:100397. https://doi.org/10.1016/j.gfs.2020.100397

FAO (2019) Microbiome: the missing link? Science and innovation for health, climate and sustainable food systems. Available at: www.fao.org/3/ca6767en/CA6767EN.pdf

FAO (2020a) The state of food security and nutrition in the world. Transforming Food Systems for Affordable Healthy Diets. http://www.fao.org/publications/sofi/2020/en/

FAO (2020b) FAO Yearbook. Fishery and Aquaculture Statistics 2018/FAO annuaire. Statistiques des pêches et de l'aquaculture 2018/FAO anuario. Estadísticas de pesca y acuicultura 2018. Rome. https://doi.org/10.4060/cb1213t

Fears R, Canales Holzeis C, Ter Meulen V (2020) Designing inter-regional engagement to inform cohesive policy making. Palgrave Commun 6:107. https://doi.org/10.1057/s41599-020-0487-3

Gephart JA, Golden CD, Asche F, Belton B, Brugere C, Froehlich HE, Fry JP, Halpern BS, Hicks CC, Jones RC, Klinger DH, Little DC, McCauley DJ, Thilsted SH, Troell M, Allison EH (2021) Scenarios for global aquaculture and its role in human nutrition. Rev Fish Sci Aquac 29(1):122–138. https://doi.org/10.1080/23308249.2020.1782342

Herrero M, Thornton P, Mason-D'Croz D, Palmer J, Benton T, Bodirsky B, Bogard J, Hall A, Lee B, Nyborg K, Pradhan P, Bonnett G, Bryan B, Campbell BM, Christensen S, Clark M, Cook M, Boer IJM, Downs C, West P (2020) Innovation can accelerate the transition towards a sustainable food system. Nature Food 1(5):266–272. https://doi.org/10.1038/s43016-020-0074-1

HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. Available at: www.fao.org/fileadmin/user_upload/hlpe/hlpe_documents/HLPE_Reports/HLPE-Report-14_EN.pdf

Hodson de Jaramillo E, Henry G, Trigo E. (2019) La Bioeconomía. Nuevo marco para el crecimiento sostenible en América Latina/Bioeconomy. New Framework for Sustainable Growth in Latin America. Bogotá: Editorial Pontificia Universidad Javeriana. ISBN 978-958-781-378-4. Available at: https://repository.javeriana.edu.co/handle/10554/43705

IANAS (2018) Opportunities and challenges for research on food and nutrition security and agriculture in the Americas. Regional analysis prepared from country assessments by IANAS. ISBN 978-607-8379-29-3. Available at: https://www.ianas.org/docs/books/Opportunities_challenges.html

IAP – InterAcademy Partnership (2018) Opportunities for future research and innovation on food and nutrition security and agriculture. The InterAcademy Partnership's global perspective. Synthesis by IAP based on the four regional academy network studies. ISBN 978-88-940784-5-9. Available at: www.interacademies.org/publication/opportunities-future-research-and-innovation-food-and-nutrition-security-and

IFPRI (2020) Global food policy report: building inclusive food systems. International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/9780896293670

IICA (2021) La I+D y la transformación del sistema alimentario: una contribución del Instituto Interamericano de Cooperación para la Agricultura (IICA) a la Cumbre sobre los Sistemas Alimentarios 2021 de las Naciones Unidas. Instuto Interamericano de Cooperación para l Agricultura, San Jose Costa Rica (forthcoming)

Lachman J, Bisang R, De Obschatko ES, Trigo E (2020) Bioeconomía: una estrategia de desarrollo para la Argentina del siglo XXI. Impulsando a la bioeconomía como modelo de desarrollo sustentable: entre las políticas públicas y las estrategias privadas/Instituto Interamericano de Cooperación para la Agricultura – Argentina: IICA, 2020. ISBN 978-92-9248-899-4

León K, Arguello JP (2021) Effects of the COVID-19 pandemic on adolescent and youth nutrition and physical activity. Available at: http://www.unicef.org/lac/en/effects-of-covid-19-pandemic-on-adolescent-and-youth-nutrition-and-physical-activity

Morris M, Sebastian AR, Perego VME, Nash JD, Diaz-Bonilla E, Pineiro V, Laborde D, Chambers TT, Prabhala P, Arias J, De Salvo CP, Centurion ME (2020) Future foodscapes: re-imagining agriculture in Latin America and the Caribbean (English). World Bank Group, Washington, D.C. http://documents.worldbank.org/curated/en/942381591906970569/Future-Foodscapes-Re-imagining-Agriculture-in-Latin-America-and-the-Caribbean

Nin-Pratt A, Falconi C, Ludena C, Martel P (2015) Productivity and the performance of agriculture in Latin America and the Caribbean: from the lost decade to the commodity boom, IDB working papers series N° 608. Inter-American Development Bank, Washington DC

OECD (2018) Agricultural policy monitoring and evaluation 2018. OECD Publishing, Paris. https://doi.org/10.1787/agr_pol-2018-en

Oliva R, Ji C, Atienza-Grande G et al (2019) Broad-spectrum resistance to bacterial blight in rice using genome editing. Nat Biotechnol 37:1344–1350. https://doi.org/10.1038/s41587-019-0267-z

Roop R, ST. Martin C.C.G. (2020) Building climate resilience of smallholder family farms by implementing integrated soil and water management strategies in Trinidad and Tobago. In: Leal FW, Luetz J, Ayal D (eds) Handbook of climate change management. Springer, Cham. https://doi.org/10.1007/978-3-030-22759-3_92-1

Rose DC, Chilvers J (2018) Agriculture 4.0: broadening responsible innovation in an era of smart farming front. Sustain Food Syst 2:87. https://doi.org/10.3389/fsufs.2018.00087

Saiz-Rubio V, Rovira-Más F (2020) From smart farming towards agriculture 5.0: a review on crop data management. Agronomy 10:207. https://doi.org/10.3390/agronomy10020207

Santos Valle S, Kienzle J (2020) Agriculture 4.0 – agricultural robotics and automated equipment for sustainable crop production. Integrated crop management series, vol 24. FAO, Rome

Singh BK, Trivedi P, Egidi E et al (2020) Crop microbiome and sustainable agriculture. Nat Rev Microbiol 18:601–602. https://doi.org/10.1038/s41579-020-00446-y

Stads G, Beintema N, Pérez S, Flaherty K, Falcioni C (2016) Investigación Agropecuaria en Latinoamérica y el Caribe. Un análisis de las instituciones, la inversión y las capacidades entre países. ASTI/BID

Swinnen J, Mcdermott J (2020) Covid-19 and global food security. EuroChoices 19(3):26–33. https://doi.org/10.1111/1746-692X.12288

Trigo E, Elverdin P (2019) Los sistemas de investigación y transferencia de tecnología agropecuaria de América Latina y el Caribe en el marco de los nuevos escenarios de ciencia y tecnología. 2030 – Alimentación, agricultura y desarrollo rural en América Latina y el Caribe, No. 19. FAO, Santiago de Chile, p 18

Trigo E, Falck Zepeda J, Falconi C (2010) "Biotecnología agropecuaria para el desarrollo en América Latina: Oportunidades y Retos", Documentos de Trabajo LAC 01/10, Programa de Cooperación, FAO/Banco Inter-Americano de Desarrollo, Servicio para America Latina y el Caribe. División del Centro de Inversiones

Trigo E, Chavarria H, Pray C, Smyth SJ, Torriba A, Wessler J, Zilverman D, Martinez JF (2021) The bioeconomy and food systems transformation. FSS Briefs by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/03/FSS_Brief_Bioeconomy_and_Food_Systems_Transformation.pdf

United Nations (2020) Policy brief: the impact of COVID-19 on food security nutrition. United Nations, 2020

Virginia Tech (2020) Productivity in times of pandemics, global agricultural productivity report. Executive summary. College of Agriculture and Live Sciences, Virginia Tech. https://globalagriculturalproductivity.org/wp-content/uploads/2019/01/2020-GAP_Report_Exec-Summary-1.pdf

The Role of Science, Technology, and Innovation for Transforming Food Systems in Asia

Paul J. Moughan, Daniel A. Chamovitz, S. Ayyappan, Morakot Tanticharoen, Krishan Lal, and Yoo Hang Kim

1 Introduction

It is now widely accepted that there is an imperative to transform food systems to provide guaranteed supplies to everyone of nutritious, healthy foods that are produced and distributed in a sustainable manner, for a rapidly growing world population (Committee on World Food Security (CFS) 2019; FAO and WHO 2019; Fanzo

P. J. Moughan (✉)
Riddet Institute, Massey University, Palmerston North, New Zealand
e-mail: P.J.Moughan@massey.ac.nz

D. A. Chamovitz
Ben-Gurion University of the Negev, Beersheba, Israel

S. Ayyappan
Central Agricultural University, Imphal, Manipur, India

Karnataka Science & Technology Academy, Bengaluru, Karnataka, India

M. Tanticharoen
King Mongkut's University of Technology Thornburi, Bangkok, Thailand

National Science and Technology Development Agency (NSTDA), Bangkok, Thailand

K. Lal
The Academy Partnership (IAP) for Science, The Global Network of Science Academies, Trieste, Italy

The Association of Academies and Societies of Sciences of Asia (AASSA), Seongnam-si, South Korea

Indian National Science Academy, New Delhi, India

National Physical Laboratory, New Delhi, India

Y. H. Kim
The Association of Academies and Societies of Sciences in Asia (AASSA), Seongnam-si, South Korea

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_39

et al. 2020a; Global Panel on Agriculture and Food Systems for Nutrition 2020; GNR 2020; International Food Policy Research Institute (IFPRI) 2020a).

A consensus view is one thing, but what is now required is **action**.

This chapter focusses primarily on the role of science, technology and innovation (STI), including research and development (R&D), education and extension, in transforming the food systems of Asia and the Pacific. The chapter draws heavily on the IAP report published in 2018: "Opportunities and challenges for research on food and nutrition security (FNS) and agriculture in Asia," but updated to include new perspectives. The working group responsible for the latter report was convened under the auspices of the Association of Academies and Societies of Sciences in Asia (AASSA). The approach was a "bottom-up" analysis of projected FNS in the region with respect to population growth and related demographics, projected regional trends in malnutrition in all its forms, climate change, resource depletion, biodiversity loss and environmental degradation. Experts from scientific academies across the region made up the working group, and each expert provided information and insight for their country or region. This facilitated synthesis of the material to allow for common themes to be developed and general, as well as specific, conclusions to be made. One strength of the inter-science academy approach was that it drew upon expertise from a broad range of relevant scientific disciplines from across a wide geographical area. This allowed for the identification of scientific and technical issues and opportunities not only at the global and regional levels, but also at a national and sometimes sub-national level, reflecting the great diversity between and within countries, sectors and populations.

2 The Overarching Framework for Developing Inclusive, Sustainable Food and Nutrition Systems

Globally, a considerably greater quantum of food and a more diverse array of food types need to be produced and distributed equitably to ensure a balanced diet that adequately nourishes a projected population of around 9 million persons by year 2050. This is against a current backdrop in which around 1 billion people are undernourished, many more suffer from 'hidden hunger,' whereby they receive inadequate amounts of vitamins and minerals, and where, in many countries, there is an escalating prevalence of obesity and metabolic syndrome.

This required increase in the production of foods must occur in the face of several constraints. The land area available for agriculture is unlikely to increase in the future, and may well decline because of the demands of urbanisation, conservation, bio-ecology and land loss from sea-level rises caused by global warming. Limitations in the supply of other vital resources (e.g., fossil fuels, fertiliser and water) are also likely to pose a challenge. Future food increases will need to be sustainable, environmentally, economically, culturally and socially, and will occur in the face of unpredictable outcomes that are consequent upon climate change. The 17 Sustainable Development Goals adopted by the United Nations in 2015 offer an important framework for addressing the challenge of the global food supply, but, if these goals are to be met, evidence-based science will be a necessary prerequisite.

The production and supply of food follow a complex web of interacting processes and systems. Agriculture and food production are part of a widely interconnected multi-functional landscape or agri-ecosystem (German et al. 2017). To achieve sustainable production, the wider ramifications of changes to the systems need to be assessed and understood and inevitable trade-offs reconciled.

A systems analytical approach is paramount to identifying impediments to FNS and providing workable holistic solutions. A wide range of both technical and non-technical factors (including purchasing power, barriers to trade, capital investment, infrastructure, government policies, cultural mores, demographic shifts, political and social stability, equity of access, gender equality and education) is relevant. Not wishing to undermine the importance of these non-technical factors, it is beyond doubt that science, technology and related innovation (SIT) will be critical in addressing FNS. The production of food in a sustainable manner, the processing and storage of food, the minimisation of food wastage and the development of healthy diets adapted to local conditions and populations are of paramount importance. The application of current scientific knowledge through improved education and extension practices, the development of new scientific knowledge in targeted areas, and related technological developments will all be essential in terms of meeting the global food challenge.

In the AASSA (2018) report on FNS for Asia, the need to focus STI efforts so as to provide high-quality relevant evidence was emphasised, a contention echoed recently by the Committee on World Food Security (2019) and Fanzo et al. (2020b).

The approach taken by the IAP Working Group was to use national and regional statistics for Asia and the Pacific on projected population growth, population age distributions, economic development and current estimates of under- and over-nutrition to allow for a focus on countries and geographical areas that are most likely in the future to face the harshest FNS issues. A strategy moving forward would be to use 'systems analysis' to identify key impediments to FNS in these areas, the same analysis also being used to prioritise extension, education, and research and development (Stathers et al. 2020; Ricciadi et al. 2020). The report emphasises the need for a territorial dimension in such an analysis, recognising often profound differences between geographical areas and socio-economic groupings. The territorial approach to investigating FNS implies a shift from a sectoral (usually agricultural production), top-down, 'one-size-fits-all' approach to one that is multi-sectoral, bottom-up and context-specific. Food systems must be inclusive of marginalised people and small holders (IFPRI 2020a, b), as should STI and education.

The work has identified several countries within the region that are at high risk for future impediments to FNS. Countries such as India, Bangladesh, Pakistan, Afghanistan, Nepal and Myanmar, as well as the Philippines, Tajikistan, Iraq and Yemen, are deemed to be particularly high risk countries for future impediments to FNS. This is not to say that other countries in the region are free from future issues concerning FNS; rather, it gives us a rational starting point as to where work may be most effective.

There is no doubt that both the global and Asian food supplies will be required to increase significantly over the next three decades. The required increase in net food supply may involve reducing food wastage and effects on the demand side brought about by changing food consumption patterns, but will also involve producing more food from existing agricultural land. This will require both closing existing yield gaps and increasing food production from land that is currently considered to be yielding at a high level, through further intensification. Intensive agricultural production is already associated with environmental costs, however, through side effects such as nutrient runoff and the eutrophication of waters, greenhouse gas (GHG) emissions, soil erosion and soil degradation, as well as resource costs such as depletion of water and fertiliser reserves. Future farm production will be expected to reduce these negative environmental impacts. 'Sustainable intensification' will be needed, and this will require a step-change in STI (Pretty 2008; Parker et al. 2014). China is already making progress in this domain (Cui et al. 2018) Clearly, increased production per plant or animal, in a sustainable manner, is beneficial in that it reduces the amount of waste material (e.g., methane) per unit of production (e.g., kilograms of grain or meat). Over recent years, there has been a renewed interest in bioecological agriculture and circular agriculture, in which an ecological harmony is sought, and resource use is optimised and solid wastes and gaseous emissions are minimised due to capture and re-use. Research in this direction is encouraged, though it is recognised that bioecological agriculture and intensive farming are not mutually exclusive systems. Traditional mixed framing models of intensive agriculture may already incorporate principles inherent in bioecological farming (e.g., crop rotations, animal/crop/pasture balance, the use of tree shelter belts, nitrogen fixation via leguminous crops and clovers, minimal tillage, integrated pest management).

Although the IAP Working Group strongly promoted the clear identification of gaps in knowledge that are currently creating impediments to lifting and diversifying food production as a critical starting point for renewed and refreshed STI effort, they also recognised that there are certain areas of contemporary science whereby investment in R&D is likely to yield immediate and widespread dividends. These areas included: (1) sustainable farming practices addressing wider issues, such as biodiversity, land and water degradation and climate change, that would include bioecological approaches; (2) genomic-based approaches (including molecular markers for selection and CRISPR/Cas9 technologies) to plant and animal breeding; (3) 'big data' capture and analysis, precision agriculture, robotics, artificial intelligence; (4) food technology innovations in harvesting, processing and storage to reduce wastage promote more equitable distribution of safe non-perishable food and lead to healthier processed foods; (5) aquaculture production and integrated farm production systems.

3 Delivering Healthy Diets

For achieving FNS in the future, calorie provision alone will not be sufficient. Rather, it will be required that a broad range of diverse foods be provided so as to meet the requirements for all dietary nutrients and non-nutrient food components known to influence human health. Just what constitutes a healthy diet is a 'moving target', and research is required to establish scientifically what constitutes healthy diets for different socio-cultural groupings and regions. Currently, for example, there is controversy over the role of saturated fats in health (Bier 2016) and over the risk of consuming unprocessed red meat in the development of bowel cancer (Alexander and Cushing 2011).

The classical approach in nutritional science has been reductionist, whereby the nutrients found in foods are considered the fundamental unit of nutrition. This concept has been challenged more recently, and, considering the clearly important 'holistic' properties of foods, it has been suggested that a food should be considered as the fundamental unit of nutrition (Kongerslev et al. 2017). A better scientific understanding is required of the nutritional and health effects of the interactions of structures within complex food matrices and among foods when mixtures of different foods are eaten together. With such knowledge, there is an opportunity to manufacture healthier foods. During traditional manufacturing, natural food structures are often degraded and new structures, potentially with less desirable properties, are formed. New approaches to food manufacturing are needed to ensure the provision of food matrices, food nutrient contents and food bioactives that are consistent with health. The food industry is clearly a powerful medium for the manufacture and distribution of healthy foods, and the way forward will be cooperative research programmes among agricultural sectors, food companies, universities and government-funded research organisations to explore new processing technologies with the aim of shifting the food supply towards nutritious healthy foods and diets.

Having accurate information on the amounts of dietary nutrients required to support body processes and long-term health (dietary requirements) is insufficient. Foods also contain many compounds that are not classically viewed as nutrients (e.g., phytochemicals, bioactive proteins and peptides, and fibre), but may have important effects upon human health. Examples, among many, are immunoglobulins in milk, probiotics in yoghurt and other fermented foods, catechins in tea, bioactive peptides released from many proteins, flavonoids in cocoa, and tannins and anthocyanins in fruits and berries. These properties of food need to be much better understood, and should be the focus of STI. Moreover, the role of diets in influencing gene expression in humans (nutrigenomics) and how genetic makeup influences dietary effects on physiology, metabolism and health (nutrigenetics) offer great potential for a better understanding of nutrition and its influence on health and pave the way for personalised nutrition (Fenech 2008). It is important to recognise that it is not only the human genome that is influencing and influenced by nutrient uptake and metabolism; the numerous genes of the prolific gut microbiome also undoubtedly have a major influence on nutrient utilisation, metabolic outcomes and health. This is a fertile area for further research and highlights again the complexity of the influence of diet on human health.

There is much evidence that poor nutritional choices are often made at the point at which foods are selected for consumption, and better education at all levels on the impact of food and nutrition on health is critical. Sociological and behavioural research is required to better understand the purchasing motivation of people of different ages and socio-cultural backgrounds. Foods must be desirable, and STI is equally needed to ensure the wide availability of foods that are not only nutritious and healthy, but also safe and convenient, and that have great taste, texture and other properties. Food science and technology, including sensory science, have a major role to play.

In the IAP study, particular attention was given to the Hindu Kush Himalayan (HKH) region, a vast area of land extending 3500 km across the high mountain regions of Afghanistan, Bangladesh, Bhutan, China, India, Nepal, Myanmar and Pakistan. Malnutrition and hunger are widespread in the region and a complex interaction of socio-economic, environmental (including food production systems), and cultural factors is considered to be the cause of the widespread malnutrition.

The mountain areas have a low ‘carrying-capacity’ for agricultural production, and cropping systems have been reliant on diverse traditional crop varieties. However, rapid socio-economic change has led to changed land use, changed crop varieties and new food consumption patterns. The planting of nutritious traditional crops, such as amaranth, buckwheat, minor millet, finger millet, proso millet, foxtail millet, sorghum, barley and sweet potato, is declining; these crops are being replaced by higher-calorie-yielding crops such as rice and wheat, leading to a decline in agro-biodiversity. The production of traditional crops is declining because of factors such as a lack of awareness of their nutritional value, a lack of local markets for the produce and an increasing demand for crops such as rice, wheat and maize. There has been a shift in foods from home-grown foods to purchased foods, from coarse-grain foods to fine-grain foods, and from traditional snacks and drinks to potato chips, instant noodles and soft drinks (Rasul et al. 2017). The consumption of the traditional coarse grains is often viewed as backward in the new value system.

The trend by the urban poor away from legumes and coarse grains, and towards the consumption of oils, fats and high-sugar products, is not unique to the HKH region, but is general in both China and India (Du et al. 2002).

Further, there would appear to be much scope for encouraging farming programmes among smallholder farmers that aim to diversify diets and improve nutrition. Such programmes (Girard et al. 2012) aim to increase household production of perishable nutrient-rich foods (e.g., fruits, eggs, meat, fish and milk). The production of such foods on the farm makes them accessible and less vulnerable to storage and transport losses. Such an approach has been shown to diversify the diet of often nutritionally vulnerable smallholders (Iannotti et al. 2009).

4 Transformation to Sustainably Produced and Healthy Diets

Not only must the diets of the future be healthy, they must also be sustainably produced. A new approach is needed to design, evaluate and monitor diverse farming systems. The complexities of diverse farming systems need to be recognised and a nuanced approach taken (Global Panel on Agriculture and Food Systems for Nutrition 2020). By means of example, ruminant livestock farming makes a major contribution to GHG emissions, but, at the same time, livestock farming is economically and culturally important to many people. Also, meat and milk are of high nutritional value and an important supply of minerals (such as calcium, zinc and iron) and vitamins, such as vitamin B12. Whereas a case may be made for the inefficiency of feed-lot cattle production (Poore and Nemecek 2018), the same is not necessarily true for large amounts of pastoral cattle production (Adesogan et al. 2019). Moreover, meat and milk are primarily produced to provide amino acids, minerals and vitamins for human nutrition. When GHG emissions from meat and milk production are expressed per unit first-limiting amino acid rather than per unit total protein, such production is seen in a new light (Moughan 2021). Recent modelling using Linear Programming demonstrates that, given current price relativities, animal-based products are needed to provide least-cost diets (diets that meet all nutrient requirements at the lowest cost) (Macdiarmid et al. 2012; Chungchunlam et al. 2020). It would appear that the cost of some animal products would need to increase greatly before they would no longer be found in a least-cost diet. Sustainable diets must be affordable. The issue is nuanced, and entrenched "blanket" positions should be avoided. The development of new farming systems (e.g., insect, algae, single-cell food production, and *in vitro* meat production and biotech foods) should be encouraged and their integration into the more traditional land-based systems carefully assessed.

The expansion of aquaculture will likely occur in the future, and STI is needed to improve the genetics of farmed fish and crustaceans, as well as to develop systems that mitigate against eutrophication. A key target in developing more sustainable farming systems will be the reduction of food/nutrient wastage, and here, food science STI has a vital role to play. The DELTA Model (https://sustainablenutritioninitiative.com/) has recently been developed, and calculates nutrient availability to consumers from differing global food production scenarios. Early findings from the model indicate that global food production currently supplies sufficient macro- and micronutrients to nourish the global population if equally distributed, with the exception of calcium and Vitamin E. These nutrients appear to be undersupplied by at least 30%. Total removal of food waste from the model, although helpful, does not solve these insufficiencies. Nutrient loss due to food waste is not constant across all nutrients: relatively little calcium and vitamin E is wasted, whereas waste of carbohydrates and protein is high. Further, while the current food system would provide sufficient energy and protein for the forecast 2030 global population of 8.6 billion, it would fail in supplying several micronutrients (calcium, iron, potassium, zinc, riboflavin and vitamins A, B12 and E).

5 Addressing the Food-Energy-Water Nexus and Other Natural Resources

The AASSA Working Group addressed land use for food production in light of competing interests (e.g., urbanisation, textiles, biofuel, ecological restoration, recreational use). An evidence-based and total systems-based (accounting for the principles of recycling and circular agriculture) approach is urged to ensure planning to make optimal use of limited land, water and other resources.

6 Supporting and Using Outputs from Fundamental Research

Although the role of applied science, technology and extension is likely to be pivotal in solving key issues, the potential for 'game-changing' new discoveries arising from fundamental science should not be overlooked. Recent-past discoveries in molecular biology, IT, and cell biology serve as shining examples of the power of 'unfettered' scientific endeavour. Strong programmes in fundamental science are encouraged. At the same time, well-targeted applied research programmes will need to place less emphasis on increasing plant and animal production *per se*, and will need to seek to optimise agricultural outputs in the face of multiple externalities. Cross-disciplinary systems research, bioecological farming, and farm management science will all be important.

7 Consequences of Covid-19

The Covid-19 pandemic has highlighted the vulnerability of global food systems (e.g., rising unemployment and loss of purchasing power, loss of seasonal labour, disruption of food processing and food distribution). Global food systems need to be resilient (International Food Policy Research Institute (IFPRI) 2020b; Di Marco et al. 2020). The pandemic further highlights the role of good nutrition and healthy diets in supporting the immune system (Calder 2020).

8 Strengthening Policy for Research and Its Uptake

Planning for and securing FNS in Asia will require dedicated and bold commitment from politicians and policymakers, while scientists in the region have the responsibility to provide robust peer-reviewed scientific knowledge, to allow for evidence-based decision-making.

The AASSA Working Group urged the establishment of a trans-national funding mechanism in the region (similar to that in the European Union), focussing on interdisciplinary FNS STI. Considering the often considerable lag time in research between investment and adoption, it is imperative that governments in the region not only maintain support for R&D, education and extension related to FNS, but also greatly increase, as a matter of urgency, the overall level of funding. Funding in agriculture and related disciplines has declined over recent decades (AASSA 2018). There needs to be a considerable resurgence in agri-food R&D, extension and education, and such an emphasis needs to be more cross-disciplinary and systems-oriented than in the past. Several areas of STI are seen as universally important for the region (see earlier section), and it is strongly recommended that a cooperative regional approach be taken, to form well-resourced regional centres of excellence that focus on key areas of opportunity.

The importance of formulating an evidence-based 'blueprint' for FNS R&D in the region is stressed. If progress is to be maximised, funding needs to be carefully targeted. Systems research needs to be applied, early on, to identify critical impediments that currently affect the region's ability to increase food production sustainably and to ensure a diversity of high-quality foods reaching the consumer. The knowledge generated must be communicated expeditiously, and shared freely and extensively. In addition to a ramping up of R&D efforts, funding should also be allocated to education at all levels and to "on-farm" and "in-factory" extension. Over and above regional cooperative STI initiatives, there is much opportunity for accelerated collaboration through targeted global alliances, and national/regional policies should incentivise this. A lesson from Covid-19 is that, with restricted travel, the necessary IT infrastructure needs to be in place and available to all to allow for unimpeded collaboration across boundaries and borders. Networking will be paramount.

Ongoing support for international STI programmes such as CGIAR, IFPRI and ICARDA is urged, as is the incentivisation of public-private partnerships (Fanzo et al. 2020b).

In formulating an STI strategy for the region, the potential power of fundamental science should not be ignored. Discoveries, often arising from fundamental science, have the capacity to lead to step-changes in agricultural productivity. Examples of emerging disruptive technologies are found in bio-based manufacturing to produce fuels, chemicals and materials through advanced, efficient and environmentally friendly approaches. Synthetic approaches to producing animal-free meat and milk have attracted much attention. Such products may have advantages in cost of production, ethical acceptance and sustainability, but consumer acceptance is yet to be tested.

Agricultural and rural development were priorities for foreign aid and international development banks before the mid-1980s, but investment in this area has declined in subsequent years. Agriculture and food have been off the global development agenda, and this must be reversed.

References

AASSA (2018) IAP report: opportunities and challenges for research on food and nutrition security and agriculture in Asia. Angkor Publishers (P) Ltd, Noida, India. ISBN: 979-11-86795-26-2

Adesogan AT, Havelaar AH, McKune SL, Eilitta M, Dahl GE (2019) Animal source foods: sustainability problem or malnutrition and sustainability solution? Perspective matters. Glob Food Sec. https://doi.org/10.1016/j.gfs.2019.100325

Alexander DD, Cushing CA (2011) Red meat and colorectal cancer: a critical summary of prospective epidemiologic studies. Obes Rev 12:e472–e493

Bier DM (2016) Saturated fats and cardiovascular disease: interpretations not as simple as they once were. Crit Rev Food Sci Nutr 56:1943–1946

Calder PC (2020, May) Nutrition, immunity and COVID-19. BMJ Nutr Prev Health 3(1):74–92. https://doi.org/10.1136/bmjnph-2020-000085. PMID: 33230497; PMCID: PMC7295866

Chungchunlam SMS, Moughan PJ, Garrick DP, Drewnowski A (2020) Animal-sourced foods are required for minimum-cost nutritionally adequate food patterns for the United States. Nat Food 1:376–381

Committee on World Food Security (CFS) (2019) HLPE Report 14: Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. The High Level Panel of Experts (HLPE) on Food Security and Nutrition. http://www.fao.org/3/ca5602en/ca5602en.pdf. Accessed 4 Feb 2021

Cui Z, Zhang H, Chen X et al (2018) Pursuing sustainable productivity with millions of smallholder farmers. Nature 555:363–366

Di Marco M, Baker ML, Daszak P et al (2020) Opinion: sustainable development must account for pandemic risk. Proc Natl Acad Sci 117:3888–3892

Du S, Lu B, Zhai F, Popkin BM (2002) A new stage of the nutrition transition in China. Public Health Nutr 5(1a):169–174

Fanzo J, Covic N, Dobermann A, Henson S, Herrero M, Pingali P, Staal S (2020a) A research vision for food systems in the 2020s: defying the status quo. Glob Food Sec 26:100397. https://doi.org/10.1016/j.gfs.2020.100397

Fanzo J, Shawar YR, Shyam T, Das S, Shiffman J (2020b) Food system PPPs: can they advance public health and business Golas at the same time? GAIN, Geneva

FAO and WHO (2019) Sustainable healthy diets – guiding principles. FAO, Rome. http://www.fao.org/3/ca6640en/ca6640en.pdf

Fenech M (2008) The human genome, nutrigenomics and nutrigenetics. Innov Manage Pol Pract 10:43–52

German RN, Thompson CE, Benton TG (2017) Relationships among multiple aspects of agriculture's environmental impact and productivity: a meta-analysis to guide sustainable agriculture. Biol Rev 92:716–738

Girard AW, Self JL, McAuliffe C, Olude O (2012) The effects of household food production strategies on the health and nutrition outcomes of women and young children: a systematic review. Pediatric Perinatal Epidemiol 26(Suppl. 1):205–222

Global Panel on Agriculture and Food Systems for Nutrition (2020) Foresight 2.0. Future food systems; for people, our planet and prosperity, London

GNR (2020) Global nutrition report: action on equity to end malnutrition. Development Initiatives, Bristol

Iannotti L, Cunningham K, Ruel M (2009) Improving diet quality and micronutrient nutrition: homestead food production in Bangladesh. IFPRI discussion paper 00928. International Food Policy Research Institute, Washington, DC, p 44. Available at: http://www.ifpri.org/sites/default/files/publications/ifpridp00928.pdf. Accessed 9 Feb 2021

International Food Policy Research Institute (IFPRI) (2020a) 2020 Global Food Policy Report: Building Inclusive Food Systems. International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/9780896293670. Accessed 4 Feb 2021

International Food Policy Research Institute (IFPRI) (2020b) COVID-19 & Global Food Security (Swinnen J, McDermott J, eds). International Food Policy Research Institute (IFPRI), Washington, DC. https://doi.org/10.2499/p15738coll2.133762

Kongerslev Thorning T, Bertram HC, Bonjour J-P et al (2017) Whole dairy matrix or single nutrients in assessment of health effects: current evidence and knowledge gaps. Am J Clin Nutr 105(5):1033–1045

Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, McNeill G (2012) Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? Am J Clin Nutr 96:632–639. https://doi.org/10.3945/ajcn.112.038729

Moughan PJ (2021) Population protein intakes and food sustainability indices: the metrics matter. Global Food Security (Invited contribution)

Parker M, Acland A, Armstrong HJ et al (2014) Identifying the science and technology dimensions of emerging public policy issues through horizon scanning. PLoS One 9:e96480

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science:987–992

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond B 363:447–465

Rasul G, Hussain A, Mahapatra B, Dangol N (2017) Food and nutrition security in the Hindu Kush Himalayan region. J Sci Food Agric. https://doi.org/10.1002/jsfa.8530

Ricciadi V, Wane A, Sidhu BS, Godde C, Solomon D, McCullough E, Diekmann F, Porciello J, Jain M, Randall N, Mehrabi Z (2020) A scoping review of research funding for small-scale farmers in water scarce regions. Nat Sustain 3:836–844

Stathers T, Holcroft D, Kitinoja L, Mvumi BM, English A, Omotilewa O, Kocher M, Ault J, Torero M (2020) A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. Nat Sustain 3:821–835

The Role of Science, Technology, and Innovation for Transforming Food Systems in Europe

Claudia Canales and Robin Fears

1 Introduction: The Transformation of European Food Systems

Combating malnutrition in all its forms – undernutrition, micronutrient deficiencies, overweight and obesity – is a problem faced by all countries. Recent data confirm that undernutrition and food insecurity are present in vulnerable groups in Europe (Loopstra 2018; Pollard and Booth 2019; Leij-Halfwerk et al. 2019) simultaneous with an increasing public health burden related to obesity (Pineda et al. 2018; Krzysztoszek et al. 2018). There is still much to be done to ensure access to safe and nutritious food for all (UN FSS Action Track 1[1]). Europe has a rich diversity of food cultures in close proximity to each other, and this diversity is mirrored in the structure of the EU farming sector: very small farms (<2 hectares) make up nearly half of the agricultural holdings, while very large farms (>100 hectares) make up just 3% of the total, but cultivate half the farmland (Kania et al. 2014). Small farms themselves differ widely, and include high-value and specialised production systems (Guiomar et al. 2018). Food has also traditionally played a central role in the EU in the shaping of individual and collective identities (Anderson et al. 2017), and it is also central in current discourses on economic, social and environmental justice and cultural recognition (e.g., Coolsaet 2016; Šūmane et al. 2018). There is large variation in food and nutrient intakes across Europe, between and within countries (Martens et al. 2019).

[1] https://www.un.org/en/food-systems-summit/action-tracks

C. Canales (✉) · R. Fears
European Academies' Science Advisory Council's (EASAC) Biosciences Programme, Halle, Germany
e-mail: canales.claudia@gmail.com

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_40

In 2017, EASAC published a report on food and nutrition security and agriculture in Europe as part of the InterAcademies Partnership (IAP) global project. That report followed an integrative food system approach to cover interrelated issues around resource efficiency, environmental sustainability, resilience and the public health agenda, while also addressing opportunities for local-global connectiveness and the bioeconomy. EASAC stressed that an earlier food security emphasis on agricultural production now has to be replaced by the food systems approach to encompass all of the steps in the food value chain in order to deliver accessible and affordable food for all, from growing through to processing, trading, consuming and disposing of, or recycling, waste. Food systems must include both supply-side and demand-side considerations for sustainability. Yearly food losses in the EU have been estimated at about 15% of the emissions of the entire food supply chain (Scherhaufer et al. 2018). An increase in agricultural productivity would likely increase the environmental footprint without necessarily delivering healthy and nutritious diets that are accessible to all, unless embedded in a profound transformation of food systems (Benton and Bailey 2019).

One issue increasing in importance is the role of public procurement in the demand for sustainable, healthy food (Sonnichsen et al. 2020; WHO 2021): provision of sustainable, healthy diets in hospitals and other public services can help to change consumer behaviour in the longer term (EASAC and FEAM 2021). European Union interest in the sustainability of the food systems approach is increasing (e.g., SAPEA 2020) and the recent Farm-to-Fork (F2F) policy initiative covers the entire food chain, together with protection of the environment.

Much of the EASAC 2017 report focused on scientific advances in agriculture, but there was also significant attention to food science and technology, e.g., for food safety and food processing, so as to reduce food losses, extend distribution and seasonal availability, and for food fortification. The comprehensive recent work of the International Union of Food Science and Technology,[2] based partly on evidence presented by IAP and its regional work streams, reviewed scientific opportunities related to diverse and sustainable primary production; sustainable process and system engineering; the elimination of waste in production, distribution and consumption; and traceability and product safety (see also Lillford and Hermansson 2020). An additional issue, brought into prominence by the COVID-19 pandemic, is the potential of the improved food value chain to address poverty by increasing entrepreneurial activity and other employment (an issue that should be highlighted in UN FSS Action Track 4, Advance equitable livelihoods).

Transdisciplinary policymaking and governance are required to make food systems more nutrition-sensitive. Food and nutrition security and food sustainability must now be considered as part of formulating European dietary guidelines. Some of the research priorities are described subsequently, but there is also a need for a better definition of what a sustainable diet is and how it can be measured, so that these

[2] Global challenges for food science and technology, 2019, https://iufost.org/global-challenges-and-critical-needs-2/).

metrics form part of national surveys and inform policies and interventions to educate consumers on sustainable behaviours and diets.

Innovation is central to delivering the required transformation of food systems, and must be based on transdisciplinary science, new financing and business models, and policy development. This topic has received renewed attention recently. For example, Herrero et al. (2020) developed an inventory of innovations organised according to their position in the value chain (i.e., production, processing, packaging, distribution, consumption and waste) and their 'readiness score': from basic research all the way to proven implementation under real-world conditions. The dissemination and uptake of these innovations should be considered a priority, and research is urgently needed on how to make options available in current food systems with minimal disruption.

In this EASAC brief, the following sections update selected priorities from the EASAC 2017 report in order to demonstrate how science, technology and innovation can provide major contributions to the UN FSS Action Tracks. There are multiple implications for EU policy, as summarised in Fig. 1.

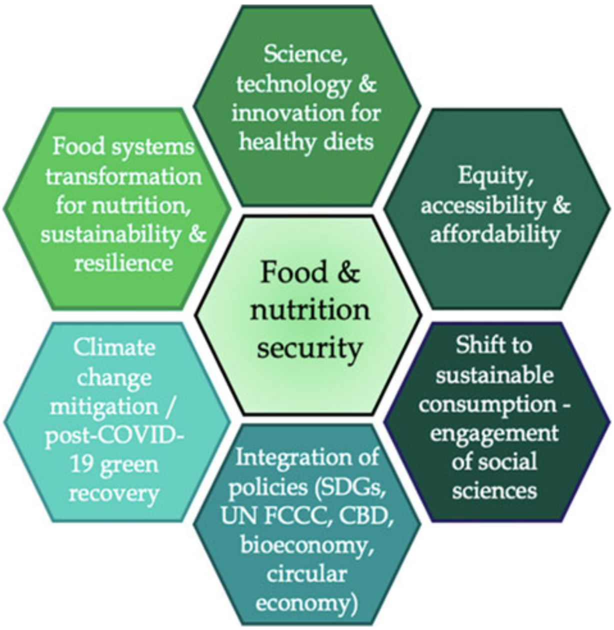


Fig. 1 Matrix of European policy objectives for food and nutrition security. Links with international policy development are particularly relevant in 2021 because of the UN FSS, as well as COP26 of the UN FCCC (Framework Convention on Climate Change) and COP15 of the UN CBD (Convention on Biological Diversity)

2 Agriculture-Environment Nexus and Agroecology in Europe

Linkage of food systems to sustainable development objectives is a core part of the integrated transformations required to attain the Sustainable Development Goals (SDGs, see GSDR 2019; Sachs et al. 2019; EASAC 2020a). Concomitantly, there is great potential for new business opportunities and economic value (WEF 2020), but also a need to understand the co-benefits and trade-offs of coupling nutritional and environmental objectives for SDGs (McElwee et al. 2020), factors that have to be taken into account in UN FSS Action tracks 2 (Shift to sustainable consumption patterns) and 3 (Boost nature-positive production) as well.

The concept of regenerative agriculture (Newton et al. 2020; Schreefel et al. 2020) embraces farming principles and practices that enhance biodiversity and ecosystem services and increase carbon capture and storage, helping to tackle climate change and improve agricultural resilience and yield. This can be viewed as a core feature of the EU's F2F strategy, but the scientific basis needs to be clarified in order to improve farming systems (Davies et al. 2020). Agroecology is an important part of regenerative agriculture innovation (HLPE 2019): scientific advances here will also help to clarify links between human and livestock health and their dependencies on the environment.

Assessing the relative contribution of different production models to sustainably delivering healthy and nutritious diets and providing important ecosystem services is an important research priority. For example, using life cycle assessments (LCAs), it was estimated that a complete switch to organic cultivation in England and Wales would lower production emissions, but also decrease yields, and the increased reliance on land use elsewhere to make up for the shortfall would result in higher emissions overall (Smith et al. 2019). However, organic agriculture can decrease the reliance on chemical inputs, improve soil carbon sequestration and soil quality, reduce the contamination of water bodies and increase biodiversity. LCAs do not accurately reflect these benefits because of their focus on the product, whereas ecosystem services from agricultural systems are not duly considered. Deploying an integrated approach requires research to quantify the economic value of ecosystems (Dasgupta 2021), as part of the improvement and standardisation of methodologies for assessing and comparing the sustainability of food systems. In addition, estimates of the levels of food production required to fulfil demand often fail to take into consideration the effects of a switch to more sustainable diets, lowered consumption patterns, and the reduction of food waste.

Research for improving the environmental assessments of production systems should include clarifying additional indicators, such as for land and soil degradation and loss of biodiversity; broadening the scope to include the provision of ecosystem services; and improving the assessment of indirect effects within a comprehensive food systems perspective, as opposed to a narrow focus on yield (van der Werf et al. 2020). Organic agriculture should also embrace innovation to improve its performance (Seufert et al. 2019; Clark 2020), and may require multiple policy interventions to realise its potential for food system sustainability (Eyhorn et al. 2019). Effectively communicating the relative environmental footprints of different foods to consumers must also be a priority (Potter and Röös 2021).

Diverse farming systems depend on soil structure and health. In discussing how to manage competition for land use and other resources, EASAC (2017) highlighted the critical role of soil, particularly with respect to its biological functions. A more recent EASAC assessment (2018) further emphasised the multiple roles of soil sustainability and implications for its management in informing policy development, a subject that has been relatively neglected in the EU of late. This neglect needs to be corrected. Among soil's biological functions, EASAC (2017) discussed emerging knowledge about the contribution of soil microbiomics (bacteria and fungi) to sustainable agriculture, e.g., in the strengthening of root systems and carbon sequestration. There is another link to the bioeconomy: the soil microbiome can be a resource for generating novel antibiotics and other high-value chemicals. Rapid progress continues in ascertaining the linkages between microbial diversity and ecosystem functions, including plant health under climate change, in particular, the role of soil microbial taxa in biogeochemical cycling, plant growth and carbon sequestration (Dubey et al. 2019; Wei et al. 2019).

There are continuing opportunities to link food systems and environmental objectives with bioeconomic policy: impetus and coordination has been imparted to the European Bioeconomy Strategy through the recent introduction of an EU-wide monitoring system[3] for tracking the balancing of bioeconomic contributions to food and other outputs, in order to reduce environmental pressures. Systematic review of the literature suggests the need to prioritise biomass strategies to increase food production over those for animal feed or biofuels (Haines 2021). Scientific advances are bringing new opportunities to drive the bioeconomy of future foods (such as mycoproteins, algal feedstocks, cultured meat, Fanzo et al. 2020; Haines 2021).

3 Delivering Sustainable and Healthy Diets Under Climate Change

Climate change is already affecting the yield and quality of crops, with the potential for adverse consequences in terms of malnutrition (undernutrition, micronutrient deficiency, obesity, EASAC 2017). Systematic reviews of the literature have documented declines in the yields of starchy staple crops (Wang et al., 2018) and in the yields and nutritional quality of vegetables and legumes (Scheelbeek et al. 2018), fruits, nuts and seeds (Alae-Carew et al. 2020). Developing climate-resilient

[3] EU Bioeconomy Monitoring System, 2020, https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en

food systems should be a core part of UN FSS Action Track 5 (Build resilience to vulnerabilities, shocks and stress).

It is important to evaluate how the agricultural sector can adapt to climate change and, at the same time, reduce its own contribution to greenhouse gas (GHG) emissions. Agriculture currently accounts for about 30% of total GHG emissions, if we include land conversion and direct, production-linked environmental costs (EASAC 2019). A key objective, therefore, for the UN FSS, when developing environment-health-climate change policies, is to simultaneously reduce both the triple burden of malnutrition and the contribution that food systems make to climate change and other environmental changes. The accumulating evidence indicates that the 1.5° and 2° C targets cannot be attained without rapid and ambitious changes to food systems (Clark et al. 2020). A combination of measures is necessary to reduce GHG emissions from agriculture, including improved agronomic practices, the reduction of waste, and an increase in sustainable consumption patterns. The evidence base indicates significant health benefits from reducing red meat consumption (where that is excessive) and increasing the use of vegetables, fruits, nuts and seeds in diets (EASAC 2019; Willett et al. 2019). The impact of changes to dietary guidelines on micronutrient intakes must be considered, especially for vulnerable groups. A recent systematic review of environmental footprints and the health effects of "sustainable diets" (Jarmul et al. 2020) concluded that, although co-benefits are not universal and some trade-offs are likely, when carefully-designed and adapted to circumstances, diets can play a pivotal role in climate change mitigation, sustainable food systems and future population health. Unfortunately, in proposing recommendations for policy solutions, issues related to the accessibility and affordability of proposed healthy and sustainable diets are often overlooked (Hirvonen et al. 2020).

Policy implications for the promotion of sustainable food systems that reward good management practices include the introduction of sustainable stewardship, food labelling and certification schemes. Current food policy in many countries concentrates more on how to protect consumer health from contaminated food than the degree to which the State should use health and environmental considerations to regulate the supply of foodstuffs (Godfray et al. 2018). Resolving this role of the State has significant implications for rebalancing consumption by introducing incentives/disincentives for carbon and biodiversity costs of populations at risk of overconsumption, while protecting vulnerable groups. At the same time, governments must consider how best to measure and monitor policy changes for their impact on food production, consumption and health.

4 Responding to COVID-19

The ongoing COVID-19 pandemic has affected all components of the food system. Long-term implications are hard to predict, as they will depend on the length and severity of the pandemic. The effects may also be compounded by shocks to production (such as drought and the interruption of seasonal labour supply for planting and harvesting), and by factors influencing the distribution, access and affordability of food (e.g., disruptions to global food trade and food price speculations; Moran et al. 2020). To date, global supply chains continue to function in spite of isolation policies (Galanakis 2020; Moran et al. 2020), although production problems that resulted in an increase in the price of fresh and perishable products have also been reported (Coluccia et al. 2021). In Europe, there has been an increase in food wastage, partly as a result of the shutdown of restaurants, schools and other community facilities. The pandemic has affected the ability of vulnerable groups within the population to access sufficient and healthy food due to rising unemployment and enforced self-isolation, in particular, families with young children, and is exacerbating diet-related health inequalities (Power et al. 2020). Consumption-related challenges reported during lockdowns include a small increase in the intake of calories and a decrease in the intake of vitamins, minerals and plant-based protein and fatty acids, in particular, by the elderly as a group (Batlle-Bayer et al. 2020; IUFoST 2020). Combined with reduced physical exercise during lockdown, these dietary changes may increase the incidence of obesity and related NCDs. Hoarding and panic buying during pandemics, also reported, could distort the food supply chain and need to be better managed (IUFoST 2020).

Planning for a sustainable economic recovery after the pandemic provides a window of opportunity to make food systems more resilient, nutritious and environmentally sustainable, avoiding a return to business-as-usual (EASAC 2020b; Benton 2020; IUFoST 2020; Rowan and Galanakis 2020; Sarkis et al. 2020). Because the pandemic exposed the vulnerability of overreliance on just-in-time and lean delivery systems, globalised food production and distribution systems based on complex value chains should be re-examined, not only in terms of economic efficiency, but also for their environmental sustainability and climate change mitigation potential. Opportunities for the increased localisation of production systems should be explored. Research priorities also include the development of food safety measures and bioanalytical protocols for food and environmental safety along the food chain; and the development of nutritional foods to promote immune function, which may include foods for medical use by the elderly population, as well as other vulnerable groups. Further areas for innovation to capitalise on scientific opportunities comprise digitisation and the implementation of smarter logistics systems, including reverse logistics for secondary materials and waste products (IUFoST 2020; Rizou et al. 2020; Rowan et al. 2020; Sarkis et al. 2020). The generation of robust baseline data on malnutrition levels in the EU Member States remains an important knowledge gap, in particular, for vulnerable sectors of the population (EASAC 2017).

5 New Breeding Techniques: A Case Study in Science, Technology and Innovation

Improved breeding of plants and animals for agricultural production is a key component of an integrated transformation of food systems to deliver healthy and nutritious diets sustainably in the face of climate change. For plants, key target traits for improvement include increased tolerance to drought (including soil water use efficiency), heat, and salinity, with a focus on the development of multiple traits; improved use of soil nutrients (nitrogen, phosphorous and essential elements) to reduce dependency on fertilisers; pest and disease resistance; and healthier nutrient composition (EASAC 2017, 2020c). Animal breeding priorities comprise animal health (disease resistance and stress tolerance, in particular, regarding heat); and nutrition, including strategies to mitigate enteric gut methane emissions. Achieving these objectives will require the use of the full toolbox of breeding technologies available, from conventional breeding assisted by advances in genetics and genomics, through to the use of a set of technologies collectively referred to as new breeding techniques (NBTs) and, in particular, genome editing.

Recent advances using genome editing include the development of varieties with improved nutritional content, such as high protein wheat with increased grain weight and more nutritious potatoes (Hameed et al. 2018; Zhang et al. 2018, 2020). In wheat, gene editing has also been used to derive low-gluten transgene-free plants (Sánchez-León et al. 2018). Gene editing allows for developing crop varieties with multiple resistances to biotic and abiotic stresses (e.g., in tomatoes: Saikia et al. 2020). Looking ahead, research priorities include the (re)domestication of high-nutrient stress-tolerant crops by targeting known domestication genes in established crops (e.g., for the cultivation of quinoa in Europe; López-Marqués et al. 2020; and see also van Tassel et al. 2020; Zhang et al. 2020), and the development of perennial grain crops to maximise sustained crop yields (DeHann et al. 2020).

Crops produced through genome editing techniques, including those with no foreign DNA, are regulated differently in different countries (Schmidt et al. 2020), with Europe holding the most restrictive regulatory regime. In 2018, the European Union Court of Justice ruled that crops produced by gene editing technologies are to be subjected to the same regulations as GM crops (Directive 2001/18/EC). The focus of this regulation is the process by which a crop is developed, not the breeding product, and as a result, crop varieties that are equivalent from a scientific perspective but were developed through different methods will be regulated differently (Jansson 2018). The legislation's far-reaching consequences include the stifling of innovation, since the cost of pre-market evaluations will deter investment in the technology, in particular, in the public sector and by small and medium enterprises (SMEs; Ricroch 2020; Jorasch 2020). Around 40% of SMEs and 33% of large companies ceased or reduced their gene editing-related R&D activities after the 2018 ruling (Jorasch 2020). The EU is also lagging behind in terms of generating innovation: while the United States and China have filed 872 and 858 patents for applications for gene editing applications, respectively, EU countries together have filed only 194 (Martin-Laffon et al. 2019). There has also been a very striking reduction in the number of EU countries carrying out field trials of crops improved by either GM or gene editing (Ricroch 2020). In addition, the impossibility of distinguishing between edited and naturally derived varieties makes the law unenforceable, especially if the varieties are considered legal elsewhere (Martin-Laffon et al. 2019; Schmidt et al. 2020; Zhang et al. 2020).

EASAC advised (EASAC 2020a, b, c) that it is the products of new technologies and their use, rather than the technology itself, that should be evaluated according to the scientific evidence base, and that the legal framework should be revised. The potential costs of not using a new technology, or being slow in adoption, must be acknowledged, as there is no time to lose in resolving the problems for food and nutrition security.

6 Strengthening Research and Its Uptake into Policy and Practice

The purpose of this Brief has been to address three questions: How can scientific advances help to fill knowledge gaps in delivering food and nutrition security? What does Europe need to build its research capabilities and help build global scientific capacity and partnerships? How best can science-based evidence be used to inform innovation, policy development and practice? Our recommendations are as follows.

Filling Knowledge Gaps with New Research

In the previous sections, we have exemplified how new research is of unequivocal value in addressing societal challenges. In addition to these examples, and referring back to other scientific priorities in EASAC 2017, there have been recent advances in big data handling, robotics, artificial intelligence and mobile communications for precision agriculture (Klerkx and Rose 2020; El-Gayar et al. 2020). There have also been substantial advances in the science of human gut microbiomics and linkages to diet and health. For example, methodological studies are rapidly clarifying characteristics of a healthy microbiome (Eisenstein 2020) and intervention studies have demonstrated the health value of a Mediterranean diet in older cohorts in different European countries, explained in terms of gut microbiome alterations (Ghosh et al. 2020). Advances in social science research are increasingly important to understanding determinants of inequity in food systems, mechanisms for empowerment of marginalised groups and models for entrepreneurial activity (Fanzo et al. 2020). Social science research is also helpful in evaluating specific instruments for the promotion of sustainable food in EU policy, e.g., taxation schemes, consumer cooperatives, labelling and governance initiatives (Marsden et al. 2018; SAPEA 2020).

Building the Research Enterprise

Europe has mature systems for research funding at the national and EU levels (EASAC 2017). Nonetheless, it is essential for the scientific community to continue making the case for investment in research, including fundamental science, and to recognise the value of involving other stakeholders in the design and conduct of research (SAPEA 2020). Greater inclusivity depends in part on building public confidence in science and shaping public understanding of the challenges to food and nutrition security in a changing public landscape often characterised by less deference to authority and scientific experts (Fears et al. 2020). Strengthening research capabilities in Europe also depends on understanding the impact from the progressive loss of key skills in the EU (e.g., in plant sciences), and on reversing those losses while also developing new skills needed by the next generation of researchers (e.g., in transdisciplinary thinking). The EU also has an important role in developing global critical mass in research, e.g., by fostering research partnerships, sharing data and infrastructure, and contributing to tackling those problems that can only be addressed at the global scale. The European Commission recently launched an important initiative to assess the need for an international platform for food systems science.[4]

Translating Research Outputs

Ensuring the robustness, legitimacy and relevance of scientific evidence is vital if its impacts on innovation, policy and practice are to be realised. Overcoming obstacles in translation also depends on public confidence in science, the integration of outputs from across diverse disciplines (evidence synthesis for sustainability, Anon 2020), and the accounting of new models (e.g., for open innovation) and trade-offs between different goals, e.g., for nutrition and environment (Fears et al. 2019). Academies of science are well placed to help lead the scientific community at the science-policy interfaces. The EU already has a relatively mature science-policy interface in place, whose operational characteristics may serve as a model for other regions (Fears et al. 2019) and, currently, there is active scientific engagement in a diverse range of public policies in development, including F2F, Common Agricultural Policy and Biodiversity strategy, bioeconomy, circular economy and the European Green Deal. The F2F strategy has important and comprehensive objectives, but it remains vital to clarify and resolve governance challenges, including the tangible links to Member State action (Schebesta and Candell 2020). There is also ambiguity in defining food sustainability and, currently, a mismatch between F2F and the Common Agricultural Policy that must be resolved by developing compatible legal instruments and ensuring better coordination between the relevant Directorate-Generals (for health and agriculture). F2F highlights several controversies, e.g., on the objectives for food pack labelling, targets for pesticide use in farming, and nature-based farming solutions, all of which require a stronger evidence base. Moreover, the modelling of different scenarios for adopting the proposed F2F targets (Beckman et al. 2020) finds reductions in EU agricultural production and diminished competitiveness in both domestic and export markets. Modelling also predicted consequences for the rest of the world, driving up food prices and negatively affecting consumer budgets. While the F2F strategy is rather inward-oriented and has given little explicit attention to external effects in the rest of the world, depending on how incentives/disincentives are applied in the EU, there is a risk of pushing consumers towards the import of food produced less sustainably than in the EU. Therefore, there must be much greater

[4] https://ec.europa.eu/info/news/new-high-level-expert-group-assess-need-international-platform-food-systems-science-2021-feb-17_en

assessment of the potential consequences of the F2F proposals within the broad context of food system transformation.

The EU can also teach a cautionary lesson on the obstacles created by inflexible regulation that delays or impedes the translation of research outputs into innovation and practice. In the case study discussed previously, the EU GMO regulatory framework was found to be inflexible, disproportionate, not based on current scientific evidence and not fit for purpose. Urgent reform of the regulation of new plant (and animal) breeding techniques is essential for agricultural innovation to realise its potential in achieving SDG targets, as well as for the EU to maintain its international competitiveness and to obtain value from its public investment in research (EASAC 2020c). The current obstacles have implications beyond the EU: EU policy decisions have consequences for those lower- and middle-income countries (LMICs) who look to the EU for scientific leadership or as a market for their innovative exports.

In conclusion, the use of science and technology to transform food systems for health, nutrition, sustainable agriculture and the environment depends on progress across a transdisciplinary research agenda, but also on facilitating the use of science by stakeholders, such as farmers, manufacturers, regulators and consumers, as well as policymakers. It is time to be more ambitious in identifying, investing in, and using scientific opportunities. Academies of science stand ready to play their part in catalysing the necessary actions for food systems in transition, and at the science-policy interface.

Acknowledgements This chapter was drafted by Claudia Canales and Robin Fears, in discussion with Volker ter Meulen. We thank colleagues from EASAC, the Biosciences Steering Panel and the Working Group on FNSA (EASAC 2017) for helpful discussions and, in particular, Tim Benton, Thomas Elmqvist and Aifric O'Sullivan for making important points.

References

Alae-Carew C, Nicoleau S, Bird FA et al (2020) The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. Environ Res Lett 15: 023002

Anderseon L, Benbow HM, Manzin G (2017) Europe on a plate: food, identity and cultural diversity in contemporary Europe. Australian and New Zealand. J Eurasian Stud 8

Anon (2020) Evidence synthesis for sustainability. Nat Sustain 3:771

Batlle-Bayer L, Aldaco R, Bala A, Puig R, Laso J, Margallo M, Vázquez-Rowe I, Antó JM, Fullana-i-Palmer P (2020) Environmental and nutritional impacts of dietary changes in Spain during the COVID-19 lockdown. Sci Total Environ 748:141410

Beckman J, Ivanic M, Jelliffe JL, Baquedano FG, Scott SG (2020) Economic and food security impacts of agricultural input reduction under the European Union Green Deal's Farm to Fork and biodiversity strategies. USDA No 1473-2020-1039

Benton TG (2020) COVID-19 and disruptions to food systems. Agric Hum Values 37:577–578

Benton T, Bailey R (2019) The paradox of productivity: agricultural productivity promotes food system inefficiency. Glob Sustain 2:E6. https://doi.org/10.1017/sus.2019.3

Clark MA, Domingo NGG, Colgan K et al (2020) Global food system emissions could preclude achieving the 1.5 °C and 2 °C climate change targets. Science 370:705–708
Coluccia B, Agnusdei GP, Miglietta PP, De Leo F (2021) Effects of COVID-19 on the Italian agri-food supply and value chains. Food Control 107839
Coolsaet B (2016) Towards an agroecology of knowledges: recognition, cognitive justice and farmers' autonomy in France. J Rural Stud 47:165–171
Dasgupta P (2021) Final report – the economics of biodiversity: the Dasgupta review. UK HM Treasury
Davies WJ, Ward SE, Wilson A (2020) Can crop science really help us to produce more better-quality food while reducing the world-wide environmental footprint of agriculture? Front Agric Sci Eng 7:28–44
De Haan L, Larson S, López-Marqués RL, Wenkel S, Gao C, Palmgren M (2020) Roadmap for accelerated domestication of an emerging perennial grain crop. Trends Plant Sci 25:525–537
Dubey A, Malla MA, Khan F et al (2019) Soil microbiome: a key player for conservation of soil health under changing climate. Biodivers Conserv 28:2405–2429
EASAC (2017) Opportunities and challenges for research on food and nutrition security and agriculture in Europe
EASAC (2018) Opportunities for soil sustainability in Europe
EASAC (2019) The imperative of climate action to protect human health in Europe. European Academies Science Advisory Council. https://easac.eu/publications/details/the-imperative-of-climate-action-to-protect-human-health-in-europe
EASAC (2020a) Towards a sustainable future: transformative change and post-COVID-19 priorities
EASAC (2020b). How can science help to guide the European Union's green recovery after COVID-19?
EASAC (2020c) The regulation of genome-edited plants in the. European Union
EASAC and FEAM (2021) Decarbonisation of the health care sector. In Press
Eisenstein M (2020) The hunt for a healthy microbiome. Nature 577:S6–S8
El-Gayar, O.F. and Ofori, M.Q. (2020). Disrupting agriculture: the status and prospects for AI and big data in smart agriculture. AI and Big Data's Potential for Disruptive Innovation. IGI Global 174–215
Eyhorn F, Muller A, Reganold JP, Frison E, Herren HR, Luttikholt L, Mueller A, Sanders J, Scialabba NEH, Seufert V, Smith P (2019) Sustainability in global agriculture driven by organic farming. Nat Sustain 2:253–255
Fanzo J, Covic N, Dobermann A et al (2020) A research vision for food systems in the 2020s: defying the status quo. Glob Food Sec 26:100397
Fears R, ter Meulen V, von Braun J (2019) Editorial. Global food and nutrition security needs more and new science. Sci Adv 5:eaba 2946
Fears R, Canales Holzeis C, ter Meulen V (2020) Designing inter-regional engagement to inform cohesive policy making. Palgrave Commun 6:107
Galanakis CM (2020) The food systems in the era of the coronavirus (COVID-19) pandemic crisis. Foods 9:523
Ghosh TS, Rampelli S, Jeffrey IB, Santoro A, Neto M et al (2020) Mediterranean diet intervention alters the gut microbiome in older people reducing frailty and improving health status: the NU-AGE 1-year dietary intervention across five European countries. Gut 69. https://doi.org/10.1136/gutjnl-2019-319654
Global Sustainable Development Report (2019) The future is now – science for achieving sustainable development. UN, New York
Godfray HCJ, Aveyad P, Garnett T et al (2018) Meat consumption, health and the environment. Science 361:eaam5324
Guimar N, Godinho S, Pinto-Correira T, Almeida M, Bartolini F et al (2018) Typology and distribution of small farms in Europe: towards a better picture. Land Use Policy 75:784–798
Haines A (2021) Health in the bioeconomy. Lancet Planet Health 5:e4–e5

Hameed A, Zaidi SSEA, Shakir S, Mansoor S (2018) Applications of new breeding technologies for potato improvement. Front Plant Sci 9:925

High Level Panel of Experts on Food Security and Nutrition (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. In: Extract from the report: summary and recommendations. Committee on World Food Security

Hirvonen K, Bai Y, Headey D, Masters WA (2020) Affordability of the EAT-Lancet reference diet: a global analysis. Lancet Glob Health 8:e59–e66

International Union of Food Science and Technology (IUFoST) Interim Report (2020). Available at: https://iufost.org/wp-content/uploads/2020/05/IUFoST-Interim-Report.May-2020.pdf

Jansson S (2018) Gene-edited plants on the plate: the 'CRISPR cabbage story'. Physiol Plant 164: 396–405

Jarmul S, Dangour AD, Green R et al (2020) Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of "sustainable diets". Environ Res Lett 15:123014

Jorasch P (2020) Potential, challenges, and threats for the application of new breeding techniques by the private plant breeding sector in the EU. Front Plant Sci 11:1463

Kania, J., Vinohradnik, K. and Knierm, A. (2014). AKIS in the EU: the inventory-final report Vol. II. Report of the Project PRO AKIS – Prospects for farmers' support advisory services in the European AKIS. Krakow

Klerkx L, Rose D (2020) Dealing with the game-changing technologies of agriculture 4.0: how do we manage diversity and responsibility in food system transition pathways? Glob Food Sec 24: 100347

Krzysztoszek J, Laudanska-Krzeminska I, Bronikowski M (2018) Assessment of epidemiological obesity among adults in EU countries. Ann Agric Environ Med 26:341–349

Leij-Halfwerk S, Verwijs MH, van Houdt S et al (2019) Prevalence of protein-energy malnutrition risk in European older adults in community, residential and hospital settings, according to 22 malnutrition screening tools validated for use in adults> 65 years: a systematic review and meta-analysis. Maturitas 126:80–89

Lillford P, Hermansson A-M (2020) Global missions and the critical needs of food science and technology. Trends Food Sci Technol. https://doi.org/10.1016/j.tifs.2020.04.009

Loopstra R (2018) Interventions to address household food insecurity in high-income countries. Proc Nutr Soc 77:270–281

López-Marqués RL, Nørrevang AF, Ache P, Moog M, Visintainer D, Wendt T, Østerberg JT, Dockter C, Jørgensen ME, Salvador AT, Hedrich R (2020) Prospects for the accelerated improvement of the resilient crop quinoa. J Exp Bot 71:5333–5347

Marsden T, Hebinck P, Mathijs E (2018) Rebuilding food systems: embedding assemblages, infrastructures and reflective governance for food systems in Europe. Food Secur 10:1301–1309

Martin-Laffon J, Kuntz M, Ricroch AE (2019) Worldwide CRISPR patent landscape shows strong geographical biases. Nat Biotechnol 37:613–620

McElwee P, Calvin K, Campbell D et al (2020) The impact of interventions in the global land and agri-food sectors on nature's contribution to people and the UN sustainable goals. Glob Chang Biol 26:4691–4721

Mertens E, Kuijsten A, Dofkova M, Mistura L, D'Addezio L et al (2019) Geographic and socioeconomic diversity of food nutrient intakes: a comparison of four European countries. Eur J Nutr 58:1475–1493

Moran D, Cossar F, Merkle M, Alexander P (2020) UK food system resilience tested by COVID-19. Nature Food 1:242

Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C (2020) What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Front Sustain Food Syst 4. https://doi.org/10.3389/fsufs.2020.577723

Pineda E, Sanchez-Romero LM, Brown M et al (2018) Forecasting future trends in obesity across Europe: the value of improving surveillance. Obes Facts 11:360–371
Pollard CM, Booth S (2019) Food insecurity and hunger in rich countries – it is time for action against inequality. Int J Environ Res Public Health 16:1804
Potter HK, Röös E (2021) Multi-criteria evaluation of plant-based foods–use of environmental footprint and LCA data for consumer guidance. J Clean Prod 280:124721
Power M, Doherty B, Pybus K, Pickett K (2020) How COVID-19 has exposed inequalities in the UK food system: the case of UK food and poverty. Emerald Open Research 2
Ricroch A (2020) The place of Europe in the new plant breeding landscape: evolution of field trials. Available at: https://www.europeanscientist.com/en/features/the-place-of-europe-in-the-new-plant-breeding-landscape-evolution-of-field-trials
Rizou M, Galanakis IM, Aldawoud TM, Galanakis CM (2020) Safety of foods, food supply chain and environment within the COVID-19 pandemic. Trends Food Sci Technol 102:293–299
Rowan NJ, Galanakis CM (2020) Unlocking challenges and opportunities presented by COVID-19 pandemic for cross-cutting disruption in agri-food and green deal innovations: Quo Vadis? Sci Total Environ 141362
Sachs J, Schmidt-Traub G, Kroll C et al (2019) Sustainable development report. Bertelsmann Stiftung and Sustainable Solutions Network, New York
Saikia B, Singh S, Debbarma J, Velmurugan N, Dekaboruah H, Arunkumar KP, Chikkaputtaiah C (2020) Multigene CRISPR/Cas9 genome editing of hybrid proline rich proteins (HyPRPs) for sustainable multi-stress tolerance in crops: the review of a promising approach. Physiol Mol Biol Plants 26:857–869
Sánchez-León S, Gil-Humanes J, Ozuna CV, Giménez MJ, Sousa C, Voytas DF, Barro F (2018) Low-gluten, nontransgenic wheat engineered with CRISPR/Cas9. Plant Biotechnol J 16:902–910
SAPEA (2020) A sustainable food system for the European Union. SAPEA Evidence Revi Report 7
Sarkis J, Cohen MJ, Dewick P, Schröder P (2020) A brave new world: lessons from the COVID-19 pandemic for transitioning to sustainable supply and production. Resour Conserv Recycl
Schebesta H, Candel JJ (2020) Game-changing potential of the EU's farm to fork strategy. Nat Food 1:586–588
Scheelbeek PFD, Bird FA, Tuomisto HL et al (2018) Effect of environmental changes on vegetable and legume yields and nutritional quality. Proc Natl Acad Sci U S A 115:6804–6809
Scherhaufer S, Moates G, Hartikainen H, Waldron K, Obersteiner G (2018) Environmental impacts of food waste in Europe. Waste Manag 77:98–113
Schmidt SM, Belisle M, Frommer WB (2020) The evolving landscape around genome editing in agriculture: many countries have exempted or move to exempt forms of genome editing from GMO regulation of crop plants. EMBO Rep 21:e50680
Schreefel L, Schultz RPO, de Boer IJM, Schrijver AP, van Zanten HHE (2020) Regenerative agriculture – the soil is the base. Glob Food Sec 26:100404
Seufert V, Mehrabi Z, Gabriel D, Benton TG (2019) Current and potential contributions of organic agriculture to diversification of the food production system. In: Agroecosystem diversity. Academic Press, pp 435–452
Smith LG, Kirk GJ, Jones PJ, Williams AG (2019) The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat Commun 10:1–10
Sonnichsen SD, Clement J (2020) Review of green and sustainable public procurement. J Clean Prod 245:118901
Šūmane S, Kunda I, Knickel K, Strauss A, Tisenkopf T et al (2018) Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. J Rural Stud 59:232–241
van der Werf HM, Knudsen MT, Cederberg C (2020) Towards better representation of organic agriculture in life cycle assessment. Nat Sustain 3:419–425

van Tassel DL, Tesdell O, Schlautman B, Rubin MJ, DeHaan LR, Crews TE, Streit Krug A (2020) New food crop domestication in the age of gene editing: genetic, agronomic and cultural change remain co-evolutionarily entangled. Front Plant Sci 11:789

Wang J, Vanga SK, Saxena R et al (2018) Effect of climate change on the yield of cereal crops: a review. Climate 6:41

Wei Z, Gu Y, Friman VP et al (2019) Initial soil microbiome composition and function predetermine future plant health. Sci Adv 5:eaaw 0759

Willett W, Rockstrom J, Loken B et al (2019) Food in the Anthropocene: the EAT-Lancet Commission on healthy diet from sustainable food systems. Lancet 393:447–492

World Economic Forum (2020) The future of nature and business

World Health Organization (2021) Action framework for developing and implementing public food procurement and service policies for a healthy diet. https://apps.who.int/iris/bitstream/handle/10665/338525/9789240018341-eng.pdf

Zhang Y, Li D, Zhang D, Zhao X, Cao X, Dong L, Liu J, Chen K, Zhang H, Gao C, Wang D (2018) Analysis of the functions of Ta GW 2 homeologs in wheat grain weight and protein content traits. Plant J 94:857–866

Zhang Y, Pribil M, Palmgren M, Gao C (2020) A CRISPR way for accelerating improvement of food crops. Nature Food 1:200–205

Transforming Chinese Food Systems for Both Human and Planetary Health

Shenggen Fan, Jikun Huang, Fusuo Zhang, Wenhua Zhao, Hongyuan Song, Fengying Nie, Yu Sheng, Jinxia Wang, Jieying Bi, and Wenfeng Cong

1 Introduction

Enormous successes have been achieved with regard to food throughout the world in the past, but future challenges are massive. Food systems embrace the entire range of actors and their interlinked value-adding activities in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are

S. Fan (✉)
Academy of Global Food Economics and Policy, China Agricultural University, Beijing, China
e-mail: S.FAN@CGIAR.ORG

J. Huang · Y. Sheng · J. Wang
China Centre for Agricultural Policy, School of Advanced Agricultural and Sciences (SAAS), Peking University, Beijing, China

F. Zhang
College of Resources and Environmental Sciences (CRES), National Academy of Agriculture Green Development, China Agricultural University, Beijing, China

W. Zhao
National Institute for Nutrititon and Health, Chinese Centre for Disease Control and Prevention (China CDC), Beijing, China

H. Song
Research Center for Rural Economy (RCRE), Ministry of Agricultural and Rural Affairs, Beijing, China

F. Nie · J. Bi
Agricultural Information Institute (AII), Chinese Academy of Agricultural Sciences (CAAS), Beijing, China

W. Cong
College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, China Agricultural University, Beijing, China

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_41

embedded (von Braun et al. 2021; Fan et al. 2021). They also generate massive externalities, and are a cause of many economic, social and health crises, including the triple burden of malnutrition (undernourishment or hunger, micronutrient deficiencies or hidden hunger, overweight and obesity), food safety scares and zoonotic pandemics such as the ongoing COVID-19. Thus, urgent actions are needed to transform the current food systems to be nutrition- and health-driven, productive and efficient (thus improving affordability), environmentally sustainable and climate-smart, resilient and inclusive.

Despite rapid ascension in global food production, consumption, trade and investment, the voices of emerging economies are largely absent in setting the global food systems agenda. This will hinder the transformation of their own food systems, as well as the global system. Taking China as an example, the country's food systems have experienced substantial transformation for the past four decades, but still face many challenges that threaten both human health and environmental sustainability. Fortunately, the government has recently made several important commitments in regard to food and nutrition security, health, the environment and climate change, including achieving carbon neutrality by 2060. This provides a unique opportunity, as well as responsibility, to reshape food systems in order to achieve these national goals.

This chapter aims to review major achievements, enabling factors, and challenges, and to propose a pathway for Chinese food systems to achieve both human and planetary health. Chinese experience, and the lessons learned therein, have global implications, not only because of its size, but also because of its strategy to strengthen the south-south cooperation in order to enhance global food security, climate mitigation, resilience to unexpected crises, and protection of the world's natural resources.

2 Evolution of Food and Nutrition Security in China

Impressive progress in China's growth in agricultural productivity and the subsequent growth in agricultural production has enabled the country to feed nearly 20% of the world's population using only 8% of the world's arable land and 5% of global fresh water (Lu et al. 2015; Huang et al. 2020). During the period 1978–2020, China's agricultural output (in real terms) has grown at the rate of 4.6% a year (more than 60% driven by total factor productivity growth), much higher than the 0.9% of annual population growth for the same period of time. In the meantime, the structure of agricultural production has shifted towards high-value and high-protein products (NBSC 2020). The farm economy is now highly commercialized and the output value of high-value commodities (including vegetables, fruits, livestock and fish) has, on average, accounted for around 70% of agricultural output value (Huang and Shi 2021).

With increased food supply, China has substantially increased the capacity of food supply for its growing and wealthier population. Over the past three decades, the prevalence of global hunger has been on the decline, among which two-thirds of the people who escaped hunger globally live in China (FAO 2020). Between 1990 and 2020, the prevalence of undernutrition in China dropped from 22.9% to below 2.5% (FAO stops reporting when the rate is below 2.5%, thus the hunger rate in China is much lower than 2.5%), and the daily calorie intake per capita increased from 2,814 kal/day in 2000 to 3,197 kal/day in 2017 (Table 1). The food consumption pattern has also become more diversified, with the proportion of high-protein and high-energy products having increased substantially. Data from national household consumption surveys shows that the overall intake of staple foods (in particular, grains) decreased by approximately one-third over the past three decades, and the daily consumption of vegetables, fruits and meat per capita were more than doubled in 2018 compared to 1997 (Zhao et al. 2018). The prevalence of stunting and underweight in China are well below the average for developing countries, and undernutrition and micronutrient deficiencies have declined sharply (Figs. 1 and 2). The overall mortality from cardiovascular diseases, all types of cancer, chronic respiratory diseases and type-2 diabetes has declined from 18.5% in 2015 to 16.5% in 2020.

The agricultural market has been gradually reformed domestically and internationally, **helping to increase the allocative efficiency of the food value chain** (Huang and Rozelle 1996; De Brauw et al. 2004). Domestically, marketization reforms started with the so-called nonstrategic products (such as vegetables and fruits) in the mid-1980s, gradually moving to animal products (fish and meat) and

Table 1 Calorie supply per capita and per day (kilocalories), 2000–2017

Year	Brazil	China	India
2000	2880	2814	2380
2005	3078	2883	2270
2010	3230	3044	2442
2015	3238	3187	2461
2016	3236	3172	2496
2017	3248	3197	2517

Source: OECD/FAO (2022)

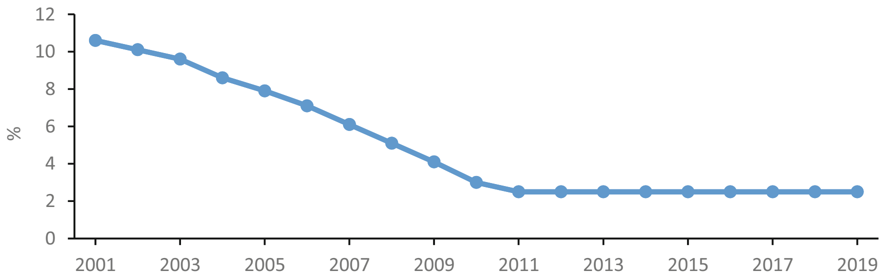


Fig. 1 Percentage of undernourished population in China, 2001–2019. (Source: The World Bank 2020)

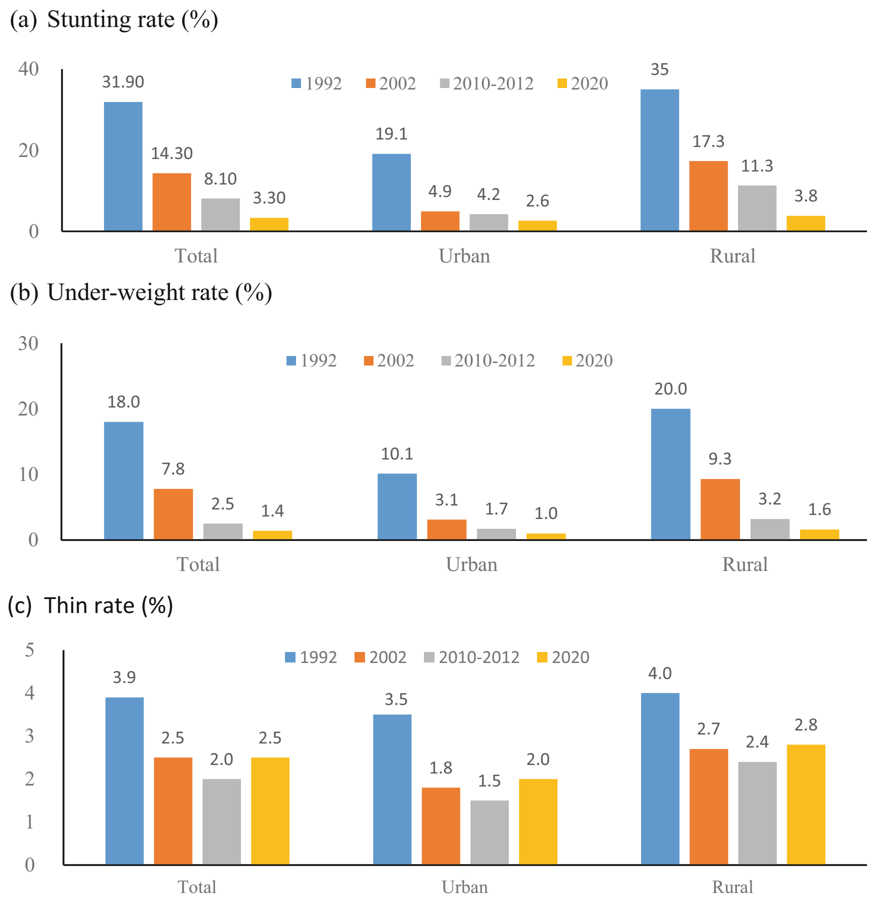


Fig. 2 Nutrition Statistics of Children under 5 years old in China, 1992–2020. (Source: 1992, 2002, 2012 and 2020 China Nutrition and Health Surveys)

then to crops such as sugarcane, edible oils, cotton and grains (Sicular 1988; Rozelle et al. 2000; Rozelle and Swinnen 2004; Huang and Rozelle 2006). Internationally, China reduced the average import tariff for all agricultural products from 42.2% in 1992 to 12% in 2004, making China one of the freest agricultural trading nations in the world. Equally, remarkable growth also occurred in the upstream and downstream sectors of agriculture. While agriculture only accounted for 6.7% GDP and 25% employment in 2019, the food system in China (including agriculture, agribusiness, food processing, packaging, transportation, wholesale and retail trade, food services, finance and insurance, advertising and input supplies) accounted for 23% of GDP and more than 30% of total employment (Fan et al. 2021). Recent trends toward greater concentration of agricultural inputs and food distribution, the increasing role of E-commerce and logistic technologies, and the growing importance of food safety, quality, and other technical requirements have all resulted in dramatic changes in Chinese agri-food systems (Chen et al. 2019; Fan and Swinnen

2020). With the rapid expansion of Internet access and the steady process of logistics infrastructure construction, China is now leading the world in E-commerce and has shown the resilience of its food system in coping with the COVID-19 pandemic in 2020.

China has facilitated rural structural transformation and off-farm employment, substantially contributing to poverty reduction and increasing equal accessibility to food. Where off-farm employment was once rare, today, a majority of rural household income is earned off-farm. The share of rural labor off-farm employment had increased from 9.3% in 1978 to 84.4% in 2018 (Li et al. 2021). Agriculture employed 71% of labor in 1978 (Rozelle et al. 1999). By 2019, the share of employment in agriculture had fallen to 25% (NBSC 2020). At the same time, the number of people in rural China living in extreme poverty fell from 250 million in 1978 down to zero in 2020 (NBS various years). According to the current nationwide poverty threshold—RMB 2300 a day in 2010 prices, or slightly more than $2 a day in purchasing power parity (PPP) terms—the number of rural poor decreased by 98.99 million over the past decade, and all of the remaining 832 poor counties (128 thousand villages) have moved out of poverty (NBS various years). China has become the first developing country to meet the Sustainable Development Goals (SDGs) target one decade ahead of schedule.

Green development and resilience have been integrated into agricultural development strategy. In terms of resource management, China is one of a few large countries to make substantial public investment in irrigation, flood control and land improvement (Wang et al. 2019). The area of irrigated agricultural land increased from 45 million hectares in 1978 to 68.7 million hectares in 2019 (NBSC 2020). Today, more than half of China's cultivated land is irrigated. Investment in low- to mid-quality land has also helped to improve soil quality and raise agricultural production capacity. In response to environmental degradation and climate change, the government has initiated the first national program to protect natural resources in 2016, and thereafter implemented a series of directories and regulations to tackle environmental degradation and restore the agroecosystem. In 2021, the newly issued regulation towards low carbon and "dual cycle" rural development highlighted measures for controlling livestock waste, agricultural plastics, and the overuse of fertilizers and pesticides. With these efforts, the use of fertilizers and pesticides has substantially declined since the mid-2010s (Figs. 3 and 4). These indicate that China is on the way to developing a greener and more resilient food system in the face of limited environmental resources and climate change.

3 Enabling Factors Driving Chinese Food System Transformation

Numerous studies have analyzed the factors contributing to China's agricultural growth and food system transformation. These include sequencing policy and investment priorities, embracing technological progress and innovation, integrating

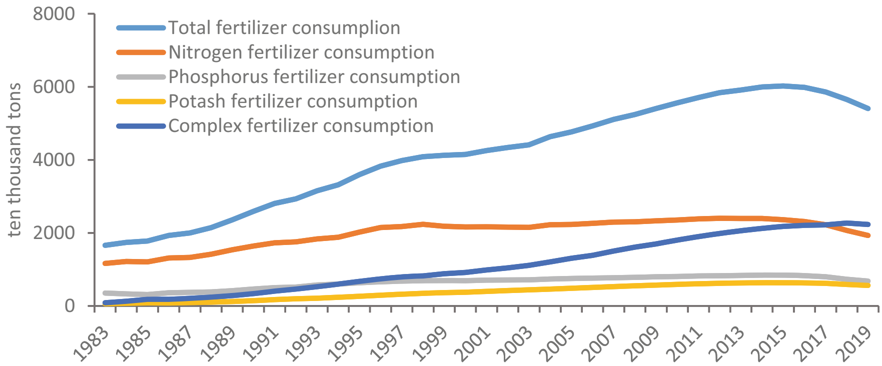


Fig. 3 Total use of fertilizers and its composition change in China: 1984–2019. (Source: China rural statistical yearbook, various years)

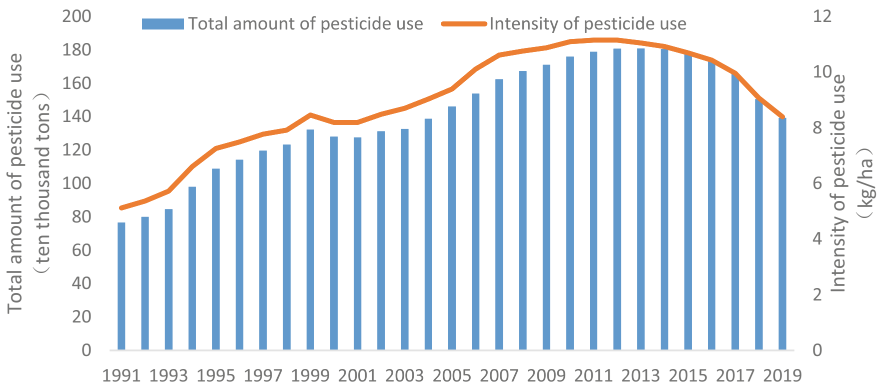


Fig. 4 Total pesticide use and its intensity: 1990–2019. (Source: China rural statistical yearbook, various years)

food and nutrition security into poverty reduction programs, protecting natural resources and the environment, building resilience against risks and shocks, and promoting ICT and E-commerce.

3.1 *Sequential Choice of Policy and Investment Initiatives*

Sequentially choosing and prioritizing policy instruments to meet the stage-by-stage development goal is key to achieving successful food system transformation. The household responsibility system (HRS), implemented during the period 1978–84, was regarded as the starting point of China's agricultural and food system transformation. The reform dismantled the people's communes and contracted cultivated land to individual households, largely on the basis of the number of people and/or laborers in the household. These triggered strong growth in both agricultural output and productivity, and thus substantially increased the food supply (Fan 1991; Lin 1992; Huang and Rozelle 1996; McMillan et al. 1989; Jin et al. 2002; Sheng et al. 2020).

Reforms in land policy have also paved the way for market reforms implemented since the mid-1980s (Huang et al. 2004; Huang and Rozelle 2006), the agricultural trade reforms of the 1990s (Anderson et al. 2004; Huang et al. 2007), and institutional reforms in labor and financial markets (particularly the gradual relaxation of the household registration system, or hukou).

Prioritizing investment initiatives is also critical. China invested substantially in rural public infrastructure even before the institutional and market reforms that began in the late 1970s, but mainly focused on production- and transportation-related infrastructures. Since the Asian financial crisis in the late 1990s, investments in rural areas have been further boosted as part of the financial stimulus package. As a result, China has become one of a few large countries with substantial increases in public investment in water (irrigation and flood) control and land improvement (Wang et al. 2019). Massive investment has also been made in rural roads and wholesale markets, fostering market integration and linking hundreds of millions of small farms with retailers and consumers. Highway mileage increased from 890,000 km in 1978 to 10 million km in 2020 (NBS various years), and nearly every village has access to a public paved road. Empirical evidence shows that government spending on rural roads has a very high impact on agricultural transformation, off-farm employment and poverty reduction (Zhang et al. 2004, 2019).

3.2 Agricultural R&D and Innovation

China has invested significantly in agricultural R&D and developed a strong technology innovation system (Hu and Huang 2011; Babu et al. 2015). In 2015, public expenditure on agricultural R&D was estimated to reach more than RMB 26 billion yuan (roughly USD$4.1 billion), overtaking the public spending of the US and ranking as number one in the world (Chai et al. 2019). This system has generated a wide range of innovative technologies used by millions of small and large farms in crop, livestock and fishery production, as well as in agricultural inputs and farm machines.

China has also developed a comprehensive agricultural extension system, despite the twisting path to reform of the past. The system covers all townships across the country, and the extension staff work closely with farmers. While the role of the private sector in providing extension services has been rising in recent years, maintaining a strong public extension system is crucial to agricultural production dominated by small farms.

The increased public agricultural R&D investment and the development of an agricultural extension system have been translated directly into productivity gains. China was one of the first developing countries to develop and extend the "green revolution" technology in rice in the 1960s (Stone 1988). Technological changes in wheat, maize, cash crops and animal production have also been impressive since the 1990s (Jin et al. 2010). Empirical studies show that the average annual growth rate of TFP in the grain sector increased by about 3% before the mid-2000s (Fan 1997; Jin et al. 2008). TFP growth rates for cash crops and livestock and the whole agricultural sector were even higher, exceeding 3.5% per year after 1992 (Sheng et al. 2020). Rapid agricultural productivity growth has enabled the country to save its limited land and water resources. Since the mid-1990s, China's agricultural productivity growth has turned towards relying on innovations from plant biotechnology. The wide cultivation with" Bt cotton" is an example of successful uses of genetic modification technology in the developing world—a technological change that has benefited millions of farmers (Huang et al. 2002). Meanwhile, the recent emerging technologies (e.g., ICT, big data technology, etc.) are also changing the path of innovations in the country's agriculture.

3.3 Poverty Reduction Schemes and National Nutrition Programs

The success in poverty reduction (and hunger) in China is not only the result of sustaining rapid economic growth, but also the result of the implementation of large-scale, long-lasting, government-led poverty alleviation strategies. Targeting poverty alleviation policies and development-oriented poverty alleviation programs (Liu et al. 2017; Fan and Cho 2021; Cheng et al. 2021) have both contributed to the success. First, continued reforms and opening-up policies reduced poverty through economic development (Wang et al. 2008; Yan 2016). Second, development-oriented poverty alleviation policies are an important part of China's anti-poverty strategies. China improved the living conditions of poor areas by implementing preferential development policies, to enable these areas to obtain special development opportunities and to partially offset the constraints associated with poor natural conditions. Development programs in infrastructure and public services were offered to poor areas, helping them improve the development environment (Yan 2016). Rapid poverty reduction directly contributed to an increase in the accessibility of food for a large proportion of the population, thereby reducing hunger in a historic record.

A number of nutrition intervention programs and policies have been implemented to improve national nutrition, in which dynamic government guidance (reflecting the changing status) has played an important role. Examples include the Children Nutrition Monitoring and Improvement Project from 1990 to 1995, the Soybean Action Plan of 1996, the Chinese Nutrition Improvement Action Plan of 1997, the School Milk Project of 2000, the Chinese Fortification

Project of 2004, the Nutrition Improvement Program for Rural Compulsory Education Students since 2012, and Nutrition Improvement Projects in Poverty Regions (YYB for Children under 2 years old) in place since 2012, among others. In contrast to the nutrition policies of the 1990s, which emphasized the abundance and availability of food, nutrition policies during the past ten years have placed increasing importance on balanced diets and food safety. The recurring themes of recent policies involve providing recommended nutrient intake and targeted agricultural development based on population and nutritional requirements.

3.4 Environment and Resource Management Practices

China's experience of policy practice in tackling environmental challenges, climate change and rural sustainable development has progressed in two ways: through economic encouragement and persuasion. Economic encouragement has been more widely used, compared to the persuasive approach. Through government subsidies, farmers are given the incentive to adopt more environment-friendly production technologies, which, in turn, play an important role in alleviating the overuse of fertilizers and chemicals and the recycling of wastes from livestock.

Taking irrigation water as an example, the government has traditionally focused on the supply side and relied on building reservoirs to meet the growing water demand (Xie et al. 2009; Wang et al. 2016a). Over time, it has become clear that catching up with the expanding water demand is a difficult task. The government started to advocate irrigation technologies to reduce irrigation withdrawal in the early 1990s (Lohmar et al. 2003; Wang et al. 2020). Another example is Water User Associations, which began replacing village collective management of surface irrigation in the mid-1990s. This approach had been adopted by most provinces by early 2001, but with mixed results. It is associations utlilizing water-saving incentives that have achieved more efficient irrigation (Wang et al. 2005, 2016b). Research also reveals a great policy scope for expanding irrigation technologies to generate real water saving in rural areas.

In addition to water preservation, land protection and soil quality improvement have also received more attention. Since the 18th National Congress, the red line for 1.8 billion mu (15 mu = 1 hectare) of arable land has been drawn to ensure agricultural production with adequate land resource. Meanwhile, the national Soil-Testing and Fertilizer Recommendation Program in 2005 and the Zero Increase Action Plan in 2015, initiated by the Ministry of Agriculture, have played a crucial role in holding back the increase in massive fertilizer inputs and nutrient losses, while increasing food production (Jiao et al. 2018). Consequently, agricultural chemical use (i.e., fertilizer and pesticides) has recently fallen (Figs. 3 and 4).

3.5 Strategies for Strengthening Food System Resilience Under COVID-19

The impact of the COVID-19 pandemic on food systems exposed the vulnerabilities of the supply chain throughout the world in 2020, although the extent of disruption varies widely, globally and in Asia. In response to this pandemic shock, food systems in China have been proven relatively resilient when compared with other regions. **The Chinese experience has been widely acknowledged globally and is believed to have played an important role in fighting the pandemic.** These experiences include (1) early actions taken to make sure that the whole supply chain worked smoothly through the green channel; (2) the well-organized and prompt response of governments; (3) the collaboration of multi-stakeholders (government, scientists, agricultural technicians, private companies, NGOs, O2O platform etc.); and (4) collaboration and joint-response between rural and urban areas.

3.6 Reducing the Food Loss and Waste as a National Strategy

Developing a national vision and strategy for reducing food loss and waste allows China to take the lead in achieving the UN SDGs for halving food loss and waste. In 2010, the State Grain Administration issued "Recommendations to Combat Food Waste," which include raising public awareness on reducing food waste, enhancing food purchase and storage, accelerating food logistic infrastructure development, improving the standard of food products, developing and disseminating new technologies for food waste reduction, and encouraging food processing businesses to combat food waste through the trusted grain and (edible) oil program. One well-known example is the "Clean Your Plate" initiative, promoted through advertising campaigns to raise public awareness on reducing food waste. More recently, China issued the Anti-Food Waste Law, and became the first country to enact anti-food waste activities in the developing world.

3.7 The ICT Revolution and E-Commerce Application

The recent development of rural E-commerce has added fuel to food system transformation, providing a new approach to help smallholder farmers overcome barriers to markets (Hamad et al. 2018; Jamaluddin 2013; Li et al. 2020a, b; Ma et al. 2020; Okoli et al. 2010; Rahayu and Day 2017; Yu and Cui 2019). Rural online retail sales in 2019 reached 1.7 trillion yuan, accounting for 16.1% of the total retail sales, and the growth rate was 19.1%, 2.6% higher than that of the total retail sales. In terms of agricultural products, online retail sales reached 397.5 billion yuan in 2019 (China's Ministry of Commerce 2020). Studies have shown that ICT and rural E-commerce have generated positive externalities for food system transformation, including in regional governance (Liu 2017), social development and women's empowerment (Oreglia and Srinivasan 2016; Xu 2016; Yu and Cui 2019), employment (Qi et al. 2019), and household income (Cho and Tobias 2010; Zapata et al. 2016). The successful expansion of rural E-commerce in China and its potential for economic development and poverty alleviation has drawn a great deal of international attention. The World Bank applauded the development of Taobao villages in China as an instrument for poverty reduction and shared prosperity (World Bank 2016).

4 Challenges Facing Chinese Food Systems

Despite impressive achievements, Chinese food systems are facing a set of emerging challenges. They include declining productivity growth, the multiple burden of malnutrition, particularly micronutrient deficiency and overweight/obesity, natural resource degradation, continued rural-urban and regional inequality and increased food imports.

4.1 Declining Agricultural Productivity Growth and the Dominance of Smallholder Farms

While exhibiting rapid growth in the past, agricultural TFP slowed down in recent years. In addition, rising wages and rural labor shortages have caused the Chinese agricultural and food sector to lose competitiveness and profitability (Liu et al. 2018; Sheng et al. 2020). Between 2000 and 2018, the average relative comparative advantage index for feed grains, oil crops and meats (other than poultry) declined from 2.0 to around 0.8 (Rao et al. 2020).

Although ongoing land reforms, such as township land right transfers and "San-Quan-Fen-Zhi," have facilitated land consolidation throughout the country since the mid-2000s (Huang and Ding 2016; Yi et al. 2019), small farms continue to dominate agricultural production. How to increase the agricultural productivity of small farms is still essential for national food security and the income equality of rural households (Sheng et al. 2019).

4.2 The Triple Burden of Malnutrition

The number of undernourished people has declined to almost zero, but it is a challenging task to tackle unbalanced diet and "hidden hunger" for better health. The deficiency of micronutrients such as vitamin A, iron, zinc, and calcium is still

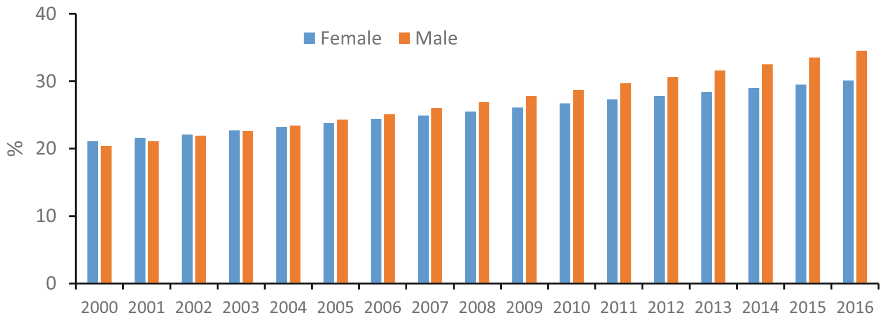


Fig. 5 Percentage of obesity and overweight in total population, 2002–2016. (Source: WHO 2020)

prevalent in both urban and rural areas, especially households with lower economic status (Yang et al. 2010). An estimated 21–34% of school-age children were classified as anemic in poorer western provinces, whereas the anemia rate among school-age children at the national level is estimated to be 6.1% (State Council 2020). Based on the World Bank (2016) estimate, micronutrient deficiency in China is expected to cause an annual loss of 0.2–0.4% of GDP, or US$2.5–5.0 billion per year.

Overweight and obesity rates are increasing—resulting from the excessive intake of fat, calories, and sugar, as well as physical inactivity. The prevalence of adult overweight and obesity in China jumped from 20.4% in 2000 to 34.3% in 2020 among males and from 21.1% to 30.1% among females (Fig. 5). Similarly, the estimated prevalence of overweight and obesity among children under the age of five increased from 5.3% to 6.8% between 1990 and 2020 (NBSC 2020).

An increasingly overweight and obese population brings with it a plethora of adverse health and economic consequences. The prevalence of adult diabetes—a chronic disease highly associated with diet—increased from 1% to more than 11.9% between 1980 and 2020 (NHFPC 2020). Hypertension, diabetes, and other cardiovascular diseases cost China nearly 4% of its GDP, and this figure is expected to double by 2025 if no preventative actions are taken (Popkin 2008).

4.3 Resource Scarcity and Degradation and Climate Change

A rapidly urbanizing and richer society puts pressure on increasingly scarce resources, including land, water and raw materials. In addition to the limited amount of land, land quality is equally worrisome. Nearly 70% of cultivated land in China is classified as low- or medium-fertility land (Jiao et al. 2018; Luan et al. 2020). Water resource constraints are severe as well. In 2019, China's per capita water resource was only 22% of the global average. In particular, the North China Plain's shallow water table has dropped from 0–3 meters below the surface in 1950 to a depth of 65 meters in recent years (Li et al. 2013; Zhao et al. 2019; Wang et al. 2019).

China is also vulnerable to climate-related risks (Cui 2018; Fang et al. 2018; Rosenzweig et al. 2020). China has been among the most disaster-prone countries in the world (Nie et al. 2010; Li et al. 2014), as agro-meteorological disasters alone affect 50 million hectares and 400 million people, and result in a loss of RMB 2000 billion (about 3% of GDP) annually (CNARCC 2011). Climate change will continue to intensify and the occurrence of extreme weather events and natural disasters associated with climate change will continue to increase (Wang et al. 2020; Rosenzweig et al. 2020).

4.4 Remaining Rural-Urban and Regional Inequality

While governments' focus on the agricultural and rural issues has shifted from "poverty reduction" to "rural revitalization," rising rural-urban inequality continues to pose a policy challenge.

The most notable income disparities in China are between urban and rural areas and between coastal and inland regions. The relative ratio of urban to rural residents' per capita disposable income increased from 2.4 in 1978 to 3.0 in 2010. Although it declined in recent years, the ratio was still as high as 2.66 in 2019 (NBSC 2020). In addition to the coastal to inland gap in GDP per capita (Luo and Zhu 2008), the recent decade witnessed a widening gap in GDP per capita between Northern and Southern regions. In 2013, the gap in GDP per capita growth between Southern and Northern provinces was 0.3, but it increased to 1.9% in 2017 (Rozelle and Hell 2020).

Inequality in China is also reflected in wealth distribution, social protection, public service delivery, nutrition, and access to jobs and social programs across and within regions, especially between rural and urban areas. Increasing farmers' incomes at a faster rate will be one of the key policy goals for achieving smooth food system transformation.

4.5 Increasing Food Imports and Uncertainty in Global Markets

China's agricultural trade with the rest of the world has grown rapidly. From 1978 to 2018, China's agricultural trade increased from $5.45 billion to $216.8 billion, with an average annual growth rate of 10% (Rao et al. 2020). At the same time, trade deficit has continued to increase (Fig. 6). China has been running an agricultural trade deficit since 2003, and it has surged to $57.3 billion in 2018 (Uncomtrade 2020). The country imported 100 million tons of soybeans and 11.3 million tons of maize in 2020.

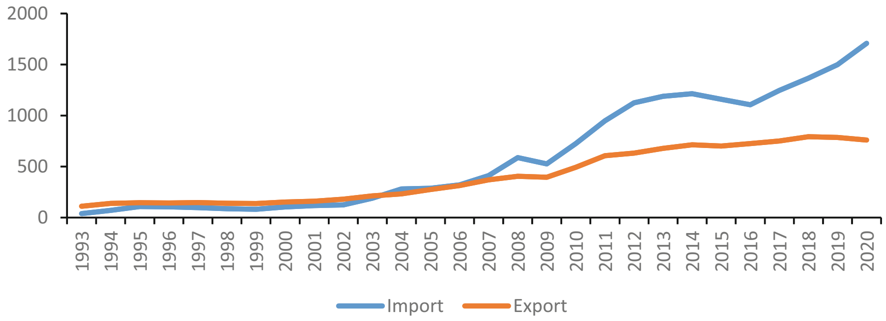


Fig. 6 China's agricultural import and export (million US$), 1993–2020 Source: National Bureau of Statistics and China Customs

While increasing trade has improved China's food security greatly, it may also bring uncertainty and risks, as seen during the China-USA trade disputes. Meanwhile, the persistent COVID-19 pandemic imposes additional uncertainty on international agricultural trade.

5 Future Strategies and Policies

5.1 New Vision Towards Better Food Systems

To facilitate food system transformation, China has recently released the Fourteenth Five-Year Plan (2021–2025) and "National Food and Nutrition Guideline toward 2035" under the National Strategy of Rural Revitalization. There are two important shifts:

- National development aims to establish "a well-off society in an all-round way" through the Rural Revitalization Strategy.
- Agriculture and rural development shifts its focus towards developing more efficient, green, inclusive and sustainable food systems.

5.2 National Food Policies Towards 2035

The following four major national food policies have been initiated to ensure successful food system transformations.

- To ensure food security as the bottom line by enforcing the strategies of "Store Grains (food) in Land" (or imposing red lines on cultivated land area and improving land productivity) and "Store Grains (food) in Technology" (or raising production capacity through technological innovation). By introducing the "Food Security Law," China is actively working to stabilize land areas to ensure grain production of 650 million tons (roughly equal to the 2018 level) by 2025.

- To facilitate the transformation of agricultural production and food consumption in safe, green and sustainable directions by developing ambitious action plans for achieving peak carbon dioxide emissions by 2030 and carbon neutrality by 2060.
- To make an overall plan for increasing the resilience of agricultural and food systems, reducing the negative impact of external shocks such as natural disasters, climate change, plant and animal diseases (i.e., COVID-19), market uncertainties, etc.
- To develop new technologies (e.g., biotechnology and ICT) that increase agricultural productivity, developing digital agriculture and extending the value chain of agricultural and food products.

5.3 Recommendations: Strengthening Institutions, Policies and Investment Using a Food Systems Approach

- Given that there are a wide range of issues and multiple dimensions of food systems from production to consumption, the government should consider establishing a new leading group to coordinate policies and investments in food systems at the national and local levels. With this leading group, the following efforts by the government and their efficiencies will be further improved:
  - Governance capacity to develop more healthy, efficient, green, inclusive and sustainable food systems in general, and addressing issues of small farm modernization, food safety, and scarcity of land and water in particular;
  - Efforts to improve management of the emergency food supply in response to external shocks;
  - Efforts to raise awareness of healthy diets and combat food loss and waste along the value chain.
- Enhance productivity of whole food systems through a more innovative science and technology system.
  - Increase and prioritize agricultural R&D investments in breeding technologies for crops, livestock and fish, and in agricultural inputs (including farming machinery, fertilizers and chemicals, irrigation, processing, storage, etc.);
  - Provide more incentives for the private sector to participate and encourage public-private partnership in agricultural R&D and extension activities.
- Further increase investment in restoring natural resources (e.g., land and water) and enhancing their productivity, as well as in the sustainable use of agricultural and food infrastructure (e.g., irrigation, transportation, etc.), and reduce the costs related to transportation, marketing and food consumption;

- Promote institutional reforms to facilitate land consolidation, help small farms that are moving up or those that are being abandoned, expand the machinery custom service, and develop more effective farmer cooperatives.
- Build a modern circulation system for agricultural products to improve inclusiveness, efficiency, nutrition, and food safety from "seed to fork." In addition to investment, this requires further reforming agricultural markets, stabilizing food prices, expanding and enhancing the agricultural insurance system to mitigate natural and market risks, establishing the integrative protection system against pests and animal diseases, making full use of E-commerce to extend the value chain from sustainable production in the fields to consumption, and mainstreaming healthy and sustainable diets into the national development strategy.
- Promote green food system transformation and sustainable development to create a balance between agricultural growth and sustainable development.
  - Invest in climate-smart agricultural technology and the subsequent adoption of sustainable agricultural practices;
  - Enforce agro-environmental legislation and regulations to strengthen natural resource management and, in particular, to hold the red line of cultivating land for sustainable food production.
- Improve the social protection system. Major efforts should be made to enhance the current social protection system in rural areas and less developed regions.
- Strengthen international cooperation to improve food security in China, as well as in the world.
  - Diversify agricultural imports from various countries and enhance trade along the Belt and Road countries;
  - Enhance partnership with CGIAR to use science to transform Chinese and global food systems for achieving both human and planetary health;
  - Participate in global governance around the agricultural and food trade;
  - Increase investment in and share the development experience and agricultural technologies with other developing countries through South-South cooperation.

Acknowledgements We would like to thank Ms. Jiajia Wang and Ms. Zhuanlin Wang (SAAS, PKU) for their execellent research support.

References

Anderson K, Huang J, Ianchovichina E (2004) Will China's WTO accession worsen farm household income? China Econ Rev 15:443–456

Babu S, Huang J, Venkatesh P, Zhang Y (2015) A comparative analysis of agricultural research and extension reforms in China and India. China Agri Econ Rev 7(4):541–572

Chai Y, Pardey PG, Chan-Kang C, Huang J, Lee K, Dong W (2019) Passing the food and agricultural R&D buck? The United States and China. Food Policy 86:101729
Chen K, Bi J, Niu F, Fang X, Fan S (2019) Nu.2019. New vision and policy recommendations for nutrition oriented food security in China. Scientia Agricultrua Sinica 52(18):3097–3107
Cheng X, Wang J, Chen K (2021) Elite capture, the "follow-up checks" policy, and the targeted poverty alleviation program: evidence from rural western China. J Integr Agri:20–880
China's Ministry of Commerce (2020) China E-commerce report 2019
Cho K, Tobias D (2010) Improving market access for small and mid-sized producers through food industry electronic infrastructure MarketMaker. Federal Reserve Bank of St Louis, St. Louis
CNARCC (Committee of National Assessment Report on Climate Change) (2011) National Assessment Report on climate change (in Chinese). Science Press, China
Cui X (2018) Economics of climate change, pollution, and adaptation in agriculture. University of California, Davis
De Brauw A, Huang J, Rozelle S (2004) The sequencing of reform policies in China's agricultural transition. Econ Transit 3:427–465
Fan S (1991) Effects of technological change and institutional reform on production growth in Chinese agriculture. Am J Agric Econ 73:266–275
Fan S (1997) Production and productivity growth in Chinese agriculture: new measurement and evidence. Food Policy 22(3):213–228
Fan S, Cho E (2021) Paths out of poverty: international experience. J Integr Agric 20(4):857–867
Fan S, Swinnen J (2020) International Food Policy Research Institute. 2020. 2020 global food policy report: building inclusive food systems. International Food Policy Research Institute, Washington, DC
Fan S, Teng P, Chew P, Smith G, Copeland L (2021) Food system resilience and COVID-19: lessons from the Asian experience. Glob Food Sec 28:1–7
Fang J, Yu G, Liu L, Hu S, Chapin FS (2018) Climate change, human impacts, and carbon sequestration in China. Proc Natl Acad Sci 115(16):4015–4020
FAO (Food and Agriculture Organization of the United Nations) (2020) Transforming Food Systems for Affordable Healthy Diet
Hamad H, Elbeltagi I, El-Gohary H (2018) An empirical investigation of business-to-business e-commerce adoption and its impact on SMEs competitive advantage: the case of Egyptian manufacturing SMEs. Strateg Chang 27(3):209–229
Hu R, Huang J (2011) The development and reform of agricultural research system: policy evaluation and recommendations. Sci Soc 3:34–40
Huang J, Ding J (2016) Institutional innovation and policy support to facilitate small-scale farming transformation in China. Agric Econ 47(S1):309–317
Huang J, Rozelle S (1996) Technological change: the re-discovery of the engine of productivity growth in China's rice economy. J Dev Econ 49:337–369
Huang J, Rozelle S (2006) The emergence of agricultural commodity market in China. China Econ Rev 17:266–280
Huang J, Shi P (2021) Regional rural and structural transformations and farmer's income in the past four decades in China. China Agri Econ Rev, vol 13, p 278
Huang J, Rozelle S, Pray C (2002) Enhancing the crops to feed the poor. Nature (London) 418(6898):678–684
Huang J, Rozelle S, Chang M (2004) Tracking distortions in agriculture: China and its accession to the World Trade Organization. World Bank Econ Rev 1:59–84
Huang J, Yang J, Xu Z, Rozelle S, Li N (2007) Agricultural trade liberalization and poverty in China. China Econ Rev 18:244–265
Huang J, Rozelle S, Zhu X, Zhao S, Sheng Y (2020) Agricultural and rural development in China during the past four decades: an introduction. Aust J Agric Resour Econ 64(1):1–13
Jamaluddin N (2013) Adoption of E-commerce practices among the indian farmers, a survey of Trichy District in the state of Tamilnadu, India. Procedia Econ Finan 7:140–149

Jiao X, He G, Cui Z, Shen J, Zhang F (2018) Agri-environment policy for grain production in China: toward sustainable intensification. China Agri Econ Rev 10(1):78–92

Jin S, Huang J, Hu R, Rozelle S (2002) The creation and spread of technology and total factor productivity in China's agriculture. Am J Agric Econ 84:916–930

Jin S, Meng E, Hu R, Rozelle S, Huang J (2008) Contribution of wheat diversity to total factor productivity in China. J Agric Resour Econ 33(3):449–472

Jin S, Ma H, Huang J, Hu R, Rozelle S (2010) Productivity, efficiency and technical change: measuring the performance of China's transforming agriculture. J Prod Anal 33:191–207

Li W, Cui Y, Zhan H 2013 China's agriculture and agricultural policy in the next decade (2012–2022) – Inspiration from international comparison. Consultant report under Asian Development Bank TA-7306-PRC: Policy Study on Government Public Expenditure in Agricultural Production

Li D, Zeng L, Chen N, Shan J, Liu L, Fan Y, Li W (2014) A framework design for the Chinese national disaster reduction system of systems (CNDRSS). Int J Digit Earth 7(1):68–87

Li L, Zeng Y, Ye Z, Guo H (2020a) E-commerce development and urban-rural income gap: evidence from Zhejiang province, China. Pap Reg Sci 100:475

Li L, Lin J, Turel O, Liu P, Luo X (2020b) The impact of E-commerce capabilities on agricultural firms' performance gains: the mediating role of organizational agility. Ind Manag Data Syst 120: 1265

Li S, Dong Y, Zhang L, Liu C (2021) Off-farm employment and poverty alleviation in rural China. J Integr Agric 20(4):943–952

Lin J (1992) Rural reforms and agricultural growth in China. Am Econ Rev 82(1):34–51

Liu KT (2017) Government reform, public governance, and Chinese economic development. J Chin Gov 2(3):255–270

Liu Y, Liu J, Zhou Y (2017) Spatio-temporal patterns of rural poverty in China and targeted poverty alleviation strategies. J Rural Stud 52:66–75

Liu S, Wang R, Shi G (2018) Historical transformation of china's agriculture: productivity changes and other key features. Chin World Econ 26(1):42–65

Lohmar B, Wang JX, Rozelle S, Huang JK, Dawe D (2003) China's agricultural water policy reforms: increasing investment, resolving conflicts, and revising incentives, Agriculture Information Bulletin Number 782. Market and Trade Economics Division, Economic Research Service, US Department of Agriculture, Washington, DC

Lu Y, Jenkins A, Ferrier RC, Bailey M, Gordon IJ, Song S, Zhang Z (2015) Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci Adv 1(1)

Luan L, Jiang Y, Cheng M, Dini-Andreote F, Sun B (2020) Organism body size structures the soil microbial and nematode community assembly at a continental and global scale. Nat Commun 11(1):6406

Luo X, Zhu N (2008) Rising income inequality in China: a race to the top. World Bank, Washington, DC

Ma W, Zhou X, Liu M (2020) What drives farmers' willingness to adopt e-commerce in rural China? The role of Internet use. Agribusiness 36(1):159–163

McMillan J, Whalley J, Zhu L (1989) The impact of china's economic reforms on agricultural productivity growth. J Polit Econ 97(4):781–807

NBSC (National Bureau of Statistics of China) (2020) China statistical yearbook 2020. Beijing. China Statistics Press

NHFPC (2020) Report on diabetes prevention and control. Beijing

Nie F, Bi J, Zhang X (2010) Study on China's food security status. Agri Agri Sci Procedia 1:301–310

OECD/FAO (2022) OECD-FAO Agricultural Outlook 2022–2031. OECD Publishing, Paris. https://doi.org/10.1787/f1b0b29c-en

Okoli C, Mbarika V, McCoy S (2010) The effects of infrastructure and policy on e-business in Latin America and Sub-Saharan Africa. Eur J Inf Syst 19(1):5–20

Oreglia E, Srinivasan J (2016) Intermediaries, cash economies, and technological change in Myanmar and India. eScholarship
Popkin BM (2008) Will China's nutrition transition overwhelm its health care system and slow economic growth? *Health Affairs* 27(4):1064–1076
Qi J, Zheng X, Guo H (2019) The formation of Taobao villages in China. China Econ Rev 53:106–127
Rahayu R, Day J (2017) E-commerce adoption by SMEs in developing countries: evidence from Indonesia. Eurasian Bus Rev 7(1):25–41
Rao S, Liu X, Sheng Y (2020) China's agricultural trade: an analysis based on the global comparative advantage. China update 2020. ANU Press
Rosenzweig C, Mbow C, Barioni LG, Benton TG, Herrero M, Krishnapillai M, Liwenga ET, Pradhan P, Rivera-Ferre MG, Sapkota T, Tubiello FN, Xu Y, Mencos Contreras E, Portugal-Pereira J (2020) Climate change responses benefit from a global food system approach. Nat Food 1(2):94–97
Rozelle S, Hell N (2020) Invisible China: how the urban-rural divide threatens China's rise. University of Chicago Press, Chicago
Rozelle S, Swinnen J (2004) Success and failure of reform: insights from the transition of agriculture. J Econ Lit 42(3):404–456
Rozelle S, Guo L, Shen M, Hughart A, Giles J (1999) Leaving China's farms: survey results of new paths and remaining hurdles to rural migration. China Q (London) 158(158):367–393
Rozelle S, Park A, Huang J, Jin H (2000) Bureaucrat to entrepreneur: the changing role of the state in China's grain economy. Econ Dev Cult Chang 48(2):227–252
Sheng Y, Ding J, Huang J (2019) The relationship between farm size and productivity in agriculture: evidence from maize production in northern China. Am J Agric Econ 101(3):790–806
Sheng Y, Tian X, Qiao W, Peng C (2020) Measuring agricultural total factor productivity in China: pattern and drivers over the period of 1978–2016. Aust J Agric Resour Econ 64(1):82–103
Sicular T (1988) Plan and market in China's agricultural commerce. J Polit Econ 96(2):283–307
State Council (2020) Report on nutrition and chronic diseases in China (2020). Beijing
Stone B (1988) Developments in agricultural technology. China Q 116:767–822
Uncomtrade (2020) Global agricultural trade data by commodities. UN Comtrade Database
von Braun J, Afsana K, Fresco L, Hassan M, Torero M (2021) Food systems-definition, concept and application for the UN food systems summit
Wang J, Xu Z, Huang J, Rozelle S (2005) Incentives in water management reform: assessing the effect on water use, productivity and poverty in the Yellow River Basin. Environ Dev Econ 10:769–799
Wang JA, Shi PJ, Yi XS, Jia HC, Zhu LY (2008) The regionalization of urban natural disasters in China. Nat Hazard 44(2):169–179
Wang J, Huang Q, Huang J, Rozelle S (2016a) Managing water on China's farms: institutions, policies and the transformation of irrigation under Scarcity. Academic, London
Wang J, Zhang L, Huang J (2016b) How could we realize a win–win strategy on irrigation price policy? Evaluation of a pilot reform project in Hebei Province, China. J Hydrol 539:379–391
Wang J, Jiang Y, Wang H, Huang Q, Deng H (2019) Groundwater irrigation and management in northern China: status, trends, and challenges. Int J Water Resour Dev 36:670
Wang J, Zhu Y, Sun T, Huang J, Zhang L, Guan B, Huang Q (2020) Forty years of irrigation development and reform in China. Aust J Agri Resour Econ 64(1):126–149
WHO (2020) Overweight and obesity. https://www.who.int/health-topics/obesity#tab=tab_1
World Bank (2016) The Taobao villages as an instrument for poverty reduction and shared prosperity. World Bank, Washington, DC
World Bank (2020) Percentage of undernourishement in China. The World Bank Data.
Xie J, Liebenthal A, Warford JJ, Dixon JA, Wang M, Gao S, Wang S, Jiang Y, Ma Z (2009) Addressing China's water scarcity: recommendations for selected water resource management issues. The International Bank for Reconstruction and Development, The World Bank, Beijing

Xu Y (2016) From E-commerce to she-commerce: the rise of she-era?: a small-scale case study on female entrepreneurs on Taobao in China

Yan K (2016) Poverty alleviation in China. Springer, Berlin

Yang W, Lu J, Weng J, Jia W, Ji L, Xiao J, Shan Z, Liu J, Tian H, Ji Q, Zhu D, Ge J, Lin L, Chen L, Guo X, Zhao Z, Li Q, Zhou Z, Shan G, He J (2010) Prevalence of diabetes among men and women in China. N Engl J Med 362:1090–1101

Yi Q, Chen M, Yu S, Huang J (2019) Mechanization services, farm productivity and institutional innovation in China. China Agri Econ Rev 11(3):536–554

Yu H, Cui L (2019) China's E-commerce: empowering rural women. China Q 238:418–437

Zapata SD, Isengildina-Massa O, Carpio CE, Lamie RD (2016) Does E-commerce help farmers' markets? Measuring the impact of MarketMaker. J Food Distrib Res 47(856-2016-58222):1–18

Zhang X, Fan S, Zhang L, Huang J (2004) Local governance and public goods provision in rural China. J Public Econ 88:2857–2871

Zhang K, Xu D, Li S, Zhou N, Xiong J (2019) Has China's pilot emissions trading scheme influenced the carbon intensity of output? Int J Environ Res Public Health 16(10):1854

Zhao L, Liu D, Yu D, Zhang J, Wang J, Zhao W (2018) Challenges brought about by rapid changes in Chinese diets: comparison with developed countries and implications for further improvement. Biomed Environ Sci 31(10):781–786

Zhao Q, Zhang B, Yao Y, Wu W, Meng G, Chen Q (2019) Geodetic and hydrological measurements reveal the recent acceleration of groundwater depletion in North China plain. J Hydrol (Amsterdam) 575:1065–1072

Key Areas of the Agricultural Science Development in Russia in the Context of Global Trends and Challenges

Nadezhda Orlova, Evgenia Serova, Vladimir Popov, and Marina Petukhova

1 Introduction

Current world food systems are entering a fundamentally new stage of technological development, which is called Agriculture 4.0 and is based on the introduction of "smart" solutions (robotics, "precision" agriculture, IoT (Internet of Things)), biotechnologies and alternative sources of raw materials. Elaboration of the scientific potential and introduction of innovative solutions are becoming critical to ensuring the competitiveness and further progressive development of the Russian agrifood sector, whereby the next decade of the Russian agrifood sector will be determined by the impact of the following trends:

- the transition to a new technological mode: in the future, the key factor in food production will be technologies that increase productivity and prevent losses;
- changes in value chains: the value added will increasingly be concentrated in knowledge-intensive sectors (genetics and breeding, the IT (Information technology) sector, industrial design and engineering);
- the growing influence of large integrator companies, which are the engines of introduction for innovative technologies;
- the shift in demand from traditional foods to products corresponding to the values of new generations, who prefer ready-to-eat food and products from improved and predetermined properties, and who also place increasing importance not only

N. Orlova (✉) · M. Petukhova
Department for Economics of Innovation in Agriculture, Institute for Agrarian Studies, HSE University, Moscow, Russia
e-mail: nvorlova@hse.ru

E. Serova
Agricultural Policy, HSE University, Moscow, Russia

V. Popov
Russian Academy of Sciences, Research Centre of Biotechnology RAS, Moscow, Russia

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_42

on the products' "benefits and safety," but also on their origin, the sustainability of their technologies and the ethics of their production;

- factors pointing to strengthened sustainability and product safety: strengthening and increasing the number of relevant standards and certification systems;
- transition to the knowledge economy: the process of digital transformation and growing robotization will radically change the employment structure.

In parallel with these trends, there are a number of challenges in the Russian agrifood sector, a timely response to which will allow domestic producers to enter new markets for products and technologies. Among the economic challenges, we can highlight the growing demand for food against the background of a slowdown in production growth with a simultaneous reduction in resources, and the concentration of the population in large cities, which leads to an aggravation of the problem of furnishing urbanized areas with an uninterrupted supply of food, as well as that of large-scale food waste and loss.

Despite the high level of availability of the country's basic resources (fertile soils, fresh water) and the average low negative effects of global warming, the development of the Russian agrifood sector is increasingly influenced by natural and climatic challenges and the subsequent decline in the agro-climatic potential of the planet; the reduction of natural breeds and variety diversity in agriculture; and the degradation of agricultural land, which threatens the sustainable development of the rural sector. All future areas of scientific research with the potential to have a key impact on the sustainable growth of the national agrifood sector should be based on needs related to climate change.[1]

One of the technological challenges involves spreading the principles of sustainable agrifood production and food consumption.

Agrifood production directly interacts with the environment, which creates environmental challenges including the loss of biological productivity of the world's oceans and NNN (non-legal, non-regulated, and non-reported (NNN)) fishing, the growth of animal waste, and the destruction of ecosystems as a result of the use of chemical plant protection products.

It is important to consider the value challenges in modern Russia, among which we can highlight the growing popularity of a healthy lifestyle and personalized diets, public resistance to the technologies of genetic engineering, modification and cloning, and the strengthening of public activity against cruelty to animals. Furthermore, social challenges such as the stratification of the population in terms of income and access to healthy food products and the lag in development between the rural areas and cities have a significant impact on the development of the Russian agrifood sector. The answer to these challenges should be the creation and implementation of innovative technologies in production. Thus, we can identify the following priority

[1] Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty/V. Masson-Delmotte et al. IPCC, 2018.

areas for the development of agricultural science in Russia in the context of the national refraction of global trends and challenges.

2 Biotechnologies

The high relevance of biotechnology in the modern scientific and technological landscape of the Russian agrifood sector is determined by its ability to respond to the global challenges of our time, especially ensuring food security and addressing environmental problems. In regard to the problems of man-made environmental pollution, soil degradation, and the growing number of chronic diseases of the country's population caused by the unfavorable environmental situation, the importance of biotechnologies continues to increase.

The biotechnology researches meet all of the requirements of Russia's sustainable development in terms of ensuring food security, obtaining high-quality, environmentally friendly products, processing agricultural waste, and restoring soil fertility. The driver of the development of biotechnologies in agriculture is the increasingly growing trends of Russian citizens maintaining a healthy lifestyle, seeking responsible consumption and caring for the environment.

Currently, in Russia, the practice of processing waste into bio-products has become most widespread in the production of solid biofuels (waste from crop production and woodworking) and feed protein (waste from pulp, paper and alcohol production, such as brewing and grain processing).

In addition, biotechnologies play an important role in the prevention and treatment of infectious animal diseases. Without biotech, Russian agrifood production will continue to be highly cost-ineffective and will lose out in regard to the competitiveness of its products in world markets. Currently, the Russian market of biotechnologies, in comparison to the European markets, is in a nascent state, and its largest segments are biotechnological feed additives, immunobiological preparations and biologics for crop production (the fastest growing segment). At the same time, the dependence on imports in this market is very high – 83%. Therefore, it is necessary to develop our own agrobiotechnologies in the following key areas:

2.1. Technologies for breeding plant varieties that are resistant to pests and adverse environmental factors. For example, selection methods based on the use of molecular markers, new-generation varieties, and hybrids that are resistant to drought, diseases, herbicides, and insect pests (Springer and Schmitz 2017).
2.2. Biological protection products, microbiological fertilizers and plant growth regulators that reduce the residues of the active substance in the final product, reduce the environmental burden on ecosystems and ensure the long-term competitiveness of the sector.
2.3. Biological products and feed additives in livestock. Development of the production of feed protein and functional additives to improve feed quality and

increase productivity in livestock, as well as technologies that reduce the use of feed antibiotics.

2.4. Technologies for processing animal waste. With the help of bacteria, the processing of organic waste can be significantly sped up, reducing both the cost of creating organic fertilizers and the environmental damage from agricultural production. Microbiological conversion allows us to process various waste products into feed protein with improved qualities.
2.5. Biological products for livestock. Creation of immunobiological medicines for veterinary use employing local strains of microorganisms that have been isolated in Russia.
2.6. Technologies of soil bioremediation and biofertilization. The introduction of bacteria into the soil can significantly improve its quality and productivity.
2.7. Technologies for the deep processing of feedstock used in the production of bioplastics.

3 Precision Agriculture

Russia's significant lag behind the leading countries in terms of productivity and relatively high volatility (primarily in crop production), as well as the need to ensure the global competitiveness of the Russian agrifood sector and reduce food losses, requires the activation of a transition to a new technological stage, including the introduction of "smart" technologies that make agriculture more accurate and controlled and that are focused on making decisions based on the needs of individual animals or plants.

In crop production, the use of precision farming technologies allows us to optimize the consumption of fertilizers and plant protection products and increase crop yields. In livestock, RFID (Radio Frequency IDentification) technologies make it possible to obtain the maximum amount of information about the livestock population, including its accounting, movement, feeding, vaccination, etc. (Ustundag and Cevikcan 2018). Given the limited resources available, the use of digital technologies is essential to improving the efficiency of agrifood production. The main areas of digitalization of the Russian agrifood sector include:

3.1. Development of precision farming technologies based on IoT (Internet of Things). Obtaining real-time data on plants, animals, machinery, soil, and air allows us to make more informed decisions about production (Marchiol 2018).
3.2. Technologies of digital systems that operate with "big data" and allow us to make more informed decisions that take into account weather forecasts, the probability of diseases, the state of soils and plants, yield estimates, and many other factors within a single model. They also allow us to design agricultural systems based on the principles of biologization, resource conservation, and environmental and sanitary-epidemiological safety.

3.3. Technologies of automated agricultural machinery and integrated management systems based on a combination of sensor (IoT) technologies, telematics, robotics and artificial intelligence.

4 Selection and Genetics in Crop Production and Livestock

The recent discoveries in the field of genome research and the introduction of post-genomic technologies are already radically changing the face of world agriculture and creating new factors of competitiveness. Russia lags behind in the field of both research and implementation of modern technologies of genetics and breeding, which determines a high degree of dependence on foreign genetic material, which risks reducing the global competitiveness of the Russian agricultural sector. Russia's import dependence on corn seeds reached 62%, 73% for sunflower, and 98% for sugar beet. Import dependence on breeding material of cattle and poultry is also high. When creating new genetic lines of meat breeds, only imported breeding genetic material is used.

The strengthening of selection and genetic research in these industries is one of the areas of highest priority for their development. The main topics of research work in this field include:

4.1. Creation of databases of genetic resources that form the basis of knowledge about hereditary variability and are a reference for the identification of new mutations and a source of valuable source material for breeding.
4.2. Development and implementation of genomic assessment tools and creation of Russian varieties and hybrids, as well as pure lines of highly productive animal breeds that correspond to the real economic and agro-climatic conditions of the agrifood sector.
4.3. Methods of accelerated selection (marker-oriented, microclonal reproduction in vitro), which significantly reduce the time of breeding of new varieties and hybrids of plants.
4.4. Technologies for breeding plant varieties that are resistant to pests and adverse environmental factors. With the help of biotechnological innovations, for example, selection methods based on the use of molecular markers, new-generation varieties and hybrids are created that are resistant to drought, diseases, herbicides, and insect pests.

5 Food Processing Technologies

Popularization of healthy food has become one of the strategic national tasks of Russia. In the period from 2010 to 2018, the number of people suffering from obesity in Russia almost doubled, exceeding two million people (1.4% of the population). At the same time, the highest specific rate of obesity within the population is observed in the cohorts of children (0–14 years) and adolescents (15–17 years): 375 and 763 per 100 thousand, respectively (for comparison, it is 304 per 100 thousand for the entire population). In the period from 2010 to 2020, the number of patients diagnosed with diabetes increased by 61% to 5.1 million people. 63% of deaths in Russia are associated with diseases arising from poor nutrition.

At the same time, the transition to a healthy diet in Russia is favored by the current socio-demographic structure, which is marked by a high level of urbanization (up to 75%), the share of the educated population (over 60% have a tertiary education), and the level of income in the largest urban agglomerations comparable to most countries in Eastern Europe. But the results of sociological research also show a rapidly growing interest of Russian consumers in healthy food in a significant proportion of the rest of the population, which is already guided by the relevant principles in the choice of products.

The following areas of scientific research are critical from the point of view of further development of food systems in Russia:

5.1. Biotechnologies for the production of food additives and enzyme products based on methods of microbial synthesis, including the use of mutant and genetically modified microorganisms; the creation of innovative domestic probiotics and starter cultures for the food industry; medical and biological studies of their safety (Ordovas et al. 2018).
5.2. Creation of mass consumption products enriched with essential nutrients and functional and specialized (therapeutic and preventive) food products that allow for correcting violations of the nutritional status, preventing the occurrence of certain diseases, promoting the growth and development of children, and slowing down the aging of the body.
5.3. New sources of protein derived from the biomass of microorganisms based on biotechnologies that allow for the conversion of low-value waste into protein products and components with high added value. Scientific support for a comprehensive sanitary and epidemiological assessment of the quality and safety of sources of their production, as well as assessment of the impact of these products and secondary products of their processing on the human environment, including microbiological and toxicological-hygienic studies.
5.4. Development of food engineering to create a new generation of probiotic products designed to maintain and preserve the normal human microbiota, so as to promote the formation of a healthy food market in Russia.
5.5. Technologies for the production of synthetic food products with high protein value from non-traditional natural food raw materials. Development of methods for the deep processing of raw materials of plant and animal origin, based on microbial synthesis and biocatalysis. Implementation of biotechnological methods for low-waste and resource-saving production, such as the processing of food industry waste and the recycling of food packaging, including non-food products.
5.6. Biotechnologies for the establishment of organic agriculture and the obtainment of organic food products, taking into consideration the requirements and

restrictions imposed on the use of fertilizers, plant protection products, and veterinary drugs.

A separate segment of the agrifood sector in Russia is the fishing industry. Russia has rich aquatic biological resources and is one of the world leaders in terms of fish and seafood exports. The share of exports from the volume of production in physical terms over the past five years has varied from 38.9% to 41.0%. Fish products, as a carrier of animal protein with a unique set of amino acids, fatty acids and vitamins not found in such an amount and variety in cereals, meat or other products, take a leading place in ensuring a balanced and healthy diet. Marine pharmacology and biotechnological methods of aquaculture are the most promising areas of research and development in this industry for Russia.

6 Aquaculture

The reduction of fish stocks and their species diversity due to overfishing and water pollution are problems that, in the near future, may become a threat to food security, both for Russia and for many other countries of the world (Barang et al. 2014). Therefore, the main priority of national legislation in this area has become the preservation of aquatic biological resources before their use – the precautionary principle surrounding the use of aquatic biological resources and the assignment of a quota of biological water resources to enterprises. The Russian fishing industry has received guarantees of the initial production resource. Therefore, to preserve the aquatic biological resources of our country, it is necessary to develop aquaculture in the following areas:

6.1. Development of recycled aquaculture (fish farming in completely closed, controlled conditions). Water recycling in aquaculture farms can ensure high and stable production of aquaculture products with a lower risk of disease. At the same time, modern methods of recycling significantly reduce the adverse impact on the environment compared to traditional methods of fish farming.
6.2. Creation of specialized feed for aquaculture, with high levels of protein, lipids, metabolic energy and vitamins, that is also resistant in aggressive aquatic environments.

7 Methods for Reducing Food Waste and Loss

Reducing food waste and loss plays an important role in the development of sustainable food systems around the world. However, Russia has not yet formed a general conceptual view of this problem; the dangers associated with food waste and loss, which go beyond environmental pollution or contamination, are not on the agenda. There is no cooperation among the nation's government, science and business sectors regarding food waste and loss, which is why there have been practically no scientific developments in this direction; existing solutions or technologies for reducing food waste and loss are local, small in scale, and not supported by the government or society as a whole (Global Food Losses and Food Waste 2011).

In addition, there are no reliable statistics on the volume of food waste and loss in Russia. There is a problem of data discrepancy: according to official statistics, the volume of food waste and loss in Russia is 0.6% of food production on average; the expert community considers these indicators to be underestimated by tenfold and points out that, in Russia as a whole, the situation regarding food waste and loss is no better than the global average, which is 30–40% of total production.

Unfortunately, in Russia, this problem is poorly studied and the focus is mainly on the disposal of food waste, rather than ways to reduce loss and waste in the process of production, processing and transportation. In this regard, it is necessary to conduct research in the following areas:

7.1. Development of methods for calculating food waste and loss throughout the entire food supply chain.
7.2. A survey of the food supply chains themselves to identify and classify the main causes of food waste and loss at all stages, as well as to develop methods for reducing them.
7.3. Development of innovative methods for storing fruit products in a controlled atmosphere.
7.4. Study of the use of methods of ionizing radiation treatment of agricultural raw materials to improve their shelf life and quality.

In addition, it is necessary to identify barriers to the introduction of advanced technologies, including restrictions present in the regulatory framework, as well as issues of costs and payback for the use of these technologies within a particular enterprise.

8 Closed Farming Systems

Russia has huge resources: our country accounts for about 10% of the global arable land fund, and it is one of the world leaders in terms of fresh water reserves. However, these resources are distributed across the country: a significant part of the agricultural area has low fertility and is located in the zone of risky farming. In turn, the main reserves of fresh water are concentrated in the northern part of the country, which is not suitable for agricultural development, while the southern agricultural regions face the threat of a shortage of water for irrigation.

In addition, Russia is a country with a high level of urbanization (up to 75%), while almost 25% of Russians live in cities with a population of more than one million people. The largest urban agglomerations are located at a considerable distance from the key centers of agricultural production and are increasingly competing with local centers for land and water resources (World Urbanization Prospects

2019). Another 2.4 million people live in the Arctic zone, which is dependent on external food supplies. Providing residents of megacities and remote regions with food products now requires the involvement of significant logistics resources, creates an additional environmental burden, and makes a significant contribution to the volume of food losses.

The transition to agricultural production in closed systems, independent of external agro-climatic factors, is also one of the most relevant and promising directions for the development of agricultural science in the context of Russia's Arctic ambitions and the implementation of long-term space programs.

8.1. Vertical farms – creation and improvement of crop production technologies in vertically arranged automated complexes with artificial lighting, heating and air conditioning, closed water circulation and sterile air. Vertical farm technologies will increase the availability of high-quality fresh produce in cities and remote areas and eliminate the seasonal factor, as well as significantly reduce the environmental burden and ensure local food security.
8.2. Non-ground crop production – hydroponics, aquaponics, and aeroponics, as well as advanced technologies derived from them (including bioponics and hyponics). Technologies of non-ground crop production allow us to (a) complete the transition of vertical farms to closed systems that do not use traditional agricultural resources; (b) level the weight and size restrictions so that products can be delivered to autonomous objects: ships, Arctic stations, spacecraft, etc.
8.3. Robotic "smart" greenhouses – technologies for integrated monitoring and management of microclimate, lighting, fertigation, and plant protection. Also, automation of processes and manipulations with plants. Technologies allow us to: (a) increase productivity and reduce the costs associated with the use of manual labor; (b) improve the quality of decision-making; (c) increase the level of availability of products for end users.
8.4. Construction of specialized greenhouse complexes adapted to permafrost conditions to provide fresh food to the population of the Far North of Russia.

9 Deep Processing of Agricultural and Fishery Feedstock

To increase the sustainability of the Russian agrifood sector, it is very important to increase the depth of processing of agricultural feedstock, for which there is still a significant gap with global agricultural producers.

The need for the development of deep processing of grain is caused by record harvests of grain crops in Russia, which, in recent years, have led to production volumes that are increasing faster than their consumption in related industries. Every year, about 40% of the country's grain reserves remain unused, which requires expanding the areas of its domestic use, strengthening the potential opportunities for entering international markets.

In addition, the intensive development of livestock in Russia in recent years has provided a significant increase in demand for feed amino acids, which the domestic deep processing industry is not able to meet.

On the scale of the world market of fish and other products from aquatic biological resources, the fisheries complex retains its role as one of the key suppliers of feedstock of the most valuable and popular types of aquatic biological resources. The main buyers of domestic fish and other products from aquatic biological resources are processing enterprises located in the countries of the Asia-Pacific region and the European Union. In some cases, the products produced for final consumption are delivered to the consumer without any indication of the Russian origin of the fish. Thus, Russian suppliers of fish products are deprived of competitive influence on the final sales price and do not participate in the formation of market demand, and also do not receive a significant part of the added value in terms of deep processing, distribution and marketing of fish and other products from aquatic biological resources. Therefore, within the framework of the deep processing of fishery feedstock, the main task is to introduce modern biotechnological methods into the practice of fish-processing enterprises that can provide cost-effective production of a wide range of food ingredients and valuable food products with high added value from hydrobionts. The production of fish meal and fat, fish feed and fish oil deep processing products has the highest growth rates in the global fish industry, due to the need to meet the growing mass demand for products containing protein.

The priorities in research and development in this industry for Russia are:

9.1. Deep processing of agricultural feedstock for the production of feed amino acids, glucose and glucose-fructose syrups, and starch.
9.2. Deep processing of low-value products from the processing of hydrobionts of the fishing industry into products with a high content of free amino acids and lower peptides that have good functional and nutritional properties for use in medicine, microbiology, and the food and feed industry. Extraction of fish oil from secondary feedstock to create functional food products based on it.

The implementation of these directions will allow for the transition from feedstock export-oriented production to the production of products with a deep degree of processing for both domestic consumption and export.

10 Sustainable Development of Agricultural Production and Rural Areas

In order to prevent the destructive consequences of the aggressive intensification of agricultural production in Russia, it is necessary now to translate it into the principles of sustainable development, which are based on the optimal use of limited natural resources, the creation of a "green" economy and the preservation of vast rural areas of our country (Dietz et al. 2018).

To minimize the negative impact of aggressive intensification on the environment, it is necessary to develop research and development in the following areas:

10.1. Technologies of organic agriculture, including methods with minimal impact on the soil, mechanical and biological weed control, and the use of sideral fertilizers and biological products, ensuring a closed cycle of agricultural production "crop production-livestock-crop production."
10.2. Integrated plant protection, safe for the environment and reducing harm to the human organism. Its goal is to maintain a balance between the economic efficiency of production and the environment.
10.3. Soil protection and resource-saving agriculture, which is based on the principles of zero tillage and diversification of crop rotation through various types of crops.
10.4. Biological reclamation technologies for increasing soil fertility and preventing water and wind erosion with the help of grass and woody vegetation.
10.5. Development of bioremediation – a complex of methods for cleaning water, soil and the atmosphere using the metabolic potential of biological objects.
10.6. Development of models for restoring biodiversity and soil productivity.
10.7. Technologies for an adaptive landscape system of agriculture.

11 Veterinary and Phytosanitary Control

In the context of globalization and the expansion of commodity turnover between Russia and other countries, the system of veterinary and phytosanitary control, the purpose of which is to prevent harmful organisms from entering the country, is becoming increasingly important. The problem is aggravated by the negative effect of climate change, against which pests and pathogens of plants and animals are beginning to spread more and more actively beyond their natural habitats (Clapper 2011). The increased risks of epizootic and epiphytotic situations for Russia are associated with the vast territories located in the European and Asian parts of the continent.

The costs of combating them and the resulting food losses can cause significant harm to Russian agriculture and public well-being.

In Russia, about 40 million cases of infectious diseases are registered annually among farm animals, while economic losses from diseases amount to 30%, and the amount of damage is more than $200 million. The following measures need to be adopted:

11.1. Blockchain technologies for tracking the entire path of food production, processing and sale.
11.2. Creation of phytosanitary and veterinary databases and digital platforms for analyzing and predicting the spread of animal and plant diseases.
11.3. Development of systems for the monitoring, diagnosis and prevention of plant and animal diseases.

12 Technologies of the Logging Industry

The technologies of the logging industry are extremely important for Russia, which has more than 20% of the world's forest reserve. The forest complex occupies an important place in the country's economy, due to the performance of important environmental protection and environmental-forming functions. The forest is one of the most valuable renewable natural resources. Such global significance of the Russian forest multiplies the country's responsibility for its conservation and reproduction, especially since it is an ecological framework for our entire planet, a colossal resource for the economy, for economic growth, and for improving the well-being and health of our citizens. To do this, it is necessary to develop research and development aimed at improving the efficiency of forest plantation management, preserving and reproducing forest genetic resources, and protecting forests from various adverse factors, such as with the following:

12.1. Technologies for the protection of forests from fires, pests, diseases and other adverse factors. The use of biological means of protection will help to contain the spread of new dangerous pests and phytopathogens of phytophages in the forests, which negatively affect fire safety there.
12.2. Technologies for predicting the spread and dynamics of the most dangerous pest foci using remote monitoring systems.
12.3. Selection of the main forest-forming species, aimed at accelerating growth, breeding new hybrids and varieties, creating biotechnological forms of trees with specified characteristics, and fostering micro-planar reproduction of genetically valuable tree forms.
12.4. Technologies for processing larch and dry wood, technologies for multi-layer and alternative molding in the production of paper and cardboard, research into the properties of wood-based materials for their use in building, and development and introduction of new wood-based materials through the deep chemical and mechanical processing of feedstock.

The only way to preserve and increase forest wealth is through the sustainable management of forests, preserving their biological diversity, productivity, resilience, viability, and ability to perform important environmental, economic, and social functions at the local, national, and global levels in the present and future.

13 Conclusions

The range of key areas for the development of agricultural science in Russia is very wide and varied, due to the presence of huge potential, both natural and climatic, and because of the human capital of our country. The main goal of all presented research areas will be to provide the population of Russia and the whole world with high-quality food products.

We should look and think one-step ahead to avoid missing the unique "windows of opportunity" for the industry that arise when technological patterns change.

It is necessary to move beyond the idea of agriculture as a very conservative industry of traditional products and technologies, to overcome isolationism in the field of scientific and technological development. The current tasks of catching up in terms of development and strengthening food security should evolve into a higher-order goal: the transition to innovative development, in which we build an effective system for generating new original ideas and supporting their transformation into specific solutions, products and technologies. The scientific and technological development of Russia's agrifood sector in the future will be based on sustainability combined with innovations. The economic, social and environmental efficiency of agribusiness is possible only with the introduction of innovative technologies.

Acknowledgements The authors express special gratitude to the experts who took part in the discussion of the most promising developmental areas for agricultural science and technology in Russia and in the world: Alina Osmakova, Executive Director of the Technology Platform BioTech 2030, Oleg Kobiakov, Director of the FAO Liaison Office with the Russian Federation, Maxim Markovich, Director of the Department of International Cooperation and Agricultural Export Development, Ministry of Agriculture of the Russian Federation, Irina Donnik, Vice-President of the Russian Academy of Sciences, Irina Chernukha, Leading Researcher, Federal Scientific Center for Food Systems named after V.M. Gorbatov, Mikhail Glubokovsky, Scientific adviser, Russian Federal Research Institute of Fisheries and Oceanography, Viktor Tutelyan, Director, Federal Research Centre of nutrition, biotechnology and food safety, Alla Kochetkova, Head of the Laboratory of food biotechnologies and specialized products, Federal Research Centre of nutrition, biotechnology and food safety, Petr Tolmachev, Head of the Department of World Economy of the Diplomatic Academy of the Ministry of Foreign Affairs of Russia.

References

Barang M et al (2014) Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat Climate Change 4:211–216

Clapper JR (2011) Worldwide threat assessment of the US Intelligence Community. U.-S. Intelligence Community Worldwide Threat Assessment

Dietz T et al (2018) Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. Sustainability 10(9). https://doi.org/10.3390/su10093190

Global Food Losses and Food Waste (2011) Extent, causes and prevention. FAO, Rome

Marchiol L (2018) Nanotechnology in agriculture: new opportunities and perspectives. https://doi.org/10.5772/intechopen.74425

Ordovas JM, Ferguson LR, Tai ES, Mathers JC (2018, June) Personalised nutrition and health. BMJ 361:bmj.k2173. https://doi.org/10.1136/bmj.k2173. PMID: 29898881; PMCID: PMC6081996

Springer N, Schmitz R (2017) Exploiting induced and natural epigenetic variation for crop improvement. Nat Rev Genet 18:563–575. https://doi.org/10.1038/nrg.2017.45

Ustundag A, Cevikcan E (2018) Industry 4.0: managing the digital transformation, Springer series in advanced manufacturing. Springer, Cham. https://doi.org/10.1007/978-3-319-57870-5_1

World Urbanization Prospects (2019) The 2018 revision (ST/ESA/SER.A/420). United Nations, Department of Economic and Social Affairs, Population Division, United Nations, New York

Food System in India. Challenges, Performance and Promise

Ashok Gulati, Raj Paroda, Sanjiv Puri, D. Narain, and Anil Ghanwat

1 Introduction

Looking into the future, towards 2030 and beyond, the challenge of feeding India's growing population is going to be a major task. According to the UN Population Prospects (2019), India will be the world's most populous country by 2027, surpassing China. Currently, its population is about 17.7% of the total world population, and it will increase from 1.38 billion (2020) to 1.5 billion in 2030 and 1.64 billion in 2050 (United Nations 2019). By 2030, 600 million Indians are expected to live in urban areas and will require a continuous supply of safe and healthy food from hinterlands. This challenge is further compounded by limited availability and the deteriorating quality of natural resources such as land, water, and air. On top of this is the challenge of climate change, with rising temperatures and greater frequency and intensity of droughts in western and southern India and floods in northern and north-eastern India (IPCC 2018).

A. Gulati (✉)
Indian Council for Research on International Economic Relations (ICRIER), New Delhi, India
e-mail: agulati115@gmail.com

R. Paroda
Indian Council of Agricultural Research (ICAR) and Secretary DARE, Government of India, New Delhi, India

Trust for Advancement of Agricultural Sciences (TAAS), New Delhi, India

S. Puri
National Council on Agriculture, Confederation of Indian Industry (CII), New Delhi, India

ITC Limited (India), Kolkata, India

D. Narain
Bayer Crop Science India and Global Sponsor, Bayer Smallholder Farming, Thane, India

A. Ghanwat
Shetkari Sanghatana (Farmers' Union), Kolhapur, India

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_43

Despite India's economic progress over the past two decades, regional inequality and malnutrition problems persist. Simultaneously, trends in overweight and obesity, along with micronutrient deficiency, portend an emerging public health challenge. There is a need to examine the interactions among India's economic development, agricultural production and nutrition through the lens of a "food systems approach."

Structurally, Indian agriculture is dominated by small and marginal land holdings. About 86.2% of holdings are less than 2 hectares (ha) that account for 47.3% of operated area (Agriculture Census Division 2015–16). And there has been a continuous decline in the average land holding size, from 2.3 ha in 1970–71 to 1.08 ha in 2015–16. This raises a fundamental policy question: how to design a food system that ensures not only sufficient availability of food, feed and fibre for India's large population, but also good nutrition, and that is environmentally sustainable and globally competitive? Achieving all of these goals seems a tall order for any government. But the efforts are on, not by government alone, but also by the large private sector, through long-term multi-stakeholder partnerships. When such partnerships are organised around crop value chain clusters, economies of scale are achieved, thereby improving efficiency and competitiveness. This has resulted in several successes, yet there are still many challenges, and one needs to continuously innovate with new technologies, institutions, and policies for better outcomes. This chapter attempts to do precisely this, dwelling on the holistic approach towards India's food system with a special focus on three aspects:

(i) Is India producing sufficient food, feed and fibre for its population in a globally competitive and environmentally sustainable manner?
(ii) Is India marketing its food with low intermediation costs and low food losses? This refers to post-harvest value chains, from farm to fork.
(iii) Is India producing a sufficient amount of nutritious and safe food for consumers?

We hope that the evidence-based research cited in this chapter will help policymakers make more pragmatic decisions that help in achieving the above goals. Let us address each one of these in some detail, looking at their challenges and their performance in the recent past, and what promise they hold for 2030 and beyond.

2 India's Food System

2.1 Producing Sufficient Food Efficiently with Environmental Sustainability

India is largely a rural economy, with 66% of the country's population living in rural areas (World Development Indicator 2019) and agriculture being the mainstay of this section of the population. The sector employs the largest share of India's working population – about 42% (National Statistical Office 2020) - and contributes 16.5% to the country's gross domestic product (GDP). However, of the total geographical area (of 328.7 million hectares (mha)), nearly half is arable (159.7 mha) and only 42.6% (about 140 mha) is actually cultivated, a number that has remained static over decades, thereby reflecting no scope for horizontal expansion. Hence, in order to feed India's growing population from limited resources, an increase in crop productivity is imperative! This requires investments in agri-R&D and extension (both by the public and the private sectors) and an enabling policy ecosystem. India needs to invest at least 1% of its agri-GDP in agri-R&D against the current level of 0.39% (NIAP 2017). In fact, India's agri-food policy of late has been highly skewed towards subsidies instead of investments (Gulati et al. 2018). In FY 2020–21, as per the Union budget, India's expenditure on agri-R&D (ICAR budget) was a meagre INR 7762 crore (about USD 1.1 billion) (Government of India 2021a). Thus, there lies a huge scope for achieving higher growth momentum, as the marginal returns from expenditures on agricultural research are almost 5 to 10 times higher than through subsidies (Fan et al. 2007). If agricultural growth is to provide food security at a national level, then the expenditure on agri-R&D needs at least to be doubled immediately (Paroda 2019).

To better understand the role of investments and enabling policies in our agri-food system, let us peep into the past and see how India transformed from being largely a food deficit nation to a food surplus one, particularly in the case of staples (wheat and rice), milk, poultry, fish, and, lately, cotton. Lessons from the past will certainly help in defining a clear roadmap towards 2030 and beyond.

2.1.1 Lessons from the Past

Who could have imagined that India, after the Bengal Famine of 1943 that claimed around 3.0 million deaths, not from disease, but starvation (Maitra 1991), and having lived in a situation of 'ship to mouth' during the mid-1960s, with heavy dependence on wheat imports under PL 480 food aid (USA), could one day emerge to be the largest exporter of rice? It also had food grain stocks of 97 million metric tonnes (MMT) in June 2020, almost 2.5 times the buffer stock norms of the country. All of this happened through an infusion of new technology (wheat and rice varieties that are high yielding, dwarf, photo-insensitive and responsive to high inputs) in partnership with CIMMYT and IRRI during the mid-1960s, technology that was then further improved and expanded over time through a domestic network of research and extension under the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUS) (Dalrymple 1975; ICAR 2017). Along with said new technology (such as high yielding variety (HYV) seeds), irrigation, fertilisers, and positive price policy played critical roles in ushering in the green revolution in India. This is a lesson for many developing countries in Africa and Asia that have small holdings and are still aiming to have a green revolution.

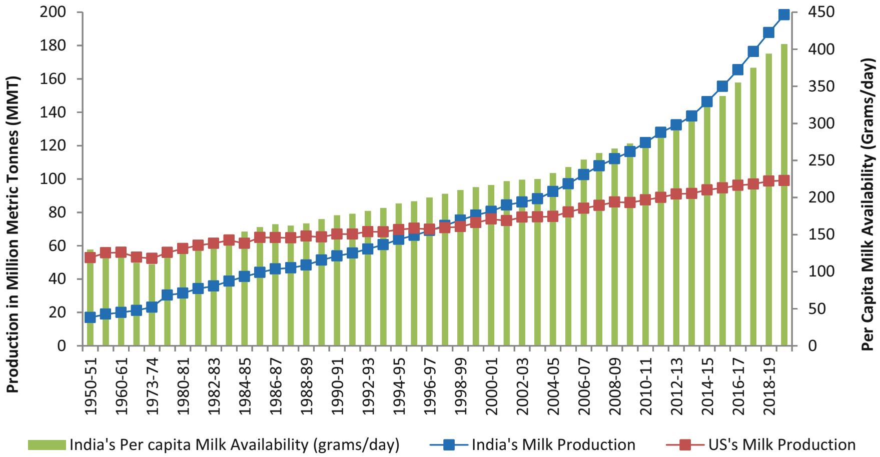


Fig. 1 Milk production in India and the US, and per capita availability in India from 1950–51 to 2019–20. (Source: FAOSTAT 2019 and DoAHD&F 2019)

Along with the green revolution, the country witnessed significant transformation in the dairy sector during the 1970s through the mid-1990s. Verghese Kurien spearheaded `Operation Flood,' which transformed the system of milk collection from smallholders under a co-operative structure, homogenising, pasteurising and distributing it to mega-cities as far as 1800 kilometres away in bulk coolers designed to keep the temperature controlled at 3.9 degrees Celsius, through an organised retail network. Subsequently, de-licensing of the dairy sector, in 2002, encouraged private enterprises in a big way, leading to accelerated growth in production and processing. As a result, India emerged as the world's largest milk producer, with 208.0 MMT in 2020/21, up from 17.0 MMT in 1950–51 (Fig. 1), leaving the United States of America (99 MMT) and China (45 MMT) way behind. And all of this was achieved through smallholders with 3–4 cows or buffalo. India's per capita milk availability also increased from 110 grams/day in 1973–74 to 407 grams/day in 2019–20 (DoAHD&F 2019), and an estimated 428 grams/day in 2020–21. However, India's productivity of dairy animals is still far below the global standard of 20 litres plus per day (indigenous cows 2.8 litres per day, crossbreeds 7.5 litres, and buffalo 5.2 litres). Improving milk productivity through genetic enhancement and better fodder and feed availability are the ways forward! This is another major lesson for smallholder-dominated agricultural economies as to what smallholders can do with the right institutional innovations, including needed policy support and building value chains from farm to fork.

Besides dairy, India's poultry sector also witnessed revolutionary transformation from backyard poultry farming to an organised commercial poultry industry, largely driven by the private sector. What was particularly successful was the indigenous pure-line breeding that used germplasm of a foreign strain, leading to genetic improvement and the spread of vertical integration and contract farming practices among the small and marginal holders. As a result, the sector experienced the fastest average annual growth, reaching 9.2% between 2000/01 and 2018/19, and emerged as the third largest producer of eggs (103.3 billion) and the fifth largest producer of broiler meat (4 MMT) in the world (2018/19).

In 2002, the introduction and commercialisation of Bt (Bacillus thuringiensis) cotton (the only genetically modified crop in India so far), along with huge investments in R&D by private seed companies, ushered in the famous Gene Revolution in the agricultural sector. This led to a breakthrough in cotton production, rising from 13.6 million bales in 2002/03 to 37.5 million bales in 2019/20 (Directorate of Economics and Statistics 2020), with India surpassing China (in 2014/15) to become the largest cotton-producer in the world. The effect of fertilisers, Bt technology and insecticides contributed to 60, 23 and 17 percent of cotton yield, respectively, in India (Paroda and Joshi 2017). The benefit of Bt technology for cotton is estimated to be USD 84.7 billion (cumulatively between 2002–03 to 2018–19) through savings in imports of cotton, as well as extra exports of raw cotton and yarn compared to the business-as-usual scenario.

Over the last five decades, India has experienced an impressive growth trajectory from a food scarce country to a food sufficient one, and then to a food surplus one. All of these revolutions in agricultural production were triggered due to a scaling of innovations, well supported by the right incentives and institutions. Today, India is a net exporter of agricultural produce. As a result, agricultural exports, in nominal US dollar terms, have increased significantly from USD 6.1 billion in 2001/02 to USD 43.6 billion in 2013/14. Imports also increased during this time, and stood at USD 18.9 billion in 2013–14. Thus, there was a net surplus in agri-trade accounting to the tune of USD 24.7 billion in 2013–14, indicating that Indian agriculture has become globally competitive. But after 2013–14, exports slipped down a bit as global prices took a downward turn while imports kept increasing. As a result, the net surplus on the agri-trade front was down to about USD 16 billion in 2018–19. Overall, agricultural trade (exports plus imports) as a percentage of agricultural GDP showed an increase from 4.7% in 1990/91 to 20.9% in 2012/13, and thereafter, it slipped from this peak to 15.1% in 2018/19.

2.1.2 Using Lessons of the Past to Create Opportunities for the Future

The lessons from the past always hold promise for what can be done in the future. HYVs and hybrid seed technologies, along with accelerated breeding programmes and vibrant R&D efforts by research institutions and companies both in India and globally, have improved crop yields in corn, vegetables, rice, pearl millet and other crops. However, increased crop productivity is no longer the only end objective today. India's agri-food system is progressing towards an ecosystem-based food system, focusing on end-to-end solutions from agri-inputs to agronomic advisory to market linkages and easy access to finance, credit, etc. Simply increasing crop productivity won't work if farmers don't get the right remunerative prices for their produce (Narain 2020). Therefore, outcome-based value chains such as 'Better Life

Farming' are also providing additional income opportunities through rural agri-entrepreneurship (Better Life Farming 2020).

The Bt cotton Gene Revolution was a game-changer for Indian cotton. Now, we need to expand it to other crops such as corn and oilseeds (soybean and canola) and reduce India's dependence on edible oil imports (TAAS 2014; Paroda and Joshi 2017). This requires the right agri-infrastructure, accelerated market reforms and an enabling policy framework that is focused on empowering farmers and protecting intellectual property rights (IPRs).

Another area where both the government and the private sector are making significant inroads is digital farming using artificial intelligence, drones, the Internet of Things (IoT), remote sensing, etc. Very recently, the Indian Government used e-locust tab and e-locust M to control a locust attack in desert areas of Rajasthan. The technology provided a precise location (GPS), as well as recording the data, which was useful for forecasting, forewarning and taking control measures. Public and private sector are investing in capacity-building to encourage wider adoption of new and existing technologies among smallholder farmers, such as water-efficient rice through hybrid seeds and direct seeded rice (DSR) (NITI 2019). Similarly, ITC Limited has expanded its extensive e-Choupal network, which is working with four million farmers to launch a 'phygital' system, with a crop-agnostic integrated solution framework that will synergistically aggregate digital technologies to empower farmers.

Sustainable and protected agricultural practices like soilless farming systems (hydroponics, aeroponics, and aquaponics) and polyhouse farming systems are also making headway. The government is aiming to increase the area (~2,00,000 ha) under protected cultivation by a factor of 4 in the next 4–5 years, another option for vertical farming and enhanced income to attract youths (including women) to agriculture (Paroda 2018, 2019).

2.2 Increasing Pressure on the Environment and Climate Change

Though India has largely been able to achieve much-needed food, feed and fibre security, which can inspire many developing countries, it has come at the cost of environmental degradation, especially in regard to water and land, in some states of India. The government is realising that longstanding policies of subsidies for agriculture inputs (e.g., power and fertilisers) and price support (MSP) with open-ended procurement of rice and wheat are inflicting significant damage on the environment. For instance, fertiliser subsidies (nitrogenous fertilisers are subsidised for almost 75% of their cost) have resulted in massive overuse of nitrogenous fertilisers, leading to an imbalanced use of nutrients and a decline in soil fertility, as well as the pollution of local water bodies. Moreover, widespread deficiency of secondary and

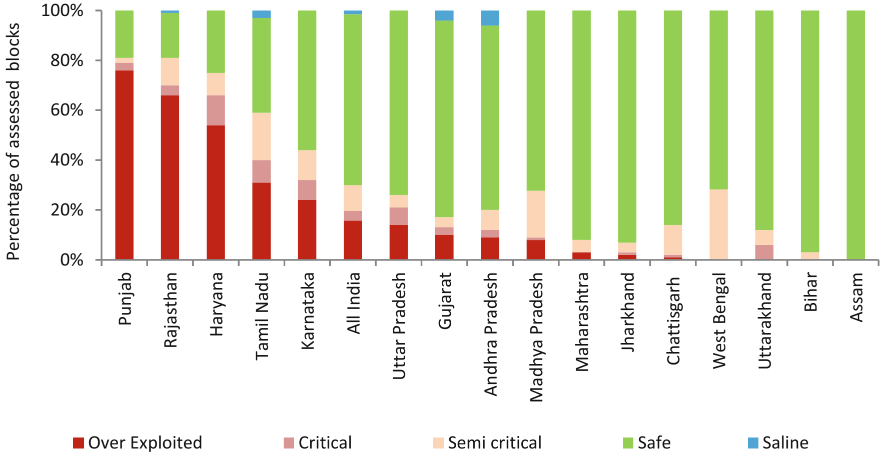


Fig. 2 Status of groundwater level in India, 2017. (Source: CGWB 2017)

micro-nutrients such as sulphur, zinc, iron and manganese has affected soil productivity adversely (Government of India 2016). On the other hand, power subsidies have resulted in an alarming overuse of scarce groundwater, especially in north-west India. This issue is poised to become one of country's big challenges in the years to come, unless jointly prioritised through good policies and corrective measures by the central and state governments.

Figure 2 presents an assessment of the groundwater table in 6584 units (blocks) across states in India by the Central Ground Water Board (CGWB) in 2017. It revealed that, overall, 1034 units are 'over-exploited,' 253 are 'critical' and 681 are 'semi-critical' (CGWB 2017). The over-exploited areas are mostly in three parts of the country, namely, north-western India (Punjab, Haryana, and western Uttar Pradesh), western India (Rajasthan and Gujarat) and southern peninsular India (Tamil Nadu, Karnataka, Andhra Pradesh and Telangana). Hence, these regions would need corrective water use approaches like micro-irrigation and enabling policies around cropping systems and water use efficiency (WUE).

In addition to the undesirable consequences of agricultural intensification, climate change is another daunting challenge for achieving overall food-feed-fibre security. As per the predictions of the IPCC, India will face greater frequency and intensity of droughts in the Deccan plateau states of the west and southern peninsula, and floods in the Himalayan foothills from melting glaciers in the Himalayas. With temperatures rising by one degree Celsius, estimates are that wheat production will drop by at least 5 MMT, and, if temperatures rise further beyond 2 °C, the losses will increase rapidly (IPCC 2018).

Several efforts are on to address the issue of sustainable and climate-resilient agriculture. The government and the private sector are joining hands to create climate-resilient villages, saving water in agriculture use through better demand side efficiency, and augmenting water resources through water harvesting to recharge groundwater. ITC, e.g., has built more than 20,000 water harvesting structures through 44 partnerships (PPP mode) covering 1.2 million acres. It has also extended its focused 'climate smart villages' initiative to more than 600 villages, which have increased yields by about 15%, incomes by about 30% and cut down greenhouse gas (GHG) emissions by more than 30% (SustainCERT 2020). It is being argued that, to protect India's agri-resource endowment, there is a need to switch from highly subsidised input price policy (power, water, fertilisers), as well as MSP/FRP policy for paddy, wheat and sugarcane, to more direct income support policies linked to the saving of soil, water, nutrients and the improvement of air quality. Such shifts will reduce the inefficient use of fertilisers and ensure sustainable use of scarce water supplies, and therefore will be more equitable and environmentally sustainable (OECD-ICRIER 2018).

For agriculture to be sustainable in the long term, it needs to go hand in hand with farm incomes and farmer prosperity. Otherwise, farmers will not take sustainability issues seriously. Globally, several players are working on sustainable agriculture models that also support income generation for farmers. The opportunities to adopt Carbon capture models to reduce carbon emissions and create additional income streams for farmers is currently being introduced by several companies, including Bayer, in the US and South America. This could be a great opportunity for smallholder farmers in India and other smallholder countries in Asia and Africa, too (Bayer 2020; World Bank 2012).

As far as the challenge of climate change is concerned, the government is putting greater emphasis on adaptation through the development of climate-resilient seeds. The ICAR has identified 400 climate-resilient germplasm lines and 58 genotypes with high water and nutrient use efficiency. It is also developing and demonstrating climate-resilient technologies under "National Innovations on Climate Resilient Agriculture (NICRA)."[1] Further, it is increasing the area under micro-irrigation technologies for water preservation, and promoting innovative rice cultivation and irrigation practices like 'Alternate Wetting Drying (AWD)' and 'Direct Seeded Rice (DSR),' which can save about 25–30% of water requirements in rice cultivation. Greater emphasis on laser levelling is also helping by raising WUE up to 30%. Shifting from cereal-cereal to cereal-legume cropping systems will result in sustainable intensification.

Another example involving climate-resilient seeds is the Water-Efficient Maize for Africa (WEMA) Public Private Partnership Project in Sub-Saharan Africa with AATF, CIMMYT, Gates Foundation, USAID and Bayer. By combining advanced breeding techniques, WEMA has delivered drought-tolerant and insect-resistant maize (corn) seed varieties to smallholder farmers in five African nations.

The Soil Health Card Scheme of the government aims to make sure every farmer has a balanced use of nutrients (N, P and K) on the basis of soil tests. The government is also encouraging the cultivation of nitrogen-efficient crops such as

[1] According to the government sources.

pulses (legumes), which fix nitrogen in the soil and boost crop productivity through Biological Nitrification Fixation (BNF), and investing in precision irrigation technologies through satellite crop-monitoring systems that assess soil moisture, expected rainfall and overall crop conditions to suggest the exact quantity of irrigation required. Use of irrigation sensors that help save water is also being encouraged.

The scaling of innovations helps reduce the inefficient use of scarce natural resources (water and soil), and hopefully makes the food system more efficient, sustainable and climate-resilient.

2.3 Marketing Food with Low Intermediation Costs and Low Food Losses

Value chain development and marketing platforms that link farms to agricultural output markets play a critical role in determining prices and incentives for farmers. However, the agri-marketing structure in India continues to be fragmented, with a large number of intermediaries leading to high transaction costs (between 30% and 50% of the retail consumer price). These costs are exacerbated by high commissions of agents, high *mandi* (market) charges and fees in certain states (like Punjab), low investments in supply chains, poor logistics, information asymmetries and a lack of sufficient storage infrastructure. As a result, high intermediation costs for many agri-commodities blunt their global competitiveness. These investments in supply chains are lacking due to restrictive marketing and trading policies, such as the Essential Commodities Act of 1955, that were designed during the era of scarcity. Similarly, indiscriminate export controls that kick in whenever prices of any essential commodity start going up hamper investments in supply lines. The OECD report on Agricultural Policies in India has clearly showed that Indian agricultural marketing policies have favoured consumers over producers by suppressing farmers' prices. The Producer Support Estimate (PSE) for India was negative 11.2% of the value of farm receipts between 2000–01 to 2019–20, while the Consumer Support Estimate (CSE) was one of the highest in the world (28.8%) (OECD 2021). Figures 3 and 4 give PSE and CSE estimates of several countries, respectively, for a period of the latest three years (2017–18, 2018–19 and 2019–20) (OECD 2021). India's PSE is about −4% vis-à-vis 13% for China and 17% for OECD as a group. Contrastingly, CSE for India is highest at 21%. Thus, the typical consumer bias in India's marketing and trade policies still continues. Correcting this bias remains a tall order.

The government's efforts to reform the agri-marketing system, through the recently passed Farmers Produce Trade and Commerce (Promotion and facilitation) Act, 2020, the Farmers Empowerment and Protection Agreement on Price Assurance and Farm Services Act, 2020, and amendment of the Essential Commodities Act, have run into rough weather, as some leaders in the farming industry, particularly from the Punjab, Haryana and western Uttar Pradesh belt regions, are opposing

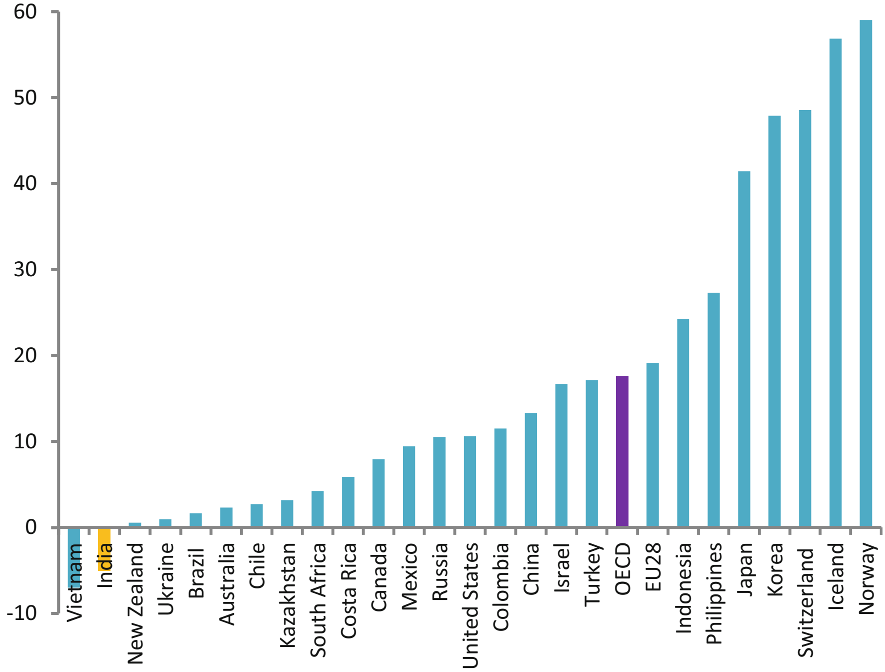


Fig. 3 Producer Support Estimate, 2017–19 (as a percentage of gross farm receipts). (Source: Author's compilation from the OECD database, 2021)

these marketing reforms and want assured procurement of all 23 commodities to be bought under the ambit of the MSP program. In the wake of this opposition, these three farm laws have now been withdrawn.

Nevertheless, emergence of digital marketing platforms such as electronic unified agricultural markets (e-NAM), negotiable warehousing and commodity futures, as well as recent government initiatives like the Agriculture Infrastructure Fund (AIF), *Atmanirbhar Bharat* (self-reliant India), and Farmers Producer Organisations (FPOs), are steps in the right direction, but are not free from implementation gaps, which need to be filled with timely incentives, investments and monitoring.

Other policy interventions to bring about efficiency in agri-marketing, lower transaction costs and reduce food losses include freeing up agricultural markets to greater competition, giving farmers the freedom to sell what they want, where they want, when they want, without any restrictions on sale, stocking, movement, or the export of farm produce, and providing an enabling ecosystem in which private enterprises can invest freely in agriculture value chain development, as it will gradually boost investment in building efficient and sustainable supply chains while ensuring a better share for farmers of consumers' rupees. For future food and nutritional security, linking farmers to markets will be a critical need.

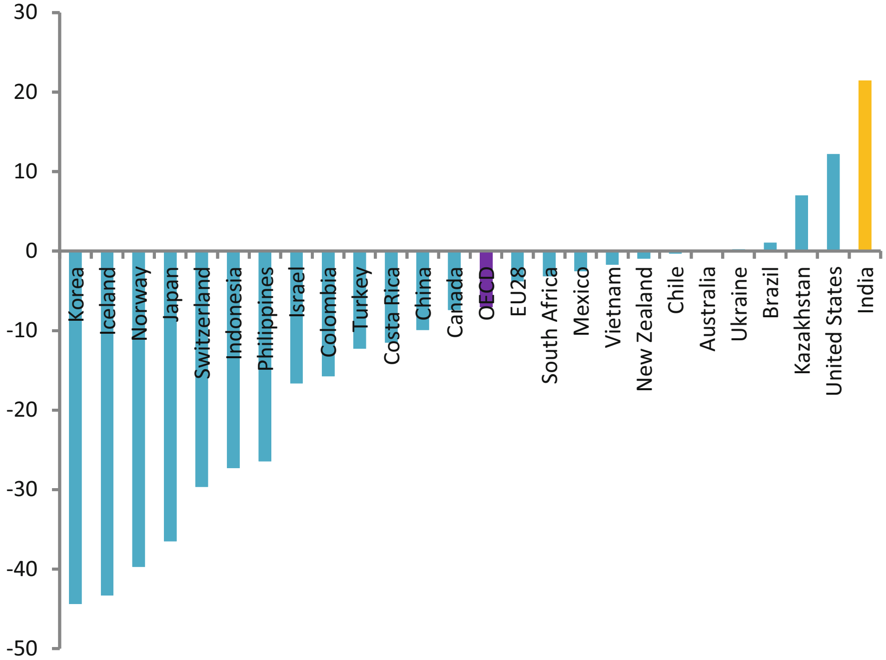


Fig. 4 Consumer Support Estimate, 2017–19 (as a percentage of consumption expenditure at the farm gate. (Source: Author's compilation from the OECD database, 2021)

Private companies like ITC are in the forefront of building such efficient value chains. For example, ITC's e-choupal sources over three million tonnes of agri-products from 225 districts in 22 States of India. Its competitive and inclusive agri-value chains, anchored by ITC's world-class FMCG brands, provide consumers with high quality products while generating substantial livelihoods. ITC's fork-to-farm value chains enable the company to manufacture world-class food brands by sourcing differentiated, value-added, identity-preserved, traceable raw materials, and simultaneously empowering farmers with best practices and technology, resulting in enhanced farmer incomes. The multi-stakeholder partnerships that build end-to-end demand-responsive value chains lead to efficiencies and the enlarging of value for farmers.

Marketing reforms also need promotion and finance for the creation of assaying, sorting and grading infrastructures at the *mandis*. This will reduce variance in the quality of produce from *mandi* to *mandi* and encourage retailers and processors to procure through e-NAM (Gulati et al. 2019). Digitalisation of value chains, bringing the physical characteristics to digital platforms, will open up further opportunities for efficient marketing channels with low market risks, benefitting both farmers and consumers. Entrepreneurship for low-cost, rural-based value chains involving youths is now being emphasised.

With solar energy costs coming down drastically, investment in solar-powered cold storage will reduce the costs, as well as losses, of agricultural produce, particularly perishables, and improve storage quality. In the case of onions, losses have been 30–35% in the absence of proper cold storage structures; further, promoting contract farming and other forms of Public Private Partnerships to drive local innovations in the supply chain will also help reduce market risk for farmers and improve their price realisation. Investing in food processing and value addition, as well as linking processing with organised retailing, will go a long way towards building efficient value chains from farm to fork. As the processing industry adds value and absorbs surpluses at the time of harvest, it is believed that, on average, about one-fourth of produce must be processed at this stage of development, as is the case in several south-east Asian economies. But India is way behind on this graph, with less than 10% of agri-produce being processed.

Finally, it should be emphasised that only by developing the forward and backward linkages can the government ease large price fluctuations, ensure a remunerative price for farmers, and provide lower prices for consumers: a win-win situation for all. The current set of Farm Laws had sought to achieve precisely this, but now have been withdrawn due to opposition from some farmers groups (most notably from Punjab, Haryana and western UP) and from opposition parties in the Parliament.

2.4 Making Food More Nutritious and Safer for Consumers While Ensuring Remunerative Prices for Farmers

India's agriculture food system is backed by a unique National Food Security Act (NFSA, 2013) that ensures the availability and affordability of a sufficient supply of food for its population. India's Public Distribution System (PDS), which is the world's largest, covering more than 800 million people, is an important channel through which the government provisions food to the identified poor under various welfare programmes. Social welfare schemes aimed at improving nutrition also focus on ensuring calorie sufficiency, neglecting the quality and diversity of diets and behavioural change towards better nutrition. On behalf of the government, the Food Corporation of India (FCI) procures and stocks food grains from the state agencies to maintain food security and price stability. There is little doubt that ample food availability has been ensured for the country, but its economic access to nutritious diets remains a challenge, as indicated by the high rates of stunting amongst children. The head count ratio of people under extreme poverty measured as a per day per capita income of USD1.9 (at PPP of 2011–12 prices) has declined from 45.9% in 1993 to 38.2% in 2004, and to 13.4% in 2015 (World Development Indicators 2019). A recent Policy Research Working Paper no. 9994 (April 2022) from the World Bank by Sutirtha Sinha Roy and Roy van der Weide, gives the head count ratio of extreme poverty at 10.2 percent in 2019. The World Poverty Clock estimates that India's poverty ratio in 2021, even after accounting for the impact of Covid-19, would be about 6% (World Poverty Clock 2021).

Given the gradual decline in extreme poverty, there is a need to re-visit the NFSA, which covers 67% of population and basically distributes rice and wheat. The FCI operations for the procurement, stocking and distribution of wheat and rice to identified beneficiaries are expensive and riddled with inefficiencies, as they add almost 40% on top of the MSP to farmers. The market prices of rice and wheat often remain way below the economic cost of FCI, especially in rural areas where poverty is concentrated. The overall cost of the food subsidy was INR 4.22 lakh crore (USD 57 billion) in 2020–21, and is provisioned to be INR 2.42 lakh crore (USD 37 billion) in 2021–22. This is huge in relation to the total tax revenue of the Union Government. This calls for a re-examination of the extent of coverage and suggests reducing it from 67% of the population to ~30%, as was suggested by the Economic Survey of 2019–20 (Government of India 2021b), as well as recommending an option of direct cash transfers to identified beneficiaries equivalent to MSP plus 25%. This will lead to demand for more nutritious and diversified food in line with changing consumption patterns.

Notwithstanding the foodgrain surpluses and the world's largest PDS distribution system, India faces a complex challenge around nutritional security. According to the National Family Health Survey (NHFS-4) 2015–16, 35.8% of children below 5 years of age are underweight, 38.4 are stunted and 21% are wasted (International Institute for Population Sciences 2017). Therefore, there is a need to assign the highest priority to addressing all forms of malnutrition.

To augment production of more nutritious food, a wide range of interventions can be undertaken, such as:

- Intervene in food systems in order to help push India's nutritional security status to higher levels. It is often assumed that, as a country's food production goes up, its nutrition levels also go up, as seems to be the case in most of the countries in the world, but this is not true for India. Over the last five decades, total production of foodgrains in India has increased *by* six-fold: from 51 million tonnes in 1950–51 to about 296.67 million tonnes in 2019–20 (estimated 303 million tonnes in 2020–21). However, India still faces relatively high levels of malnutrition.
- Leverage agricultural policies and programmes to be more "nutrition-sensitive" and reinforce diet diversification towards a nutrient-rich diet. The government has already renamed the National Food Security Mission as the National Food and Nutritional Security Mission from the year 2021–22 onwards, so as to put emphasis on nutrition aspects along with food security. One way is to work with schools in promoting sustainable kitchen gardens to grow vegetables and use them to provide nutritious midday meals to school students. The use of soybean as a food and a good source of protein is another option (TAAS 2014; Paroda and Joshi 2017).
- Bio-fortify basic staples, as a very cost-effective technological innovation for improving the diets of households and the nutritional status of children. The

HarvestPlus programme of the Consultative Group on International Agricultural Research (CGIAR) is already working towards this in many countries around the world. In India, too, the HarvestPlus programme is working in collaboration with the Indian Council of Agricultural Research (ICAR) to grow new varieties of nutrient-rich staple food crops, such as iron and zinc bio-fortified pearl millet, zinc bio-fortified rice and wheat, and iron bio-fortified beans (HarvestPlus 2020). The Extension Division of ICAR has also launched two special programmes viz. Nutri-sensitive Agricultural Resources and Innovations (NARI) and Value Addition and Technology Incubation Centres in Agriculture (VATICA) for up-scaling the bio-fortified varieties through its Krishi Vigyan Kendras (KVKs).

– Contribute towards the holistic nourishment of children and a malnutrition-free India by 2030 through initiatives such as the Prime Minister's recent "POSHAN Maah," which is a step in the right direction. The PM has also announced an effort to scale up production of 17 bio-fortified varieties of eight crops and some nutri-cereals (water-saving crops) that can be further integrated with government support initiatives, like midday meals for elementary school children, to reach millions of vulnerable population groups. The Government of Bihar has also come forward and announced that it will establish a 'Nutritional Village,' where farming families will cultivate bio-fortified crops. These policy interventions need to be scaled up across the country and emphasis shall now be on local food systems for enhanced food and nutritional security while ensuring the "One Health" concept.
– Improve the nutritional status of the population, particularly for pre-school children and women of reproductive age. A game-changer policy intervention in this direction could be devoting a part of the food subsidy from wheat and rice to nutritious food crops. Even the private sector, NGOs, and civil society partners can be incentivised towards a mission mode that develops and markets bio-fortified foods.
– Have the Government address other determinants of malnutrition on a war footing, such as the enabling of women's education through liberal scholarships, separate sanitation facilities for girls in schools, and safe drinking water and nutritious food for all at affordable prices. *Swachh Bharat Abhiyan* (Clean India Mission) is a commendable step towards eliminating open defecation and bringing about behavioural changes in hygiene and sanitation practices.

Thus, this chapter overall argues that fundamental reforms in the agri-food system are the need of the hour, if we are to increase production to feed the growing Indian population, lower transaction costs to achieve marketing efficiency and provide safe, nutritious and affordable food to consumers in an effort to build a healthy India in ways that increase farmers' income and are more fiscally and environmentally sustainable.

In the final analysis, it is like a symphony orchestra in which our farmers, industry and society are all playing their instruments in perfect synchrony. And success is defined by winning the battle of producing a sufficient amount with efficiency and sustainability, and with an aim towards delivering wellbeing for both the people and the planet by 2050!

Acknowledgements We would like to thank Ritika Juneja, Consultant (ICRIER), for her excellent research support in writing this paper.

References

Agriculture Census Division (2015–16) Agriculture Census. Ministry of Agriculture and Farmers Welfare, Government of India, Delhi

Bayer (2020) Mitigating climate change: a carbon zero future for agriculture. Retrieved March 16, 2021, from Shaping Agriculture: https://www.cropscience.bayer.com/who-we-are/sustainable-agriculture/climate-change

Better Life Farming (2020) About us. Retrieved March 16, 2021, from Better Life Farming: betterlifefarming.com/index.php?id=3

CGWB (2017) Dynamic groundwater resources of India (as on March 31, 2013). Central Ground Water Board, Ministry of Water Resources, River Development & Ganga Rejuvenation, Faridabad

Dalrymple DG (1975) Measuring the green revolution: the impact of research on wheat and rice production. Foreign Agricultural Economic Report, Economic Reserach Service, Washington, DC

Directorate of Economics and Statistics (2020, August 06) Advance estimates of food grains, oilseeds and other commercial crops. Retrieved from Third Advance Estimates of Production of Foodgrains for 2019–20: https://eands.dacnet.nic.in/Advance_Estimate/3rd_Adv_Estimates2019-20_Eng.pdf

DoAHD&F (2019) Basic animal husbandry and fisheries statistics. Ministry of Agriculture and Farmers Welfare (MoA&FW), Government of India, New Delhi

Fan S, Gulati A, Thorat S (2007) Investment, subsidies, and pro-poor growth in rural India. IFPRI Discussion Paper

FAOSTAT (2019) https://www.fao.org/faostat/en/#home

Government of India (2016) Economic survey: 2015–16. Ministry of Finance, Government of India, Delhi

Government of India (2021a) Union budget. Ministry of Finance, Government of India, Delhi

Government of India (2021b) Economic survey. Ministry of Finance, Government of India, Delhi

Gulati A, Ferroni M, Zhou Y (2018) Supporting Indian farms the smart way. Academic Foundation, Delhi

Gulati A, Kapur D, Bouton MM (2019) Reforming Indian agriculture. Center for the Advanced Study of India

HarvestPlus (2020, October 16) On world food day, India PM Modi endorses biofortification to address Malnutrition. HarvestPlus

ICAR (2017) ICAR-CGIAR agricultural cooperation. Department of Agricultural Research and Education, Indian Council of Agricultural Research, Delhi

International Institute for Population Sciences (2017) National Family Health Survey (NFHS-4), 2015–16: India. International Institute for Population Sciences (IIPS), Mumbai

IPCC (2018) Impacts of 1.5°C global warming on natural and human systems. The intergovernmental panel on climate change (IPCC), United Nations

Maitra R (1991) How India became self-sufficient in food. Executive Intelligence Review

Narain D (2020, September) Transforming Indian Agriculture: A Policy Framework to Guide US-India Partnership. Antlatic Council

National Statistical Office (2020) Periodic Labour Force Survey: July 2018–June 2019. MOSPI, Government of India, Delhi

NIAP (2017) Agricultural R&D Policy in India: the funding, institutions and impact. ICAR–National Institute of Agricultural Economics and Policy Research, Delhi

NITI (2019) Better Rice, Better Life. Bayer, Mumbai
OECD (2021) Agricultural support. Retrieved March 16, 2021, from OECD data: https://data.oecd.org/agrpolicy/agricultural-support.htm
OECD/ICRIER (2018) Agricultural policies in India. OECD Food and Agricultural Reviews, OECD Publishing, Paris
Paroda RS (2018) Motivating and attracting youth in agriculture. Trust for Advancement of Agricultural Sciences, Delhi
Paroda RS (2019) Urgency for scaling agricultural innovations to meet sustainable development goals (SDGs). Trust for Advancement of Agricultural Sciences (TAAS), Delhi
Paroda RS, Joshi PK (2017) Proceedings of the National Conference on sustainable development goals: India's preparedness and the role of agriculture. In: Indian Council of Agricultural Research (ICAR), Trust for Advancement of agricultural sciences (TAAS) and international food policy research institute (IFPRI). ICAR, New Delhi, p 48
SustainCERT (2020) Ecosystem service market consortium and SustainCERT team up to deliver certified greenhouse gas impacts. Ecosystem Services Market Consortium. SustainCERT
TAAS (2014) Brainstorming workshop on soybean for household food and nutrition security: proceedings & recommendations. Trust for Advancement of Agricultural Sciences, Delhi
United Nations (2019) World population prospects. Department of Economics and Social Affairs: Population Dynamics
World Bank (2012) Carbon sequestration in agricultural soils. Agriculture and Rural Development (ARD), The World Bank, Washington, DC
World Development Indicator (2019) Poverty and equity data portal. Retrieved February 22, 2020, from povertydata.worldbank.org: http://povertydata.worldbank.org/poverty/country/CHN
World Poverty Clock (2021) India. Retrieved March 15, 2021, from World Poverty: https://worldpoverty.io/map

Part VII
Strategic Perspectives and Governance

The Role of Science, Technology and Innovation in Transforming Food Systems Globally

Robin Fears and Claudia Canales

1 Introduction: The Transformation of Food Systems

The world is not on track to meet the Sustainable Development Goal (SDG) targets linked to hunger and food and nutrition security. According to FAO data (FAO 2020), the number of hungry people has increased by 10% in the past 5 years and 3 billion people cannot afford a healthy diet. Some countries in Asia and Africa have made significant progress in increasing food and nutrition security alongside reducing poverty in the past decade, but others have not (EIU 2020). The risks continue to be compounded by the impacts of population growth, urbanisation, climate and other environmental changes, market instability and economic inequality. Furthermore, the Covid-19 pandemic has exacerbated problems and imposed disproportionate effects on the economically vulnerable, including marginalised groups in urban areas and smallholder farmers in rural areas (FAO 2020; EIU 2020). However, while there are unprecedented challenges, there are also unprecedented opportunities to capitalise on science, technology and innovation for the purpose of transforming food systems.

In 2018, the InterAcademy Partnership (IAP), the global network of more than 140 academies of science, engineering and medicine, published a global report on food and nutrition security and agriculture, drawing on information from four regional reports prepared by academy networks in Africa (NASAC), Asia (AASSA), the Americas (IANAS) and Europe (EASAC) and emphasising the value of taking a transdisciplinary approach. In the present chapter, we present an update on some of the issues from that global report linked to the assessments made

R. Fears · C. Canales (✉)
European Academies' Science Advisory Council's (EASAC) Biosciences Programme, Halle (Saale), Germany
e-mail: canales.claudia@gmail.com

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_44

in the chapters in this volume prepared by the regional academy networks for the UNFSS.

The work of the academies has adopted an integrative food systems approach that considers all points along the value chain, encompassing food processing, transport, retail, consumption, and recycling, as well as agricultural production. Moreover, in the transformation of food systems towards economic, social and environmental sustainability, setting agricultural priorities must take account of climate change and pressures on other critical natural resources, particularly water soil and energy, and the continuing need to avoid further loss in ecosystem biodiversity. Interest worldwide in the sustainability of food systems is accelerating (e.g., Global Panel 2020; IFPRI 2020; Food Systems Dashboard 2020; von Braun et al. 2021).

In this chapter, which covers the opportunities and challenges for food systems in tackling malnutrition in all its forms (undernutrition, micronutrient deficiencies, overweight and obesity), we frame the contribution that science can make to the local-global connectivity of food systems: (i) to strengthen and safeguard international public goods, i.e., those goods and services that have to be provided at a scale beyond that of individual countries or that can be better achieved collectively; (ii) to understand and tackle environmental and institutional risks in an increasingly uncertain world; and (iii) to help to address the SDGs by resolving complexities within evidence-based policies and programmes and their potential conflicts.

2 Regional Heterogeneity

Inevitably, in a summary of the global position, it is difficult to capture the diversity within and between regions relating to the challenges for food systems. The regional chapters are indicative of the territorial dimension in analysing obstacles to food and nutrition security, emphasising specific contexts for marginalised peoples and smallholder farmers, e.g., for the Hindu Kush Himalayan region (AASSA 2021). In Africa, although remarkable progress has been made over the last two decades in reducing extreme hunger, there are increasing pressures on food systems that require radical action (discussed in detail in NASAC 2021). Most African Union member states are not on track to achieve the Comprehensive Africa Agricultural Development Plan goals (African Union 2020). In the comprehensive publication on country-level data in the Americas that accompanied the regional report on food and nutrition security and agriculture (IANAS 2017, regional update IANAS 2021), there was detailed discussion of diversities within the region and of variation in the social determinants of food and nutrition security, e.g., related to gender. Other regional assessments find moderate-severe food insecurity (SDG Indicator 2.1.2) across the FAO Europe-Central Asia region, varying from 6.7% in the EU to 19% in the Caucasus. Obesity throughout this region is higher than the world average,[1] a challenge that has been examined by EASAC (2021).

3 Agriculture-Environment Nexus

IAP defines the desired outcome for food systems as access for all to a healthy and affordable diet that is environmentally sustainably produced and culturally acceptable. The IAP report from 2018 cautioned that an emphasis on increasing total factor productivity (TFP, the efficiency in the use of labour, land, capital and other inputs) is not warranted if such a focus leads to reductions in environmental protection. Since then, there has been continuing interest in using research to leverage TFP for sustainable and resilient farming (e.g., Coomes et al. 2019). In particular, the paradox of productivity has been highlighted (Benton and Bailey 2019), whereby agricultural productivity may generate food system inefficiency. That is, productivity, when leading to the increased availability of cheaper calories, may help to promote obesity, although nutritional content matters as much as calories. Current global competition policies incentivise producers who can produce the most food for the least amount of money, typically with accompanying environmental damage, including biodiversity loss (Chatham House 2021). The strategic focus of research and development, as well as production systems, should shift from staple crops, with the current emphasis on production of a narrow range of calorie-intensive staples, to a balanced strategy for crops that are of more value in terms of nutritional, social and environmental benefits, including fruit, vegetables, seeds, nuts and legumes (as food and feed, NASAC 2021).

Reform of food systems requires decision-makers to recognise the interdependence of supply-side and demand-side (including dietary change and waste reduction) actions. There must be further consideration given to strengthening coherence between global agreements, e.g., on responsible investment, and national action (Chatham House 2021). And, the continuing food system sustainability challenge of balancing production objectives for agricultural exports with satisfying domestic food and nutrition requirements is an issue for some countries (e.g., IANAS 2021).

Current intensive agricultural production depends heavily on fertilisers, pesticides, energy, land and water, with negative consequences for environmental sustainability. Changing environmental conditions and competition for key resources such as land and water provoke violence and conflict, exacerbating the vicious circle of hunger and poverty (NASAC 2021). Discussion in the NASAC (2021) Policy Brief exemplifies some of the particular issues for managing water demand, including conservation and the recycling of waste water, and notes the opportunities for

[1]FAO (2020) "Sustainable food systems and healthy diets in Europe and Central Asia." ERC/20/2, on www.fao.org/3/nc226en/nc2262n.pdf. This report discusses multiple issues around diversified and sustainable food systems, improving supply chains and reducing food loss and waste.

science, technology and innovation in new irrigation schemes. Research and innovation play a crucial role in the transformation to sustainable food systems that produce more efficiently by environmentally friendly means. The options for the convergence of technological and societal innovation (including outputs from biotechnology, AI, digitalisation, and from social and cognitive sciences), exemplified later in this chapter, help to underpin the objectives for sustainable food systems.

Agro-ecology encompasses various approaches to using nature-based solutions for regenerative agriculture innovation (HLPE 2019) and systems research is still needed to help strengthen the evidence base for agro-ecological (nature-based) approaches. For example, agroforestry in sub-Saharan Africa has the potential to help tackle health concerns associated with a lack of food and nutrition security (non-communicable diseases) and with human migration, but requires additional research to characterise any increased risk from infectious disease alongside the beneficial outcomes (Rosenstock et al. 2019).

Developing diverse and resilient production systems worldwide is important in preparing for the likelihood of cumulative threats from extreme weather events through spillover across multiple food sectors on land and sea (Cottrell et al. 2019). In this context, it is relevant to note the interest in the potential of oceans for sustainable economies in addressing food security, biodiversity and climate change. One of the UK Presidency's core themes for UN FCCC COP26 is "Nature," with objectives for sustainable land use, sustainable and resilient agriculture, and increasing ambition and awareness of the ocean's potential. This potential is also of great importance for the UN FSS Action Track on nature-positive production. By contrast with difficulties in expanding land-based agriculture, the potential for the sustainable production of fish and other seafood is increasingly recognised (Lubchenco et al. 2020; Costello et al. 2020) and brings new possibilities for local livelihoods. Fish supplies provide 19% of the animal protein in African diets (Chan et al. 2019; NASAC 2021). However, currently, one-third of the world's marine fish stocks are overfished (FAO 2020). Realising the potential of the oceans requires technological innovation and policy reform for fishery management and governance, to restore wild fish stocks, eliminate illegal and unregulated fishing, and ensure sustainable mariculture so as to minimise environmental impacts. Oceans can contribute to climate change mitigation as well as to improved food systems, but it is important to be aware of inadvertent consequences of policy action, e.g., adoption of industrial-scale aquaculture can be associated with rapid growth in GHGs (in China, Yuan et al. 2019). Genetic improvement of fish species may help to reduce the environmental footprint of aquaculture (for example, in Africa, where aquaculture has been expanding at a faster rate than in some other places, NASAC 2021). This exemplifies a general point about seeking co-ordinated policy across sectors to avoid unintended effects and negative trade-offs. Another example is provided by poorly-designed land use policies to increase bioenergy production, which drive increases in land rent with negative implications for food and nutrition security (Fujimori et al. 2019).

4 Delivering Healthy Diets, Sustainably Produced, Under Climate Change

An accumulating evidence base demonstrates that climate change exacerbates food insecurity in all regions by reducing crop yield and nutritional content and by posing additional food safety risks from toxins and microbial contamination (e.g., IPCC 2019; Park et al. 2019; Ray et al. 2019; Watts et al. 2021). The effects are most pronounced in those groups who are already vulnerable, e.g., children, because of reduced nutrient intake (Park et al. 2019) or a decline in dietary diversity (Niles et al. 2021). A systematic review of the literature identified climate change and violent conflict as the most consistent predictors of child malnutrition (Brown et al. 2020). By increasing the volatility of risks in the global food system, climate change may also reduce the incentive to invest (IAP 2018), and rising heat- and humidity-induced declines in labour productivity reduce the income of subsistence farmers (Andrews et al. 2018).

Although better international integration of food trade can be a key component of climate change adaptation at the global scale, it requires sensitive implementation to benefit all regions (Janssens et al. 2020): in hunger-affected export-oriented regions, partial trade integration may exacerbate food and nutrition insecurity by increasing exports at the expense of domestic food availability. When assessing trade implications, it is also important to appreciate that climate change presents a risk to global port operations, with the greatest risk being projected for ports located in the Pacific Islands, the Caribbean Sea, the Indian Ocean, the Arabian Peninsula and the African Mediterranean (Izaguirre et al. 2021).

There are twin, overarching challenges for food systems: how can they adapt to climate change and, at the same time, reduce their own contribution to it, including in regard to GHG emissions? These intertwined challenges are discussed in all of the regional assessments. Multiple scientific opportunities have been identified to adapt by developing climate-resilient agriculture, e.g., from the application of biosciences to breed improved crop varieties resistant to biotic and abiotic stresses, as well as for the social sciences to understand and influence the behaviour of farmers, manufacturers and consumers in responding to climate change (see, for example, EASAC 2021). Combining evidence-based measures will also be essential to mitigate GHG emissions from the sector (currently contributing approximately 30% of global GHGs, Watts et al. 2021), including improving agronomic practices, reducing waste, and shifting to diets with a lower carbon footprint. For example, a background paper prepared in 2020 for the Subsidiary Body for Scientific and Technological Advice (SBSTA) of UN FCCC COP[2] explored agronomic case studies (in South America, Asia, Africa and Europe) for managing nitrogen pollution (including the powerful GHG nitrous oxide) and improving manure management so as to decrease GHGs and benefit the environment. Capitalising on such research requires better

[2] SBSTA 52nd Session 2020. "Improved nutrient use and manure management towards sustainable and resilient agricultural systems". FCCC/SB/2020/1.

connections between science and the broader community, along with relevant policy processes. There is particular need to dismantle obstacles to the transferability of practices and the scaling up of local research results to guide decision-making at the national and regional levels.

One major mitigation opportunity discussed by IAP (2018) and in all of the regional assessments relates to the potential to adjust dietary consumption patterns so as to reduce GHGs and, at the same time, gain significant potential health benefits (see Neufeld et al. 2021 for discussion of the definition of a healthy diet). For example, there is evidence that reducing red meat consumption, where it is excessive, can improve population health (Willett et al. 2019; systematic review of the literature in Jarmul et al. 2020). Red meat supplies only 1% of calories worldwide, while accounting for 25% of all land use emissions (Hong et al. 2021), though meat is an important source of protein, minerals and vitamins. The policies for reaching such consumption adjustments require more research to actually identify solutions. The proportion of excess deaths attributable to excess red meat consumption is highest in Europe, the Eastern Mediterranean, the Americas and the Western Pacific (Watts et al. 2021). However, some populations consume sustainable diets that are meat-based, e.g., the Inuit Indigenous People in the Canadian Arctic: proposals for dietary change must be carefully designed, evidence-based and culturally sensitive in being adapted to circumstances and protecting nutrient supplies for the most vulnerable groups. It should also be acknowledged that the efficiency of livestock production varies according to farming system, such that conclusions, e.g., about the sustainability of pastoral cattle production, may be different from those for feed-lot cattle production (Adeosogen et al. 2019; AASSA 2021), and that livestock may be the only agricultural activity possible in dryland regions that do not support the cultivation of crops.

Although Africa accounts for the smallest regional share of total anthropogenic GHG emissions, about half of this is linked to agriculture, and the continent is experiencing the fastest increase of all regions (Tongwane and Moeletsi 2018; Latin America and South East Asia are also demonstrating rapid growth, Hong et al. 2021). As part of the whole systems approach, formulation of mitigation solutions must decouple increases in livestock productivity (and cereal productivity, Loon et al. 2019) from increases in GHGs. Progress is being made (e.g., in China, Cui et al. 2018; AASSA 2021), and decoupling can be informed by better use of the research evidence available, e.g., for improving herd management and animal health, breeding new varieties (with better feed conversion and energy utilisation efficiencies), improving forage provision (e.g., NASAC 2021) and strengthening targeted social protection mechanisms, alongside more generic recommendations for dietary change (EASAC 2021).

There are unprecedented scientific opportunities coming within range, but there are also multiple obstacles to mainstreaming climate change solutions into food system development planning. Evaluation of obstacles in India (Singh et al. 2017) highlights the limited access to finance, difficulties in accessing research and education, and delays in accessing weather information. Systematic review of the literature on smallholder production systems in South Asia (Aryal et al. 2020) notes weaknesses in the institutional infrastructure for implementing and disseminating available solutions: the application of science requires institutional change. At the global scale, there is a need for enhanced access to climate information and services around climate-resilient food security actions (WMO 2019), e.g., to aid decisions on the most suitable crops and planting times.

5 Responding to Covid-19

Climate change and Covid-19 are converging crises for health in many respects (Anon 2021), including food and nutrition security. Observations early in the pandemic[3] indicated that the production of staple food crops during critical periods (planting and harvesting) was vulnerable to interruptions in labour supply; food processing, transport and retail were also affected early on, particularly the relatively perishable, nutritionally-important fresh fruit and vegetables (Ali et al. 2020). Subsequent comprehensive assessment of consequences for global food security (Swinner and McDermott 2020) has evaluated how adverse effects on local practice and routines are transmitted to longer-term impacts on poverty and food systems worldwide in increasingly interconnected trade and markets. In some cases, supply disruption has been aggravated by national decisions to restrict the export of food.[4] The combined effects of Covid-19 in regard to economic recession and food system disruption are particularly detrimental to the poor (Ali et al. 2020; Swinner and McDermott 2020, which includes case studies in Ethiopia, China, Egypt and Myanmar; NASAC 2021). However, in some regions, food systems proved relatively resilient (IANAS 2021), and there are also examples of good practice in new safety net programmes, including school feeding programmes that should be more widely shared and implemented. Tackling the consequences for child malnutrition has been identified as a particular priority for action (Fore et al. 2020), as has attention to gender bias, whereby women are suffering more adverse effects as a consequence of Covid-19-changed household and community dynamics (Swinner and McDermott 2020).

As emphasised by EASAC (2021), the pandemic has exposed the vulnerability of over-reliance on just-in-time and lean delivery systems, globalised food production and distribution based on complex value chains. Therefore, opportunities for increasing the localisation of production systems should be re-examined. However, there is often a mismatch in the timescale needed to adapt to Covid-19 between the imperative for early action to protect vulnerable groups and the relatively slow policy responses (Savary et al. 2020). Capitalising on the scientific opportunities may help to minimise this mismatch, e.g., improving food safety and reducing post-harvest losses (IAP 2018), implementing evidence-based social protection measures and

---

[3] CGIAR's response to COVID-19. www.cgiar.org/news-events/all-news/our-response-to-covid-19

[4] International Monetary Fund "Policy responses to COVID-19". https://www.imf.org/en/Topics/imf-and-covid-19/Policy-Responses-to-COVID-19

using Information and Communication Technologies for e-commerce, food supply resilience, early warning systems, and health delivery. Post-Covid-19 initiatives on novel foods, and urban and peri-urban farming systems, can also strengthen food supply chains and create new livelihoods for expanding urban populations, although it is also important to understand and manage inadvertent consequences for rural employment and the environment (Ali et al. 2020).

6 Using Science, Technology and Innovation to Promote and Evaluate Action

Continuing with business as usual will not meet the objectives for transformative change. To reaffirm a core message from IAP (2018): there is urgent need to use currently available evidence to strengthen policies and programmes, and to invest in initiatives to gain new knowledge. Examples of what is possible are discussed extensively elsewhere (e.g., Fanzo et al. 2020; Lillford and Hermansson 2020).[5] It is not the purpose here to provide a detailed assessment of transdisciplinary research priorities, but in Table 1, we map some onto the UN FSS Action Tracks to emphasise new opportunities that are coming within range and the need for science to achieve its potential. Examples are illustrative, not comprehensive; more detail on these and other research priorities are provided in IAP (2018), the regional chapters and in Sects. 1, 2, 3, and 4 of this chapter. There are also, of course, many interactions between research streams and objectives that cannot be captured in Table 1.

Several general recommendations can be made:

- There is a need to increase the commitment to invest in fundamental science, and then connect that to applications and align it all with development priorities. There is also an important priority to develop improved methodologies for understanding the levers of change, including the attributes of "game-changers." That is, how to attribute outcomes and impact to investments chosen and scientific or other actions undertaken.
- There are new opportunities to improve collaboration and coordination worldwide, as well as build partnerships among the public and private sectors, NGOs and other stakeholders to co-design and conduct research. Transdisciplinary approaches should be encouraged. There is increasing entrepreneurial activity worldwide, e.g., in the Latin America region, a wide range of start-up company activities includes novel foods, novel production systems, and novel approaches to the optimisation of water and other natural resources (IANAS 2021). There are also considerable opportunities in Africa for action on agriculture to stimulate

[5] See also repositories of recent literature, e.g., Sustainable solutions to end hunger (https://www.nature.com/collections/dhiggjeagd); Sustainable nutrition (https://www.nature.com/collections/fibbgbiebc); and Socio-technical innovation bundles for agri-food transformation (https://www.nature.com/documents/Bundles_agrifood_transformation.pdf).

Table 1 The power of fundamental science

UN FSS Action Track	Examples of research opportunities
1. Ensure access to safe and nutritious food for all	Clarifying the scientific basis for balancing of food systems for a greater emphasis on nutrition, not just calories; incentives to promote sustainable practices and products, and disincentives for foods with high environmental footprints or adverse health effects. Integration of local, regional and global scales for sustainability, including renewed emphasis on the value of indigenous crops. Broad research agenda for the agriculture-environment nexus, including livestock biometrics. Plus, bio/chemical sciences to identify the health value of novel foods, the holistic properties of foods (interactions within complex food matrices and mixtures), and components not ordinarily considered as nutrients (such as flavonoids, probiotics, anthocyanins) (Kongerslev et al. 2017 for dairy products; Thorrez and Vandenburgh 2019 for cultured meat; Nuffield Council on Bioethics 2019 for ethical issues).
2. Shift to sustainable consumption patterns	Social sciences to understand demand-side issues, the role of public procurement, value-driven consumption patterns (Smith et al. 2016; Cuevas et al. 2017; Eker et al. 2019; Laar et al. 2020). Using advances in food science and technology in food processing to reduce post-harvest losses (Lillford and Hermansson 2020).
3. Boost nature-positive production	Understanding the value and vulnerabilities of mixed farming systems; reduction in the use of external inputs (including antimicrobials); mapping and using soil microbiomics (Singh et al. 2020); conserving and using genetic diversity in breeding (FAO 2019; Pironen et al. 2019). Realising the potential of the oceans (Lubchenko et al. 2020).
4. Advance equitable livelihoods	Big data capture, analysis and communication, e.g., for precision agriculture (Hodson de Jaramillo et al. 2019; Basso and Antle 2020), supporting smallholders and new livelihoods
5. Build resilience to vulnerabilities, shocks and stress	Earth Observation Sciences to monitor agronomic status and guide interventions at a large scale (Jain et al. 2019), linked to other technologies for crop sensors, mobile devices and remote monitoring. Development of baselines, attribution methodologies, reconciling differences in temporal and spatial scales in measurement, increasing understanding of synergies and trade-offs. Plus, the broad research agenda for tackling climate change and Covid-19 in the provision of equitable services, including health care and social protection.

economic growth, reducing poverty while also increasing food and nutrition security (Baumuller et al. 2021; NASAC 2021).

- Training and mentoring the next generation of researchers worldwide is essential: academies of science have a key role in encouraging younger scientists.

- Obstacles, especially in low- and middle-income countries, in the use and production of data and in the scaling up of applications must be addressed. For example, although big data/mobile-based communications bring significant benefits (e.g., IANAS 2021; NASAC 2021) and there have been advances in using mobile technology to deliver climate services for agriculture in Africa (Dayamba et al. 2018), more should be done to increase access for small-scale farmers (Mehrabi et al. 2021). A digital inclusion agenda is needed for governments and the private sector to increase access to data-driven agriculture.
- In addition to generating excellent science, it is vital to reduce the delay in translating research outputs into innovation, public policy and practice (IAP 2018). Time lags may arise from negative attitudes associated with perceived risks, from excessive regulatory requirements in some countries or from an absence of regulation in others. This leads to fragmentation in the capture of benefits. For example, there is current heterogeneity in considering whether new plant-breeding techniques – such as those based on genome editing – should be included within older legislation governing genetically modified organisms. Scientific advances are occurring worldwide, e.g., collaborative work in Colombia, Germany, France, the Philippines and the USA to develop rice that is resistant to bacterial blight (Oliva et al. 2019; IANAS 2021). The controversy created by a situation in which regulatory frameworks are disconnected from robust science is discussed by EASAC (2021). Figure 1 demonstrates the resulting incoherence that acts to deter science, innovation and competitiveness, creates non-tariff barriers to trade and undermines collective action to enhance food and nutrition security. This may have particular adverse consequences for those already suffering malnutrition; for example, the acceptance of gene-based technologies has

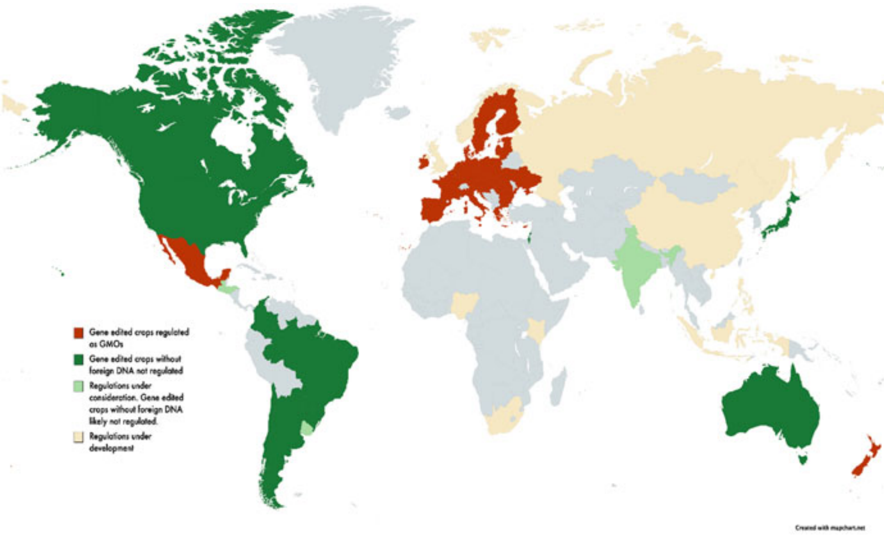


Fig. 1 Variation in the regulation of genome editing for plant breeding

been mixed in Africa, even though there may be considerable scientific opportunities for using biotechnology in crop breeding programmes to increase resistance to biotic and abiotic stress and to improve nutrient content and nitrogen use efficiency (NASAC 2021).

7 Strengthening the Contribution of Research to Policymaking

Alongside action to accelerate investment in agriculture and food systems research (von Braun et al. 2020), there must be transdisciplinary integration of priorities at the science-policy interface across all relevant sectors (Fears et al. 2019), including agriculture, the environment, health and social care, rural and urban development, and fiscal policy. There must also be linkage of policy at the local, regional and global levels (Fears et al. 2020), while taking account of local values and circumstances and recognising the challenges for coordination. One recent example from Asia (Islam and Kieu 2020) of developing critical mass in regional policy for climate change and food security discusses criteria for successive steps in policy planning, implementation, cooperation and legal obligation, and observes that the latter two steps often present fundamental barriers to moving from the priorities in a national development agenda to regional coherence. In the African region, the recent Joint Ministerial Declaration and Action Agenda (AU 2020) calls upon governments to build greater productive capacity in agriculture and strengthen resilience throughout Africa's agri-food systems.

Scaling efforts for critical mass requires individual countries to recognise that their policy decisions may have an impact on other countries and regions. For example, some countries export their lack of environmental sustainability by increasing food imports from elsewhere (IAP 2018).

Academies and others within the scientific community (STCMG 2020) have a key role in overcoming obstacles to effective policy by working together across disciplines to show the value of an inclusive approach, e.g., to the SDGs. Moreover, systematic review of the literature indicates that public support for a policy can be increased by communicating evidence of its effectiveness (Reynolds et al. 2020; Fears et al. 2020). Therefore, the work of academies in using the evidence base to inform policy development and implementation can help to provide the bridge between policymakers and the public.

What are the implications for the UN FSS? UN FSS discussions have highlighted the place of "game-changers" in driving transformative action, and the scientific community has much to contribute in exploring the potential of game-changers to underpin transformation at the science-policy interface (see AASSA 2021). For

Table 2 The scientific community has a continuing role in assessing and implementing game-changers to strengthen the contribution of research to policymaking

Game-changers in Action Track 1	How are academies helping to inform policy options? Examples from the regional chapters
Changing the fundamental incentives that created the present situation	Identifying research priorities for providing diversified, sustainable, healthy diets and pricing in negative externalities; developing better connections between data sets across health, environment and economics.
Taking advantage of shifts in underlying conditions	Clarifying the consequences of Covid-19 in improving system resilience and a sustainable, equitable, healthy recovery.
Recognising the value of multiple organisations working on related themes	Convening and catalytic roles to help reduce barriers between countries, sectors, and disciplines, and encourage shared perspectives.
Avoiding neglect of the obvious	Reaffirming the importance of current strategies for tackling all malnutrition, including fundamental science and food science and technology in support of innovation; paying more attention to understanding the value of indigenous crops (and improving their domestication) and traditional diets (e.g., in Africa, Mabhaudi et al. 2019).
Changing mind sets so as to think in terms of systems	A food systems approach has been central to the academies' work in providing evidence to policymakers and other stakeholders, and in involving those whose voices have sometimes been muted.

example, a recent commentary on Action Track 1[6] identified some key precepts that can be illustrated by academies' work at the regional and global levels (Table 2).

We suggest that there is an additional game-changer, applicable to all Action Tracks: the development of a new international science advisory Panel on Food and Nutrition Security (IAP 2018), with a broad remit for food systems, focused on shaping policy choices and strengthening governance mechanisms. A new Panel, recognising the new opportunities and challenges for food system governance, could help to streamline research efficiency in its linkage to policy action and increase the legitimacy of that science advice by using robust assessment procedures (Global Panel 2020). The impetus created by the UN FSS requires the coordination and management of food systems by more sectors of government and stakeholders than had been the case for food security, creating an unprecedented opportunity to develop a framework for greater transparency, accountability and the sharing of knowledge. By consolidating the present myriad, fragmented, array of panels and advisory committees, the proposed international advisory Panel could draw on the large scientific community already working on these topics – including academies – and should be asked to address the most pressing issues for transformative change in the face of the mounting global challenges. Food and nutrition security, particularly

[6] Haddad, L. 2021 "Food systems "game changers": reflections so far", on https://un-food-systems.medium.com/food-systems-game-changers-reflections-so-far-d4c8200c5663

for high-risk groups, must be a top priority on every country's national agenda, yet many countries do not have a national security strategy in place (EIU 2020). Furthermore, as already noted, advisory capacities, governance policies, and institutions are sometimes weak at the regional level (AASSA 2021; NASAC 2021). Thus, in addition to building the critical mass for evaluating complex issues at the global scale, an international advisory Panel could help to drive momentum for a national food system strategy in all countries and engender regional-level initiatives in policy development and implementation.

IAP recommends that the UN FSS now consider options for constituting a new international advisory Panel, so as to make best use of the rapid advances in science, technology and innovation, and to motivate evidence-based policymaking at all levels. IAP and its regional academy networks are eager to be involved.

8 Conclusions

- Achieving food and nutrition security worldwide by transforming food systems remains a major challenge, compounded by recent pressures from climate change and the Covid-19 pandemic. Actions to promote food systems are relevant to multiple SDGs. It is essential to identify opportunities for synergies and trade-offs while avoiding inadvertent negative consequences, and to engage everybody, in order to enable change. This requires advances in complex food system modelling.
- Food systems are diverse and heterogeneous. Continuing research is needed to inform diverse yet equitable solutions for sustainable, healthy diets that are culturally sensitive, focusing on vulnerable groups. That calls for stronger connections between local and international research entities. The opportunities for complex and innovative remote sensing and web-based data should also be explored for this purpose.
- Greater transdisciplinarity is needed in research to progress from the current scientific agenda, which is still too often focused on individual components of food systems or on agriculture separate from its environmental context. Social science research must be better integrated with other disciplines, e.g., to understand and inform consumer, farmer and manufacturer behaviours and to guide policies to deliver objectives for social justice. The development of improved methodologies for understanding the attribution of impact is also a critical research priority.
- Science is a public good, yet the conduct and use of basic and other research is often fragmented. There is still much to be done to build critical mass worldwide, to share skills and a research infrastructure, and to collaborate in agreeing upon and addressing research priorities and avoiding unnecessary duplication. There is a continued convening role for academies of science to facilitate the exploration of opportunities and tackle the obstacles to research collaboration between disciplines and between the public and private research communities.

- There are also opportunities to improve science-policy interfaces and integrate policy development at the local, regional and global levels. One game-changer would be to constitute an international advisory Panel on Food and Nutrition Security with new emphasis on food systems to make better use of the best science to inform, motivate and implement evidence-based policymaking at all levels.

Acknowledgements This IAP Brief was drafted by Robin Fears and Claudia Canales in discussion with Volker ter Meulen. We thank Sheryl Hendriks (NASAC), Elizabeth Hodson (IANAS) and Paul Moughan (AASSA) for their helpful advice.

References

AASSA (2021) Regional brief for UN FSSS

Adesogan AT, Havelaar AH, McKune SL, Eilitta M, Dahl GE (2019) Animal source foods: sustainability problem or malnutrition and sustainability solution? Perspective matters. Glob Food Secur 25:100325. https://doi.org/10.1016/j.gfs.2019.100325

Ali Z, Green R, Zougmore RB et al (2020) Long-term impact of West African food system responses to COVID-19. Nat Food 1:768–770

Andrews O, Le Quere C, Kjellstrom T, Lemke B, Haines A (2018) Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study. Lancet Planet Health 2:e540–e547

Anon. (2021) Climate and COVID-19 converging crises. Lancet 397:71

Aryal JP, Sapkota TB, Khurana R, Khatri-Chhetri A, Rahut DB, Jat ML (2020) Climate change and agriculture in South Asia: adaptation options in smallholder production systems. Environ Dev Sustain 22:504505075

AU (African Union) (2020) Joint virtual meeting of the African Ministers responsible for agriculture, trade and finance on the impact of COVID-19 on food and nutrition security in Africa, 27 July 2020. Joint Ministerial Declaration and Action Agenda. AU, Addis Ababa

Basso B, Antle J (2020) Digital agriculture to design sustainable agricultural systems. Nat Sustain 3: 254–256

Baumüller K, Admassie A, Hendriks S, Tadesse G, von Braun J (eds) (2021) From potentials to reality: transforming Africa's food production – investment and policy priorities for sufficient, nutritious and sustainable food supplies. Peter Lang Publ. (Forthcoming, an earlier draft is available at https://www.zef.de/fileadmin/downloads/ZEF_Akademiya2063.pdf)

Benton TG, Bailey R (2019) The paradox of productivity: agricultural productivity promotes food system inefficiency. Glob Sustain 2:e6

Brown ME, Backer D, Billing T et al (2020) Empirical studies of factors associated with child malnutrition: highlighting the evidence about climate and conflict shocks. Food Secur. https://doi.org/10.1007/s12571-020-01041-y

Chan C, Tran N, Pethiyagoda S, Crissman C, Sulser T, Phillips M (2019) Prospects and challenges of fish for food security in Africa. Glob Food Sec 20:17–25

Chatham House (2021) Food system impacts on biodiversity. ISBN: 978 1 78413 433 4

Coomes OT, Barham BL, MacDonald GK, Ramankutty N, Chavas J-P (2019) Leveraging total factor productivity growth for sustainable and resilient farming. Nat Sustain 2:22–28

Costello C, Cao L, Gelcich S et al (2020) The future of food from the sea. Nature 588:95–100

Cottrell RS, Nash KL, Halpern BS et al (2019) Food production shocks across land and sea. Nat Sustain 2:130–137

Cuevas RP, de Guia A, Demont M (2017) Developing a framework of gastronomic systems research to unravel drivers of food choice. Int J Gastron Food Sci 9:86–99
Cui Z, Zhang H, Chen X et al (2018) Pursuing sustainable productivity with millions of smallholder farmers. Nature 555:363–366
Dayamba DS, Ky-Dembele C, Bayala J et al (2018) Assessment of the use of Participatory Integrated Climate Services for Agriculture (PICSA) approach by farmers to manage climate risk in Mali and Senegal. Clim Serv 12:27–35
EASAC (2021) Regional brief for UN FSSS
Economist Intelligence Unit (2020) 2020 Global food security index. https://foodsecurityindex.eiu.com/index
Eker S, Reese G, Obersteiner M (2019) Modelling the drivers of a widespread shift to sustainable diets. Nat Sustain 2:725–735
Fanzo J, Covic N, Dobermann A et al (2020) A research vision for food systems in the 2020s: defying the status quo. Glob Food Sec 26:100397
FAO (2019) Tracking progress on food and agriculture-related SDG indicators. FAO
FAO (2020) State of food security and nutrition in the world. FAO
Fears R, ter Meulen V, von Braun J (2019) Global food and nutrition security needs more and new science. Sci Adv 5:eaba2946
Fears R, Canales Holzeis C, ter Meulen V (2020) Designing inter-regional engagement to inform cohesive policy making. Palgrave Commun 6:107
Food systems Dashboard (2020) A food systems framework. https://foodsystemsdashboard.org/about-food-system
Fore HH, Dongyu O, Beasley DM, Ghebreyesus TA (2020) Child malnutrition and COVID-19: the time to act is now. Lancet 396:517–518
Fujimori S, Hasegawa T, Krey V et al (2019) A multi-model assessment of food security implications of climate change mitigation. Nat Sustain 2:386–396
Global Panel on Agriculture and Food systems for Nutrition (2020) Future food systems: for people, our planet, and prosperity. Foresight 2.0
High Level Panel of Experts on Food Security and Nutrition (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. Committee on World Food Security
Hodson De Jaramillo E, Henry G, Trigo E (2019) La Bioeconomía. Nuevo marco para el crecimiento sostenible en América Latina/Bioeconomy. New Framework for Sustainable Growth in Latin America. Editorial Pontificia Universidad Javeriana, Bogotá. ISBN 978-958-781-378-4. Available at https://repository.javeriana.edu.co/handle/10554/43705
Hong C, Burney JA, Pongratz J et al (2021) Global and regional drivers of land-use emissions in 1961-2017. Nature 589:554–561
IANAS (2017) Challenges and opportunities for food and nutrition security in the Americas. The view of the academies of sciences
IANAS (2021). Regional brief for UN FSS
IAP (2018) Opportunities for future research and innovation on food and nutrition security and agriculture. The InterAcademy Partnership's global perspective
IFPRI (2020) Building inclusive food systems. Global Food Policy Report
IPCC (2019) Climate change and land. In: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
Islam MS, Kieu E (2020) Tackling regional climate change impacts and food security issues: a critical analysis across ASEAN, PIF, and SAARC. Sustainability 12:883
Izaguirre C, Losada IJ, Camus P, Vigh JL, Stenek V (2021) Climate change risk to global port operations. Nat Clim Chang 11:14–20
Jain M, Singh B, Rao P et al (2019) The impact of agricultural interventions can be doubled by using satellite data. Nat Sustain 2:931–934

Janssens C, Havlik P, Krisztin T et al (2020) Global hunger and climate change adaptation through international trade. Nat Clim Chang 10:829–835
Jarmul S, Dangour AD, Green R et al (2020) Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of "sustainable diets". Environ Res Lett 15:123014
Kongerslev TT, Bertram HC, Bonjour J-P et al (2017) Whole dairy matrix or single nutrients in an assessment of health effects: current evidence and knowledge gaps. Am J Clin Nutr 105:1033–1045
Laar A, Barnes A, Aryeetey R et al (2020) Implementation of healthy food environment policies to prevent nutrition-related non-communicable diseases in Ghana: national experts' assessment of government action. Food Policy 93:101907
Lillford P, Hermansson A-M (2020) Global missions and the critical needs of food science and technology. Trends Food Sci Technol. https://doi.org/10.1016/j.tifs.2020.04.009
Lubchenco J, Haugan P, Pangestu ME (2020) Five priorities for a sustainable ocean economy. Nature 588:30–32
Mabhaudhi T, Vimbayi V, Chimonyo G et al (2019) Prospects of orphan crops in climate change. Planta 250:695–708
Mehrabi Z, McDowell MJ, Ricciardi V et al (2021) The global divide in data-driven farming. Nat Sustain 4:154–160
NASAC (2021) Regional brief for UN FSS
Neufeld LM, Hendriks S, Hugas M (2021) Healthy diet: a definition for the United Nations Food Systems Summit 2021. Scientific Group Report. https://sc-fss2021.org
Niles MT, Emery BF, Wiltshire S et al (2021) Climate impacts associated with reduced diet diversity in children across nineteen countries. Environ Res Lett 16:015010
Nuffield Council on Bioethics (2019) Meat alternatives. Bioethics Briefing Note
Oliva R, Ji C, Atienza-Grande G et al (2019) Broad-spectrum resistance to bacterial blight in rice using genome editing. Nat Biotechnol 37:1344–1350
Park CS, Vogel E, Larson LM et al (2019) The global effect of extreme weather events on nutrient supply: a superposed epoch analysis. Lancet Planet Health 3:e429–e438
Pironen S, Etherington TR, Borrell JS et al (2019) Potential adaptive strategies for 29 sub-Saharan crops under future climate change. Nat Clim Chang 9:758–763
Ray DK, West PC, Clark M et al (2019) Climate change has likely already affected global food production. PLoS One. https://doi.org/10.1371/journal.pone.0217148
Reynolds JP, Stautz K, Pilling M et al (2020) Communicating the effectiveness and ineffectiveness of government policies and their impact on public support: a systematic review with meta-analysis. R Soc Open Sci 7. https://doi.org/10.1098/rsos.190522
Rosenstock TS, Dawson IK, Aynekulu E et al (2019) A planetary health perspective on agroforestry in sub-Saharan Africa. One Earth 1:330–344
Savary S, Akter S, Almekinders C et al (2020) Mapping disruption and resilience mechanisms in food systems. Food Secur 12:695–717
Scientific and Technological Community Major Group (2020) Position paper on the theme of the 2020 High-Level Political Forum. https://council.science/wp-content/uploads/2020/06/Position-Paper-STC-29_June.pdf
Singh NP, Arathy A, Pavithra S et al (2017) Mainstreaming climate change adaptation into development planning, Policy Paper 32. ICAR – National Institute of Agricultural Economics and Policy Research, New Delhi
Singh BK, Trivedi P, Egidi E et al (2020) Crop microbiome and sustainable agriculture. Nat Rev Microbiol 18:601–602
Smith J, Andersson G, Gourlay R et al (2016) Balancing competing policy demands: the case of sustainable public sector food procurement. J Clean Prod 112:249–256
Swinnen J, McDermott J (eds) (2020) COVID-19 and global food security. IFPRI
Thorrez L, Vandenburg H (2019) Challenges in the quest for "clean meat". Nat Biotechnol 37:215–216

Tongwane MI, Moeletsi ME (2018) A review of greenhouse gas emissions from the agriculture sector in Africa. Agric Syst 166:124–134
van Loon MP, Hijbeek R, ten Berge HFM et al (2019) Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. Glob Chang Biol. https://doi.org/10.1111/gcb.14783
von Braun J, Chichaibelu BB, Torero CM, Laborde D, Smaller C (2020) Ending hunger by 2030 – policy actions and costs. ZEF Policy Brief
von Braun J, Afsano K, Fresco L, Hassan M, Torero M (2021) Food systems – definition, concept and application for the UN Food Systems Summit. Scientific Group Report. https://sc-fss2021.org
Watts N, Amann M, Arnell N et al (2021) The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. Lancet 397:129–170
Willett W, Rockstrom J, Loken B et al (2019) Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492
WMO (2019) 2019 State of climate services. Report WMO-No. 1242
Yuan J, Xiang J, Liu D et al (2019) Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. Nat Clim Chang 9:318–322

The Bioeconomy and Food System Transformation

Eduardo Trigo, Hugo Chavarria, Carl Pray, Stuart J. Smyth, Agustin Torroba, Justus Wesseler, David Zilberman, and Juan F. Martinez

1 Bioeconomy Concepts and Contributions

The most widely and well-recognized definition of bioeconomy was proposed in the framework of the Global Bioeconomy Summit, which was held in 2018, whereby the: "bioeconomy is the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy" (IACGBS 2018). The bioeconomy, as a policy framework and developmental approach, makes use of material and energy found in biodiversity, biomass and genetic resources, which contributes to sustainability initiatives and climate change mitigation targets. Additionally, the knowledge that is generated about biological principles and processes can be replicated in the design of new products (IACGB 2020).

E. Trigo (✉) · H. Chavarria · A. Torroba · J. F. Martinez
Bioeconomy and Productive Development Program, Inter-American Institute for Cooperation on Agriculture (IICA), San José, Costa Rica
e-mail: ejtrigo@gmail.com

C. Pray
School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ, USA

S. J. Smyth
Department of Agricultural and Resource Economics, University of Saskatchewan, Saskatoon, SK, Canada

J. Wesseler
Agricultural Economics and Rural Policy Group, Wageningen University, Wageningen, the Netherlands

D. Zilberman
Department of Agricultural and Resource Economics, University of California, Berkeley, CA, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_45

The concept of bioeconomy as a development approach arises from the context of the current era, driven by the advance of science and technology (S&T) and the need to address new problems and concerns (Patermann and Aguilar 2018). In recent decades, this definition has been boosted not only by the progress in research and developments in the field of biological sciences, but also by its complementarity and convergence with the S&T of materials (especially nanotechnology) and information (e.g., artificial intelligence (AI), digitization, information and communication technologies (ICT), and the Internet of Things (IoT)) (Krüger et al. 2020; Torres-Giner et al. 2020; van Dijk et al. 2021). The emergence of the bioeconomy has also been favored by concerns associated with climate change, since material replacement and the energy base of production processes are essential components of the actions needed to mitigate its impact. This new paradigm is proposed as an important complement to the fossil decarbonization of the economy (Lewandowski 2018). Moreover, interest in the bioeconomy also emerges out of societies' concerns around meeting the increased demand for food through agriculture that more sustainably uses natural resources and reduces the potential for negative environmental impacts (Wesseler and von Braun 2017).

In addition to the above, consumers are moving towards increasingly sustainable lifestyles and are inclined to buy environmentally-friendly products (Sandra and Alessandro 2021). These new demands are an opportunity for the utilization of biomass (agricultural residual and food waste) not only to help reduce pollution, but also as an alternative feedstock for the production of a wide range of materials, from fuels and energy to chemicals, bioplastics and pharmaceuticals, among others (Usmani et al. 2021). Furthermore, future bioeconomic innovations are expected to generate greater positive impacts on sustainability (Biber-Freudenberger et al. 2020), like synthetic biology, novel nitrogen-fixing crops, nanofertilizers, etc. (Herrero et al. 2020a).

The bioeconomy has similarities and differences with concepts of the circular economy and the green economy, which are also currently being discussed as approaches to sustainable development (D'Amato et al. 2017; Kardung et al. 2020). All of them are multi-dimensional concepts that have as goals: the reduction of greenhouse gas (GHG) emissions; the efficient use of energy and material; responsible consumption; and social inclusion through innovation (D'Amato et al. 2019). However, what distinguishes the bioeconomy is its focus on the transformation of the structure of production, because the basis for this is that material and energy are biological resources, as well as the use of knowledge for processing and the creation of value-added chains (Fig. 1).

The bioeconomy makes important contributions to sustainable economic growth from the environmental and social points of view, especially in rural areas (Refsgaard et al. 2021). For example, the European Union (EU) bioeconomy (post-Brexit composition) employed around 17.5 million people and generated €614 billion of added value in 2017 (Ronzon et al. 2020). In that same year, in Latin American countries such as Argentina, the bioeconomy generated 2.47 million direct jobs (Coremberg 2019). Similarly, Nordic countries have experienced bioeconomy-related employment growth of 5–15%, especially in Iceland, Denmark

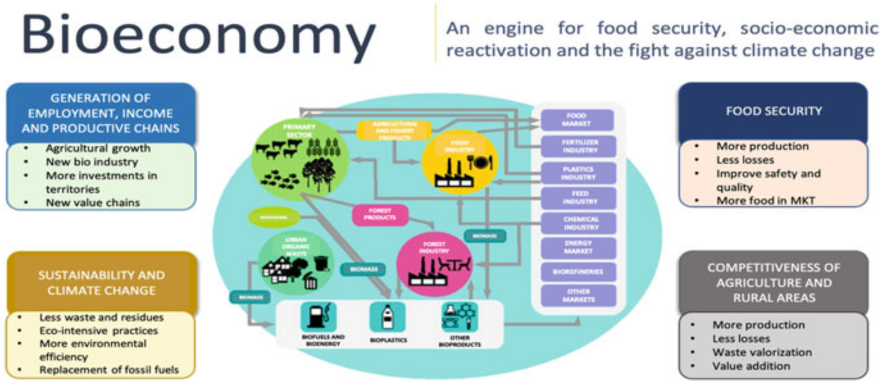


Fig. 1 Sectors and networks of the bioeconomy. (Source: Adapted from the Andalusian Bioeconomy Strategy 2018)

and Sweden (Refsgaard et al. 2021). It is estimated that the bioeconomic development model will have an economic potential of US$7.7 trillion between now and 2030 (WBCSD 2020). Additionally, in 2017, countries such as Italy expected to increase employment by 15% through its bioeconomic strategy (Italian Government 2019). Meanwhile, Colombia plans the generation of 2.5 million new jobs in its bioeconomic sectors (Colombian Government 2020). Previous projections are supported by trends in the bioeconomy markets. While commodities such as vegetable oil, sugar and cereals have a growth rate of less than 4.45%, sectors with higher added value such as biofuels, bioplastics and biofertilizers grew by 25%, 20% and 14%, respectively (Betancur et al. 2018). Using new S&T to add value to biological resources leads to more profitable and sustainable markets.

Finally, links between the bioeconomy and the 2030 Agenda for Sustainable Development have been demonstrated by using the indicators of the United Nation's Sustainable Development Goals (SDGs) for monitoring and evaluating the bioeconomy (Calicioglu and Bogdanski 2021). In an analysis of national bioeconomic strategies carried out by Linser and Lier (2020), it was found that topics related to the SDGs were indirectly related to objectives, planned actions and proposed measurements for policy instruments aimed at promoting the bioeconomy. Fourteen relevant SDGs for the bioeconomy were identified. For example, the bio-based economy can play a fundamental role in the decarbonization of the planet (SDG 13: Climate Action) and the production of agricultural bio-inputs, healthy food and the sustainable intensification of agricultural production (SDG 2: Zero Hunger, SDG No. 3: Good Health and Well-being and SDG No. 15: Life on Land). In addition, the closure of production cycles through the use of residual biomass improves the sustainable production indicators (SDG No. 12: Responsible Consumption and Production and SDG No. 11: Sustainable Cities and Communities). Another important contribution of this new paradigm is the design of biomaterials and production of different types of bioenergy (SDG No. 9: Industry, Innovation and

Table 1 Potential contributions of the bioeconomy to the SDGs

Potential Contribution	SDGs that contribute
Productive models that take advantage of science and technology to use biological resources sustainably and efficiently to make substitutes for petrochemicals (for example, bioenergy, biofertilizers, or bioplastics) or to satisfy new consumer demands (for example, functional foods or biocosmetics).	SDG 2: Sustainable Food Production SDG 3: Good Health and Well-Being SDG 7: Affordable and Clean Energy SDG 9: Industry and Innovation SDG 13: Climate Action
Use of productive practices that contribute to environmental sustainability and resilience while adding productivity and efficiency.	SDG 13: Climate Action SDG 15: Life on Land
Circular economy production systems, through the productive use of waste biomass derived from production and consumption processes.	SDG 11: Sustainable Cities and Communities SDG 12: Responsible Consumption and Production
Development of products, processes, and systems replicating processes and systems observed in nature.	SDG 9: Industry and Innovation SDG 14: Sustainable Use of Underwater Biodiversity SDG 15: Sustainable Use of Land Biodiversity
Bioremediation to face environmental contamination problems (for example, recovery of degraded or contaminated soils, and treatment of water for human consumption and wastewater).	SDG 6: Clean Water and Sanitation SDG 15: Prevention of Soil Degradation
Increase in the economic density of rural territories from new industrialization processes and local use of biomass for the generation of bioproducts and bio services.	SDG 8: New Sources of Decent Work and Sustainable of Economic Growth

Source: Chavarría et al. (2020)

Infrastructure and SDG No. 7: Affordable and Clean Energy), which help generate new jobs (SDG 8: Decent Work and Economic Growth).

The approach and application of the bioeconomy as a development model, contributing towards the achievement of the SDGs related to food security and nutrition, health and well-being, and clean water and sanitation, among others, is presented and analyzed in Table 1.

2 Bioeconomic Contributions to Food System Transformation

The transformation towards more sustainable and equitable food systems seeks to provide healthy and nutritious food for all, while creating livelihood opportunities and reducing negative impacts (von Braun et al. 2020). To achieve this goal, the UN Food Systems Summit has established five Action tracks, which are related to the bioeconomy as follows: **Action Track 1** seeks to ensure the availability of safe and nutritious food for everyone. This will require increasing crop and livestock yields through sustainable intensification activities in multifunctional landscapes, the diversification of production and good soil management (Hendriks et al. 2020). Another engine for the transformation of food systems is the shift to healthy and sustainable consumption patterns (**Action Track 2**). In this case, the bioeconomy can strengthen local value chains, promoting the reuse and recycling of food resources (Herrero et al. 2020b). **Action Track 3** aims to optimize the use of natural resources in food production, processing and distribution as pollution, soil degradation and loss of biodiversity are reduced. For this, the bioeconomy proposes strategies focused on value chains with integrated cycles, which increase efficiency and recycling through products and co-products in different biological systems (Hodson et al. 2020). These strategies for integrating chains and adding value to products at the local level contribute to poverty reduction through the creation of new rural jobs (**Action Track 4**) (Neufeld et al. 2020). Finally, **Action Track 5** seeks to promote resilience in the face of vulnerabilities, impacts and stresses in food systems (Hertel et al. 2020). Resilience can be strengthened by a growing bioeconomy based on the diversification of agricultural commodity production, the increased use of bio-based inputs in agriculture and the diversification of rural incomes into rural production of bioenergy, bio-based industry and environmental services. The current contingency caused by COVID-19 and recent natural disasters highlights the importance of innovations to prepare food systems for future pressures.

2.1 Advantages of Scientific and Technological Developments

Advances in the fields of biology, ICT and engineering are repositioning the role played by biological resources and improving our ability to understand and take full advantage of the opportunities they offer. In recent decades, advances in biology have accelerated, with new research tools such as genome editing contributing new knowledge of plant, animal and microbial genomes and big data. The increases in knowledge are being used to enhance the efficiency of crops, animals, biofuel, bioplastics and bioenergy production. The new tools have highlighted the full potential of the intrinsic value of natural and biological processes (IACGB 2020). The impact of these trends, which are transformative in themselves, is augmented by the interaction among them, what is beginning to be referred to as 'technological convergence.' By interacting with each other, different disciplines – biology, biotechnology, chemistry, nanotechnology, data science, ICT, engineering, etc. – are driving the progress of each specific field, blurring the traditional boundaries between sectors of the economy and changing the competitive advantages of countries and their businesses (MIT 2005; Park 2017).

Information and communication technologies and digitalization are becoming important determinants of the organization and competitiveness of economies. Widespread connectivity, satellite technologies, data science and artificial intelligence mechanisms, robotics, autonomous systems, electronic and biological sensors, virtual and augmented reality, the IoT and blockchain applications are increasing the efficiency of agriculture, food and biomass supply chains, which reduce waste and resource use while increasing the quality of food and biomass. It is also becoming increasingly possible to predict climate phenomena, foresee their consequences and generate risk management programs to better deal with the consequences and monitor climate impact, all of which will undoubtedly reduce farm management costs (Draca et al. 2018).

Through the use of such groundbreaking S&T, the bioeconomy makes it possible to improve the productivity and sustainability of biological resources by developing more productive, disease-resistant and environmentally-friendly varieties of plants and animals. S&T increases the productivity of biomass (including waste and residues), developing new bioproducts with high added value, such as nutraceuticals, bioenergy and other biological materials used by the cosmetic, pharmaceutical, chemical and other industries. Furthermore, it generates a range of new services and attaches greater value to biodiversity (Lokkoa et al. 2017; Malyska and Jacob 2018), for example, integrated pest management based on biological pesticides and fertilizers (Akutse et al. 2020).

Technological convergence is one of the trends making the biggest contribution to the renewed, modernized vision of agriculture and food systems, value-added chains and international trade. Convergence is especially important because of young people's technological skills – which far exceed those of previous generations – and the need to halt the migration of young people from rural territories to more urbanized areas. These new technological scenarios are already beginning to be reflected in agriculture, agribusiness and the rural regions, and are increasingly perceived as offering the basis for the development of 'sustainable intensification.' Furthermore, they are expected to have significant effects on the ways in which agricultural production is organized, improved rural employment opportunities and equity in rural territories.

Technological advances and convergence support SGDs: 3 (Good Health and Well-being); 8 (New Sources of Decent Work and Sustainable of Economic Growth); 9 (Industry and Innovation) 11 (Sustainable Cities and Communities); 12 (Responsible Consumption and Production); and 15 (Sustainable Use of Land Biodiversity).

2.2 Transforming Rural Environments, Generating Income and Employment Opportunities

One of the key issues around the bioeconomy comes from the implications of moving from fossil- to bio-based value chains. Fossil raw materials are relatively homogenous, are globally extracted in high volumes from only a few highly productive deposits of limited area, and come out almost completely ready to be transformed into products predominantly for the energy sector, but also for the multi-stage chemical sector and the construction sector, through large-scale industrial and logistical infrastructures. The defining attributes of the associated value chains are that they are global and large-scale. In contrast, biological carbon – biomass – comes from a highly decentralized context because of the diverse nature of agriculture and forestry and 'does not travel well.' Due to its large volumes, limited shelf-life and low energy and carbon density, it is not economical to transport biomass long distances before processing it, an issue that calls for biorefineries – integrated biomass processing facilities – to also be organized in a decentralized way in locations close to the areas producing the raw materials.

It is these characteristics of bio-based value chains that open up opportunities for significant transformations of the rural landscape and the way rural areas integrate into the economy. These bio-based value chains can significantly increase the economic 'density' of the territories. In the first place, bio-based value chains bring new activities – biorefineries and other industrial and logistical infrastructures – into the rural landscape, diversifying sources of income and the nature of employment opportunities. Greater economic density will generate greater opportunities for Latin American and Caribbean (LAC) territories that have high unemployment, informal jobs (76% of those employed), poverty (45%; two to three times higher than urban rates) and exclusion. The use of biomass for new industries will increase economic opportunities for both the agricultural and non-agricultural sectors, as the non-agricultural sector in LAC generates 58% of the income of rural territories (ILO 2020).

Bioeconomic value chains can address one of the common concerns in rural communities around the world: out-migration to urban centers and aging populations due to the lack of interest among young people to remain in farming vis-a-vis the promise of a more 'attractive' future in non-agricultural jobs. There is no possibility of success in achieving better livelihoods in the context of a decaying rural space. According to an Organisation for Economic Co-operation and Development (OECD) study that included 24 developing countries around the world, only 45% of rural youths are satisfied with their employment (OECD 2018). Among the reasons for seeking a new job, rural youths mentioned: a better income (36.7%); greater stability in contracts (20%); better working conditions (17%); and an increase in skills (13%).

A second strategic component of the impact of bioeconomic developments on transforming rural environments is the implications of improved energy availability in terms of attracting other economic activities beyond the bio-based value chain activities proper. In this sense, there is considerable evidence that rural electrification stimulated local business development (Riva 2020), which suggests that bioenergy options could not only significantly lower the cost of energy through the decentralization of costly energy grids – a continuing hurdle for many rural areas, particularly in the poorer countries – but also improve environmental performance by using residual biomass and waste (Tamburini et al. 2020). This should be especially important for a region like LAC, where forest biomass is equivalent to half of its land area (and 25% of the world's forests), and its agriculture represents 12% of world agricultural production and contributes to the 16% of the world export of agricultural products. Furthermore, it is a region where more than 120 million tons of food are wasted annually (55% of fruits and vegetables, 40% of roots and tubers, 25% of cereals, meats and dairy products) (ECLAC et al. 2019).

Energy – in affordable, stable supply – is a critical restriction to economic development, and the bioeconomy is increasingly offering it through options that are not competitive with food production (Gabashwediwe et al. 2019). Furthermore, in an increasingly interconnected world, the emerging bioeconomy networks (i.e., value adding, energy diversification) are a viable strategy for reversing the conditions that have been fueling rural out-migration, making the rural areas more competitive spaces for social and economic development (Hartley et al. 2019). In 2018, bioenergy generated 3.18 million jobs – equivalent to 30% of all jobs in the renewable energy sector. Moreover, the employment generated by the biofuels sector worldwide is highly concentrated in the western hemisphere. Latin America and the Caribbean accounts for 50% of liquid biofuel jobs worldwide, while North America accounts for 16%. Brazil leads among countries as the largest employer in biofuels, employing 832,000 persons (Torroba 2020a).

Improved rural economies through bioeconomy and bio-based energy contribute to supporting SDGs: 3 (Good Health and Well-being); 7 (Affordable and Clean Energy); 8 (New Sources of Decent Work and Sustainable of Economic Growth); 9 (Industry and Innovation); 11 (Sustainable Cities and Communities); and 15 (Sustainable Use of Land Biodiversity).

2.3 Improving Food Chain Resource Use

The diversification and efficient use of biomass to produce biofuels contributes to GHG reduction, generates added value and employment, and can contribute to safer and more efficient agri-food systems. From the point of view of the economy of the industry, biomass utilization gives rise to various co-products, among which are a series of biomaterials of different added value. The energetic biomaterials are liquid, solid and gaseous biofuels, which, aggregated under the term 'bioenergy,' represent the production of 10% of the world's primary energy supply (IEA 2019). In an associated way, a wide range of products linked to animal and human food (flour proteins, expeller, bagasse, distiller's dried/wet grains with solubles, etc.) and other high value-added products linked to the pharmaceutical, alcohol chemical and oleo chemical industries are also produced.

In this way, the efficient and integral use of biomass gives rise to an industry categorized as 'multi-product' (Baumol et al. 1982), in which the production of co-products allows for diversification and complements the production of food, facilitating better distribution in the production costs of raw materials, which makes the system more efficient. In addition, a safer agri-food system is generated, since diversified uses make up a reserve or buffer of raw materials that can be used as food in case of a food crisis. Moreover, the production of biofuels has generated a more stable demand for raw materials (especially of those multi-annual crops), generating an additional sales channel that allows for expansion in the supply of raw materials involved in the process. According to Torroba (2020b), 16% of corn production worldwide, 20% of sugar, 19% of soybean oil and 16% of palm oil were destined towards biofuels. When the prices of related commodities are not attractive, the redirection of raw material derived from crops, especially multi-annual ones, can be particularly beneficial to farmers. It generates more stable demand for raw materials. The more stable demand for raw materials, and the potential positive impact this has on prices, can benefit a neglected group in LAC: family farmers, of whom there are 60 million working in the sector.

The productivity of the bioeconomy sectors has significantly improved over time, reflecting learning-by-doing and ongoing technological updating. The processing costs of US corn ethanol declined by 45% between 1983 and 2010, while production volumes increased seventeen-fold; learning-by-doing and economies of scale played an important role in reducing these processing costs. Similarly, the cost of producing sugarcane ethanol in Brazil declined by 70% between 1975 and 2010 (Chen et al. 2015). With advances in biotechnology to enhance the productivity of feedstock crops, the efficiency of refining and the use of residue, the cost of biofuels and their environmental impacts will decline while the added value is enhanced (Debnath et al. 2019).

Finally, the use of biomass residues to produce alternative biofuels (e.g., biogas, advanced biofuels, etc.) lends a higher degree of efficiency to the system, allowing for the transformation of losses of raw materials or waste into energies of biological origin. The potential of residues originating from forestry, agriculture, and other sources is estimated to amount to 40–170 exajoule/year, with a mean estimate of around 100 exajoule/year by 2050 (IPCC 2012). For comparison purposes, annual energy consumption in the US amounts to 94 exajoules. The use of biomass could amount to a considerable percentage in the total generation of bioenergy, however, adoption of biomass as a source of bioenergy will vary widely, depending on supply availability and cost.

Enhancing the utilization of resources in supply chains supports SGDs: 7 (Affordable and Clean Energy); 9 (Industry and Innovation); and 13 (Climate Action).

2.4 Improved Nutrition and Health

The growing interest of consumers in products with natural ingredients can promote new value chains associated with tropical biodiversity. Agroforestry systems with native fruit trees and traditional forest foods can provide the necessary macro- and micro-nutrients needed to improve nutrition and food security (Chamberlain et al. 2020). Simultaneously, food innovations have helped diversify diets, especially with new protein sources such as those based on micro-algae (Melgar-Lalanne et al. 2019; Ordoñez-Araque and Egas-Montenegro 2021) and insects. Micro-algae possess a high nutritional value, containing protein, polyunsaturated fatty acids, bioactive carbohydrates and antioxidants, including pigments such as carotenes and chlorophylls phycobiliproteins (Fernández et al. 2021). Moreover, other technologies under development, such as cultured meat products, promise to be a sustainable protein source (Post et al. 2020).

On the other hand, innovations in plant breeding technologies, such as those used to create genetically modified (GM) crops, have made significant contributions towards addressing the SDGs, in particular, goals one (reducing poverty) and two (reducing hunger). While increased yields have contributed to higher household incomes, which reduces poverty, the increased yields have also enhanced household food security (Klümper and Qaim 2014; Subramanian and Qaim 2010; Smyth 2022). Biofortified GM crops have been adopted, increasing micro-nutrient availability (Hefferon 2014). Research to improve the nutritional quality of food includes protein increases (canola, corn, potato, rice, wheat); improved oils and fatty acids (canola, corn, rice, soy); improved carbohydrates (corn, potato, sugar beet, soy); increased vitamins (potato, rice, strawberry, tomato); and increased mineral availability (lettuce, rice, soy, corn, wheat) (Newell-McGloughlin 2014). Nutritionally enhanced foods improve an individual's nutrient intake, preventing and/or treating leading causes of death such as cancer, diabetes, cardiovascular disease and hypertension. Improving the nutritional content of daily food consumption certainly has day-to-day effects, but of significant importance are the long-term effects that extend for decades over the course of an individual's lifetime.

In many instances, improving macro-nutrients (e.g., proteins, carbohydrates, lipids, fiber) and micro-nutrients (e.g., vitamins, minerals, functional metabolites) results in significant childhood health improvements, such as reducing blindness due to the lack of vitamin availability (Wesseler and Zilberman 2014; Dubock 2014). Improved food nutrient content, especially the increase in mineral availability, contributes to improved immunity systems and reduces stunting (Wesseler et al. 2017). In many developing countries, plant-based nutrient intake accounts for 100% of an individual's nutrient diet, further highlighting the importance of nutritionally enhanced crop-derived foods. Health benefits are extended into adulthood through reductions in cancer-causing mycotoxins, as is the case with GM corn, in which the presence of these mycotoxins is 30% lower (Pellegrino et al. 2018). As the later-in-life benefits from improved childhood nutrition become better understood, the full value of nutritionally enhanced crops and foods may not be realized for several decades.

One quality of life improvement that has resulted from the small land-holder adoption of GM crops is the reduction in drudgery (Gouse et al. 2016). The majority of weed control in developing countries is done, as it has been for thousands of years, through back-breaking manual labor. Manual weeding is labor commonly assigned to women. The assessment of GM corn adoption impacts on female manual weeding by Gouse et al. (2016) found that this task was reduced by three weeks over the course of a year. This reduction in the amount of time spent manually weeding corn fields allowed these women to have larger vegetable gardens, as they had more time to haul water and be with their children. Another human health benefit from GM crops is the reduction in the incidence of pesticide poisoning following GM cotton adoption. In an assessment of the impacts of GM cotton adoption in India, Kouser and Qaim (2011) estimated that there were between 2.4 and 9 million fewer cases of pesticide poisoning annually. With GM cotton first adopted in India in 2003, the cumulative reduction in the number of pesticide poisonings can be estimated to be in excess of 100 million cases (Smyth 2020).

Innovative research in the agriculture and food sectors is transforming food systems through both the increased provision of food and more nutritious and healthy food. The increased provision of safe, nutritious food has life-long health benefits, thereby contributing to reduced healthcare system expenses.

Improved biofortification of food and health benefits from biotechnology support SDGs: 1 (End Poverty); 2 (Sustainable Food Production); and 15 (Sustainable Use of Land Biodiversity).

2.5 Improved Environmental Sustainability and Climate Resilience

Investments in the bioeconomy and biotechnology have made substantial environmental improvements and offer tremendous potential to be a leading strategy in the efforts to mitigate climate change. It is estimated that biomass could save 1.3 billion tons of carbon dioxide (CO_2) equivalent emissions per year by providing 3,000 terawatt-hours (TWh) of electricity by 2050 (Zihare et al. 2018). Concerning biofuels, their performance shows different emission reductions according to multiple factors, including considering the product's life cycle, and is closely linked to agricultural yield and the technologies applied during the primary and industrial production process. According to the IPCC (2011), the "good use of bioenergy can significantly reduce greenhouse gas emissions compared with alternative fossils." In this sense, it is necessary to establish national instruments of measure for GHG emissions throughout the life cycle of biofuels according to the different raw materials used to corroborate the environmental advantages. Besides, bio-based products release fewer GHG emissions compared to fossil carbon commodities (Antar et al. 2021). For example, since bioplastics consume less energy during their production than plastics derived from petroleum, they tend to emit less carbon dioxide in their life cycle (Yadav et al. 2020).

Another contribution of the bioeconomy towards sustainability is the reduction and use of food waste. In the agro-industrial sector in LAC, food waste is around 127 million tons per year, enough to satisfy the nutritional needs of 300 million people (Macias et al. 2018). Thanks to the advances in S&T, multiple technologies allow for the reduction of waste and its use to produce new bioproducts (e.g., for the food, energy, chemical, pharmaceutical, and construction industries). Food waste can be considered as a cheap feedstock for producing value-added products such as biofertilizers, biofuels, biomethane, biogas and value-added chemicals (Hassan et al. 2018). These new industries have the potential to contribute to the mitigation objectives of climate change and the environmental sustainability of productive commercial activities thanks to the switch from products of fossil origin with a high carbon footprint to inputs (waste) that had a high generation of carbon dioxide emissions and to the change in the energy matrix.

The commercialization of GM herbicide tolerant canola, corn and soy in the mid-1990s revolutionized land management practices, resulting in tens of millions of acres being transitioned to zero tillage. The additional commercialization of GM insect-resistant corn, cotton and soy has resulted in millions of fewer pesticide applications. The reduction in tillage and chemical applications has produced a significant environmental benefit, with 2.4 billion kg fewer carbon dioxide emissions and 775 million kg fewer chemically active ingredients being applied (Brookes and Barfoot 2020). It has been estimated that the commercialization of insect-resistant crops has reduced global pesticide use by 37% (Klümper and Qaim 2014). Not only are there fewer GHG emitted during the production of crops, the continuous cropping of fields with no tillage is increasing the soils' sequestration and storage of carbon dioxide (Sutherland et al. 2021). Conventional agricultural practices that require the use of tillage for weed control are estimated to have a net global warming potential that is 26–31% higher than zero-tillage land (Mangalassery et al. 2014).

The adoption of GM crops is driving the movement to sustainable crop production by removing tillage as the leading form of weed control. The environmental benefits from this are significant for sustainability, as, in one analysis, 86% of farmers reported decreased soil erosion and 83% reported increased moisture conservation (Smyth et al. 2011). A further benefit from the removal of tillage is that the rate of herbicide resistance development in weed populations has declined following the wide adoption of GM crops (Kniss 2018). The adoption of GM technology in corn, soybean and cotton reduced agricultural land and input use and saved 0.15 Gt of GHG emissions, equivalent to roughly one-eighth of the emissions from automobiles in the US (Barrows et al. 2014).

One emerging and vital area of innovative bioeconomy research is the use of innovative breeding technologies, including genome editing, to improve the abilities of plants to sequester increased amounts of carbon dioxide, allowing agricultural food production to make significant contributions to reducing the impacts of changing climates (Ort et al. 2015). Changes in a plant's ability to photosynthesize can have additional yield-enhancing benefits (Baslam et al. 2020). Bioeconomy photosynthesis research that results in plants sequestering greater volumes of carbon dioxide and higher yields will ensure that crop production levels do not decline in the face of changing climates.

Plant breeding involving biotechnology and genome editing is also providing additional sustainability benefits by developing new varieties that are resistant to diseases that threaten to destroy species. Fungal diseases and viruses have had devastating impacts on the production of coffee, for which an estimated 60% of all production is threatened (Davis et al. 2019). Similar circumstances exist regarding the production of bananas (FAO 2020), oranges (Nelson 2019) and cocoa (Ploetz 2007). The technology is also being applied to reintroduce species into regions where they were previously made extinct due to disease, such as the case with the American chestnut tree (The American Chestnut Foundation 2015).

The environmental benefits from GM crops are making substantial contributions to improving the sustainability of agriculture and food production. The reduction in GHG emissions, increased carbon dioxide sequestration and improved photosynthesis provide a leading solution for the mitigation of changing climates.

The application of biotechnologies that improve environmental sustainability and climate resilience supports SDGs: 2 (Sustainable Food Production); and 3 (Good Health and Well-being).

2.6 Upscaling Biotechnology Innovations

Humanity is facing major challenges, including climate change, food security and rural development. The bioeconomy is poised to play a central role in addressing these challenges. New technologies in the life and information sciences, combined with practical knowledge of production practices and ecosystems, can unleash the bioeconomy's potential. This requires significant investment in basic and applied research, training highly skilled professionals and fostering a fluid relationship between academia and industry. Zilberman et al. (2013) suggest that the 'educational industrial complex' has been essential in establishing the biotechnology and information technology sectors in the US and throughout the world. In the educational industrial complex, publicly supported basic research within universities and other research institutions leads to discoveries and innovations that are transferred to and expanded by startups and other private sector actors. Their development efforts lead to products that are produced and marketed by the private sector and transferred to final users. The educational industrial complex has already led to the establishment of supply chains of new products, including biofuels and oils, fine chemicals, pharmaceuticals and foods. University researchers have led some of these new ventures and the exchange between universities and the private sector in clusters like the Bay Area, St. Louis, Davis, Sao Paolo, San Diego, Austin, Mendoza, Santiago, etc.

The supply chains that emerge from these industrial clusters provide direct employment in the production of technological devices and even greater opportunities in the industries resulting from these technologies. The resulting bioeconomy industries are more likely to be concentrated in rural regions, alleviating rural poverty. For example, biofuel and fine chemical production can transfer rents from owners of non-renewable resources like fossil fuels to the expanded agri-food sector. The success of the educational industrial complex depends on maintaining academic and research excellence. The pioneering knowledge produced by EMBRAPA was key to the emergence of Brazil as an agricultural powerhouse, suggesting that support for outstanding research institutes linked with industry is a sound social investment.

The three main obstacles to the development of the bioeconomy sector are regulatory uncertainty, high transaction costs and financial constraints (Zilberman et al. 2013). Upscaling and applying new knowledge requires a science-based regulatory environment that aims to reduce regulatory burden and accelerate the development and application of new, safe technologies. The emergence of entrepreneurial startups is more likely when venture investors and capital markets are established to support new industries and when regulatory procedures are streamlined to reduce the cost and time needed to establish the venture.

Greater efficiencies in the commercialization and adoption of innovative biotechnological techniques and products contribute to SDGs: 7 (Affordable and Clean Energy); 9 (Industry and Innovation); and 15 (Sustainable Use of Land Biodiversity).

3 The Path Forward

Food systems, the "activities involved in producing, processing, transporting and consuming food" (UN 2021), are an integral part of the bioeconomy concept as a development approach. New developments in the biological sciences allow countries to address the many challenges society is facing. We have summarized the many opportunities the biological sciences have to offer. The translation of these opportunities into practice will not be trivial. There are a number of institutional factors that delay or prevent full exploitation of the opportunities that the bioeconomy has on offer. To move forward, these constraints must be addressed. First, research capacity at universities and government institutes that can turn these opportunities into technical and social innovations must be developed. Second, the growth-supporting industries based on these innovations and the supply chains that generate employment and economic growth should be supported. Third, regulations of innovations that protect society, but do not disrupt the application of these opportunities in production, transportation, and consumption and unnecessarily restrict sustainable growth, jobs and resilience, are needed. The differences in regulations and support for innovations and the industries that can spread them in different countries often reflect different societal norms and values. These institutional barriers are difficult to solve by one country alone. The UN Food Systems Summit brought together many countries and many people to discuss the removal of institutional barriers.

Our overview has shown that a lot can be achieved by building research capacity and reducing institutional barriers. The impacts will go beyond the food systems and affect other sectors of national economies as well. An open discussion will be needed that takes differences in norms and values into account without discriminating one against another. The UN Food Systems Summit provided the opportunity. The results depend on us.

References

Akutse K, Subramanian S, Maniania N, Dubois T, Ekesi S (2020) Biopesticide research and product development in Africa for sustainable agriculture and food security – experiences from the International Centre of Insect Physiology and Ecology. Front Sustain Food Syst 4:152. https://doi.org/10.3389/fsufs.2020.563016

Andalusian Bioeconomy Strategy (2018) Estrategia Andaluza de Bioeconomía Circular. Available at: https://www.juntadeandalucia.es/export/drupaljda/Estrategia_Andaluza_Bioeconomia_Circular_EABC_18.09.2018.pdf

Antar M, Lyu D, Nazari M, Shah A, Zhou X, Smith DL (2021) Biomass for a sustainable bioeconomy: an overview of world biomass production and utilization. Renew Sust Energ Rev 139:110691. https://doi.org/10.1016/j.rser.2020.110691

Barrows G, Sexton S, Zilberman D (2014) Agricultural biotechnology: the promise and prospects of genetically modified crops. J Econ Perspect 28(1):99–120. https://doi.org/10.1257/jep.28.1.99

Baslam M, Mitsui T, Hodges M, Priesack E, Herritt MT, Aranjuelo I, Sanz-Sáez A (2020) Photosynthesis in a changing global climate: scaling up and scaling down in crops. Front Plant Sci 11:882. https://doi.org/10.3389/fpls.2020.00882

Baumol W, Willing R, Panzar J (1982) Contestable markets and the theory of industrial structure. San Diego, United States of America, Harcourt, Brace and Jovanovich

Betancur C, Moñux D, Canavire G, Villanueva D, García J, María L, Méndez K, Cristina A, Olaguer E (2018) Estudio sobre la bioeconomía como fuente de nuevas industrias basadas en el capital natural de Colombia N.°1230667, Fase I. BIOINTROPIC, Colombia. Available at: https://www.dnp.gov.co/Crecimiento-Verde/Documents/ejes-tematicos/Bioeconomia/informe%201/1-INFORME%20BIOECONOMIA%20FASE%201%20FINAL%2024012018.pdf

Biber-Freudenberger L, Ergeneman C, Förster JJ, Dietz T, Börner J (2020) Bioeconomy futures: expectation patterns of scientists and practitioners on the sustainability of bio-based transformation. Sustain Dev 28(5):1220–1235. https://doi.org/10.1002/sd.2072

Brookes G, Barfoot P (2020) Environmental impacts of genetically modified (GM) crop use 1996–2018: impacts on pesticide use and carbon emissions. GM Crops Food 11(4):215–241. https://doi.org/10.1080/21645698.2020.1773198

Calicioglu Ö, Bogdanski A (2021) Linking the bioeconomy to the 2030 sustainable development agenda: can SDG indicators be used to monitor progress towards a sustainable bioeconomy? New Biotechnol 61:40–49. https://doi.org/10.1016/j.nbt.2020.10.010

Chamberlain JL, Darr D, Meinhold K (2020) Rediscovering the contributions of forests and trees to transition global food systems. Forests 11. https://doi.org/10.3390/f11101098

Chavarria H, Trigo E, Villarreal F, Elverdin P, Piñeiro V (2020) Bioeconomy: a sustainable development strategy. The G20 Insights Platform, Think 20 Engagement Group. Available at: https://www.g20-insights.org/policy_briefs/bioeconomy-a-sustainable-development-strategy/

Chen X, Nuñez HM, Bing X (2015) Explaining the reductions in Brazilian sugarcane ethanol production costs: importance of technological change. GCB Bioenergy 7:468–478. https://doi.org/10.1111/gcbb.12163

Colombian Government (2020) Estrategia Nacional de Bioeconomía de Colombia. Bioeconomía para una Colombia Potencia viva y diversa: Hacia una sociedad impulsada por el conocimiento. Available at: https://minciencias.gov.co/sites/default/files/upload/paginas/bioeconomia_para_un_crecimiento_sostenible-qm_print.pdf

Coremberg A (2019) Medición de la cadena de valor de la bioeconomia en Argentina: hacia una cuenta satelite. Ministerio de Producción y Trabajo, Bolsa de Cereales, Grupo Bioeconomía. Buenos Aíres. Available at: https://www.magyp.gob.ar/sitio/areas/bioeconomia/_archivos/Medicion_de_la_Bioeconomia2018.pdf

D'Amato D, Droste N, Allen B, Kettunen M, Lähtinen K, Korhonen J, Toppinen A (2017) Green, circular, bio economy: a comparative analysis of sustainability avenues. J Clean Prod 168:716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

D'Amato D, Korhonen J, Toppinen A (2019) Circular, green, and bio economy: how do companies in land-use intensive sectors align with sustainability concepts? Ecol Econ 158:116–133. https://doi.org/10.1016/j.ecolecon.2018.12.026

Davis AP, Chadburn H, Moat J, O'Sullivan R, Hargreaves S, Nic Lughadha E (2019) High extinction risk for wild coffee species and implications for coffee sector sustainability. Sci Adv 5(1):3473. https://doi.org/10.1126/sciadv.aav3473

Debnath D, Khanna M, Rajagopal D, Zilberman D (2019) The future of biofuels in an electrifying global transportation sector: imperative, prospects and challenges. Appl Econ Perspect Policy 41:563–582. https://doi.org/10.1093/aepp/ppz023

Draca M, Martin R, Sanchis-Guarner R (2018) The evolving role of ICT in the economy. A report by LSE consulting for Huawei. The London School of Economics and Political Science. Available at: https://www.lse.ac.uk/business-and-consultancy/consulting/assets/documents/the-evolving-role-of-ict-in-the-economy.pdf

Dubock A (2014) The politics of golden rice. GM Crops Food 5(3):210–222. https://doi.org/10.4161/21645698.2014.967570

ECLAC (Economic Commission for Latin America and the Caribbean, Chile), FAO (Food and Agriculture Organization of the United Nations, Italy), and IICA (Inter-American Institute for Cooperation on Agriculture, Costa Rica) (2019) Outlook for agriculture and rural development in the Americas: a look at Latin America and the Caribbean 2019–2020. IICA, San José. Available at: https://repositorio.iica.int/bitstream/handle/11324/12380/BVE20107947e.pdf?sequence=1&isAllowed=y

Fernández FGA, Reis A, Wijffels RH, Barbosa M, Verdelho V, Llamas B (2021) The role of microalgae in the bioeconomy. New Biotechnol 61:99–107. https://doi.org/10.1016/j.nbt.2020.11.011

Food and Agriculture Organization (2020) Banana fusarium wilt disease forecasting. Available at: http://www.fao.org/food-chain-crisis/how-we-work/plant-protection/banana-fusarium-wilt/en/

Gabashwediwe MS, Zikhona LL, Sukoluhle M, Tshwafo M (2019) Economic and technical feasibility studies: technologies for second generation biofuels. J Eng Design Technol 17(4): 670–704. https://doi.org/10.1108/JEDT-07-2018-0111

Global Bioeconomy Summit (2018) Global Bioeconomy Summit Communique. https://biooekonomierat.de/fileadmin/Publikationen/empfehlungen/GBS_2018_Communique.pdf

Gouse M, Sengupta D, Zambrano P, Falck-Zepeda J (2016) Genetically modified maize: less drudgery for her, more maize for him? World Dev 83:27–38. https://doi.org/10.1016/j.worlddev.2016.03.008

Hartley F, van Seventer D, Tostão E, Arndt C (2019) Economic impacts of developing a biofuel industry in Mozambique. Dev South Afr 36(2):233–249. https://doi.org/10.1080/0376835X.2018.1548962

Hassan SS, Williams GA, Jaiswal AK (2018) Emerging technologies for the pretreatment of lignocellulosic biomass. Bioresour Technol 262:310–318. https://doi.org/10.1016/j.biortech.2018.04.099

Hefferon KL (2014) Nutritionally enhance food crops; progress and perspectives. Int J Mol Sci 16: 3895–3914

Hendriks S, Soussana JF, Cole M, Kambugu A, Ziberman D (2020) Ensuring access to safe and nutritious food for all through transformation of food systems (Action track 1). Scientific Group for the UN Food Systems Summit

Herrero M, Thornton PK, Mason-D'Croz D, Palmer J, Benton TG, Bodirsky BL et al (2020a) Innovation can accelerate the transition towards a sustainable food system. Nature Food 1(5): 266–272. https://doi.org/10.1038/s43016-020-0074-1

Herrero M, Hugas M, Lele U, Wira A, Torero M (2020b) Shift to healthy and sustainable consumption patterns (Action track 2)

Hertel T, Elouafi I, Ewert F, Tanticharoen M (2020) Building resilience to vulnerabilities, shocks and stresses (Action track 5). Scientific Group for the UN Food Systems Summit

Hodson E, Niggli U, Kaoru K, Lal R, Sadoff C (2020) Boost nature positive production at sufficient scale (Action track 3). Scientific Group for the UN Food Systems Summit

IACGB (International Advisory Council on Global Bioeconomy) (2020) Communiqué: expanding the sustainable bioeconomy – vision and way forward. Available at https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf

IACGBS (International Advisory Council of the Global Bioeconomy Summit 2018) (2018) Communiqué: innovation in the global bioeconomy for sustainable and inclusive. Transformation and wellbeing. Available at: https://gbs2018.com/fileadmin/gbs2018/Downloads/GBS_2018_Communique.pdf

IEA (International Energy Agency, Francia) (2019) World Energy Balances 2019 (online). Paris. Retrieved January 21, 2020. Available at: https://webstore.iea.org/world-energy-balances-2019

ILO (International Labour Organization) (2020) Sector rural y desarrollo local en América Latina y el Caribe. Available at: https://www.ilo.org/americas/temas/sector-rural-y-desarrollo-local/lang%2D%2Des/index.htm

IPCC (Intergovernmental Panel on Climate Change) (2011) Summary for policymakers. In: IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press, Cambridge

IPCC (Intergovernmental Panel on Climate Change) (2012) Renewable energy sources and climate change mitigation. Cambridge University Press, Cambridge

Italian Government (2019) The updated Italian bioeconomy strategy BIT II. Available at: http://cnbbsv.palazzochigi.it/media/1774/bit_en_2019_02.pdf

Kardung M, Cingiz K, Costenoble O, Delahaye R, Heijman W, Lovrić M, van Leeuwen M, M'Barek R, van Meijl H, Piotrowski S, Ronzon T, Sauer J, Verhoog D, Verkerk PJ, Vrachioli M, Wesseler JHH, Zhu BX (2020) Development of the circular bioeconomy: drivers and indicators. Sustainability 13(1):413. https://doi.org/10.3390/su13010413

Klümper W, Qaim M (2014) A meta- analysis of the impacts of genetically modified crops. PLoS ONE 9:1–7. https://doi.org/10.1371/journal.pone.0111629

Kniss AR (2018) Genetically engineered herbicide-resistant crops and herbicide-resistant Weed evolution in the United States. Weed Sci 66(2):260–273. https://doi.org/10.1017/wsc.2017.70

Kouser S, Qaim M (2011) Impact of Bt cotton on pesticide poisoning in smallholder agriculture: a panel data analysis. Ecol Econ 70:2105–2113

Krüger A, Schäfers C, Busch P, Antranikian G (2020) Digitalization in microbiology – paving the path to sustainable circular bioeconomy. New Biotechnol 59:88–96. https://doi.org/10.1016/j.nbt.2020.06.004

Lewandowski I (2018) Bioeconomy: shaping the transition to a sustainable, biobased economy. https://doi.org/10.1007/978-3-319-68152-8

Linser S, Lier M (2020) The contribution of sustainable development goals and forest-related indicators to national bioeconomy progress monitoring. Sustainability 12. https://doi.org/10.3390/su12072898

Lokkoa Y, Marc H, Karl S, Philippe S, Van Montagu M, Mauro G (2017) Biotechnology and the bioeconomy – towards inclusive and sustainable industrial development. New Biotechnol. https://doi.org/10.1016/j.nbt.2017.06.005.

Macias M, Girón C, Nieto M, Chavrier N, Páez D, Ureña M, Moreno J, García M, de la ViñHassan SS, Williams GA, Jaiswal AK (2018) Emerging technologies for the pretreatment of lignocellulosic biomass. Bioresour Technol 262:310–318. https://doi.org/10.1016/j.biortech.2018.04.099

Malyska A, Jacob J (2018) Plant breeding as the cornerstone of a sustainable bioeconomy. New Biotechnol 40(Part A, 25):129–132

Mangalassery S, Sjögersten S, Sparkes DL, Sturrock CJ, Craigon J, Mooney SJ (2014) To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Sci Rep 4:4586. https://doi.org/10.1038/srep04586

Melgar-Lalanne G, Hernández-Álvarez A-J, Salinas-Castro A (2019) Edible insects processing: traditional and innovative technologies. Compr Rev Food Sci Food Saf 18(4):1166–1191. https://doi.org/10.1111/1541-4337.12463
MIT (Massachusetts Institute of Technology) (2005) The third revolution: the convergence of the life sciences, physical sciences, and engineering. Consulted at: https://www.aplu.org/projects-and-initiatives/research-science-and-technology/hibar/resources/MITwhitepaper.pdf
Nelson D (2019) 75 percent of Florida's oranges have been lost to disease. Can science save citrus? Available at: https://www.universityofcalifornia.edu/news/75-percent-floridas-oranges-have-been-lost-disease-can-science-save-citrus#:~:text=%E2%80%9CCitrus%20is%20so%20important%20to,threatened%20by%20a%20devastating%20disease.%E2%80%9D&text=The%20disease%20is%20called%20huanglongbing,is%20now%20spreading%20in%20California
Neufeld L, Huang J, Badiane O, Caron P, Sennerby-Forsse L (2020) Advance equitable livelihoods (Action track 4). Scientific Group for the UN Food Systems Summit
Newell-McGloughlin M (2014) Health effects. In: Ludlow K, Smyth SJ, Falck-Zepeda J (eds) Socio-economic considerations in biotechnology regulations. Springer, New York, pp 125–143
Ordoñez-Araque R, Egas-Montenegro E (2021) Edible insects: a food alternative for the sustainable development of the planet. Int J Gastro Food Sci 23:100304. https://doi.org/10.1016/j.ijgfs.2021.100304
Organisation for Economic Co-operation and Development (OECD) (2018) The future of rural youth in developing countries: tapping the potential of local value chains. OECD Publishing, Paris. https://doi.org/10.1787/9789264298521-en
Ort DR, Merchant SS, Alric J, Barkan A, Blankenship RE, Bock R, Croce R, Hanson MR, Hibberd JM, Long SP, Moore TA, Moroney J, Niyogi KK, Parry MAJ, Peralta-Yahya PP, Prince RC, Redding KE, Spalding MH, van Wijk KJ, Vermaas WFJ, von Caemmerer S, Weber APM, Yeates TO, Yuan JS, Guang Zhu X (2015) Redesigning photosynthesis to sustainably meet global food and bioenergy demand. PNAS 112(28):8529–8536. https://doi.org/10.1073/pnas.1424031112
Park HS (2017) Technology convergence, open innovation, and dynamic economy. J Open Innov 3:24. https://doi.org/10.1186/s40852-017-0074-z
Patermann C, Aguilar A (2018) The origins of the bioeconomy in the European Union. New Biotechnol 40:20–24. https://doi.org/10.1016/j.nbt.2017.04.002
Pellegrino E, Bedini S, Nuti M, Ercoli L (2018) Impact of genetically engineered maize on agronomic, environmental and toxicological traits: a meta-analysis of 21 years of field data. Sci Rep 8(3113):1–12
Ploetz RC (2007) Cacao diseases: important threats to chocolate production worldwide. Phytopathology 12:1634–1639. https://doi.org/10.1094/PHYTO-97-12-1634
Post MJ, Levenberg S, Kaplan DL, Genovese N, Fu J, Bryant CJ et al (2020) Scientific, sustainability and regulatory challenges of cultured meat. Nature Food 1(7):403–415. https://doi.org/10.1038/s43016-020-0112-z
Refsgaard K, Kull M, Slätmo E, Meijer MW (2021) Bioeconomy – a driver for regional development in the Nordic countries. New Biotechnol 60:130–137. https://doi.org/10.1016/j.nbt.2020.10.001
Ronzon T, Piotrowski S, Tamosiunas S, Dammer L, Carus M, M'barek, R. (2020) Developments of economic growth and employment in bioeconomy sectors across the EU. Sustainability 12(11):4507. https://doi.org/10.3390/su12114507
Riva F (2020) to meeting the challenges of the rural electricity-development nexus. Energy Sustain Dev 59:226–242. https://doi.org/10.1016/j.esd.2020.10.009
Sandra N, Alessandro P (2021) Consumers' preferences, attitudes and willingness to pay for bio-textile in wood fibers. J Retail Consum Serv 58:102304. https://doi.org/10.1016/j.jretconser.2020.102304
Smyth SJ (2020) The human health benefits from GM crops. Plant Biotechnol J 18(4):887–888

Smyth SJ (2022) Contributions of genome editing technologies towards improved nutrition, environmental sustainability and poverty reduction. Front Genome Edit 4:1–9. https://doi.org/10.3389/fgeed.2022.863193
Smyth SJ, Gusta M, Belcher K, Phillips PWB, Castle D (2011) Environmental impacts from herbicide tolerant canola production in Western Canada. Agric Syst 104(5):403–410
Subramanian A, Qaim M (2010) The impact of Bt cotton on poor households in rural India. J Dev Stud 46:295–311
Sutherland C, Gleim S, Smyth SJ (2021) Correlating genetically modified crops, glyphosate use, and increased carbon sequestration. Sustainability 13:11679. https://doi.org/10.3390/su132111679
Tamburini E, Gaglio M, Castaldelli G, Fano EA (2020) Biogas from agri-food and agricultural waste can appreciate agro-ecosystem services: the case study of Emilia Romagna region. Sustainability 12. https://doi.org/10.3390/su12208392
The American Chestnut Foundation (2015) Science strategies. Available at: https://acf.org/science-strategies/tree-breeding/
Torres-Giner S, Prieto C, Lagaron JM (2020) Nanomaterials to enhance food quality, safety, and health impact. Nanomaterials 10. https://doi.org/10.3390/nano10050941
Torroba A (2020a) Liquid biofuels in the Americas: current situation and potential for development. Inter-American Institute for Cooperation on Agriculture (IICA). San José. Available at: http://repositorio.iica.int/bitstream/handle/11324/9975/BVE20058034i.pdf?sequence=2&isAllowed=y
Torroba A (2020b) Atlas de los biocombustibles líquidos 2019–2020. San José. Available at: https://repositorio.iica.int/bitstream/handle/11324/13974/BVE20128304e.pdf?sequence=1&isAllowed=y
United Nations (2021) Food systems summit 2021. https://www.un.org/en/food-systems-summit/about. Accessed 14 Feb 2021
Usmani Z, Sharma M, Awasthi AK, Sivakumar N, Lukk T, Pecoraro L et al (2021) Bioprocessing of waste biomass for sustainable product development and minimizing environmental impact. Bioresour Technol 322:124548. https://doi.org/10.1016/j.biortech.2020.124548
van Dijk ADJ, Kootstra G, Kruijer W, de Ridder D (2021) Machine learning in plant science and plant breeding. iScience 24(1):101890. https://doi.org/10.1016/j.isci.2020.101890
von Braun J, Afsana K, Frescom L, Hassan M, Torero M (2020) Food systems – definition, concept and application for the UN Food Systems Summit. Scientific Group for the UN Food Systems Summit
WBCSD (World Business Council for Sustainable Development) (2020) The circular bioeconomy: A business opportunity contributing to a sustainable world. Geneva. Available at https://www.wbcsd.org/Programs/Circular-Economy/Factor-10/Resources/The-circular-bioeconomy-A-business-opportunity-contributing-to-a-sustainable-world?fbclid=IwAR0qdYD0UCczuTvzV3YhSqhxkllAu6ftnvbR7kQ1ee758pT4S_cn_iLg7e0
Wesseler J, von Braun J (2017) Measuring the bioeconomy: economics and policies. Ann Rev Resour Econ 9:17.1–17.24
Wesseler J, Zilberman D (2014) The economic power of the Golden Rice opposition. Environ Dev Econ 19(6):724–742. https://doi.org/10.1017/S1355770X1300065X
Wesseler J, Smart RD, Thomson J, Zilberman D (2017) Foregone benefits of important food crop improvements in Sub-Saharan Africa. PLoS ONE 12(7):e0181353. https://doi.org/10.1371/journal.pone.0181353
Yadav B, Pandey A, Kumar LR, Tyagi RD (2020) Bioconversion of waste (water)/residues to bioplastics- a circular bioeconomy approach. Bioresour Technol 298:122584. https://doi.org/10.1016/j.biortech.2019.122584
Zihare L, Muizniece I, Spalvins K, Blumberga D (2018) Analytical framework for commercialization of the innovation: case of thermal packaging material. Energy Procedia 147:374–381. https://doi.org/10.1016/j.egypro.2018.07.106
Zilberman D, Kim E, Kirschner S, Kaplan S, Reeves J (2013) Technology and the future bioeconomy. Agric Econ 44:95–102. https://doi.org/10.1111/agec.12054

In the Age of Pandemics, Connecting Food Systems and Health: A Global One Health Approach

Gebbiena M. Bron, J. Joukje Siebenga, and Louise O. Fresco

1 The Challenges

Local, regional and global food security are affected by the occurrence of epidemics of zoonotic infectious diseases, caused by pathogens that spillover from animals to humans. Inversely, the susceptibility of animals and humans to infectious diseases is shaped by their health status, as largely determined by their nutritional status. Currently, this is clearly illustrated by the COVID-19 crisis (FAO and CELAC 2020; Swinnen and McDermott 2020). Diseases that affect animals and plants also continue to disrupt food security by interrupting the food supply. A One Health approach embraces the notion that the health of animals (also including aquatic species and insects), people, plants and the environment are inextricably connected. Simultaneously, innovations that address climate change, urbanization and mobility challenges should evaluate the risk for new and (re-)emerging human, animal and plant pathogens.

The COVID-19 pandemic lays bare the interwovenness of our food systems and health (FAO et al. 2020). In addition, the pandemic exposes how human health is shaped by socio-economic status and how health affects economic and social systems in return. The current pandemic was not the first, nor will it be the last. Here, we discuss the link between global food security and healthy people, animals, plants and environments, and how we can better prepare for, and minimize the chance of, future pandemics. We conclude that both public and private parties should strengthen their One Health approach to jointly realize resilient and strong global agri-food systems and health.

G. M. Bron (✉) · J. J. Siebenga · L. O. Fresco
Wageningen University and Research, Wageningen, The Netherlands
e-mail: Bieneke.Bron@wur.nl

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_46

1.1 Interconnection Among Ecosystems, Human and Animal Health – Zoonotic Infectious Diseases

COVID-19 is only one example of a zoonosis, a disease caused by the ‘successful’ transmission, spillover, of a pathogen from animals to humans. SARS-CoV-2 emerged from wildlife. There are ample similar examples; ~60% of emerging infectious diseases in humans originated from animals, and ~70% thereof originated from wildlife. Such spillover events occur most commonly where the agri-food system interfaces with natural ecosystems, as this is where humans, domesticated animals and wildlife interact.

Through humanity’s long history with animal husbandry and consumption, hygiene practices have evolved, reducing the likelihood of successful spillover events (e.g., food safety, clean water, and the elimination of rodents from shelters). However, increasing mobility, population densities and urbanization, as well as the growing length and scale of the global food supply chains and pressure on natural ecosystems by changing land use and water flow, have created new challenges. For example, dams can impact the availability of fresh water, fishing opportunities and yield, and change the ecosystem, possibly leading to an increased risk of human disease (e.g., schistosomiasis). These transitions put the need for adaptation of current restoration, prevention, surveillance and intervention strategies in sharper focus.

1.2 Poor Human Health Facilitates Infectious Disease Spread

Sub-optimal human health adds to the favorable conditions for pathogen transmission. Poor nutritional status and impaired general health of individuals and populations, for example, due to the absence of nutritious foods and access to (affordable) health care, increase susceptibility to infectious diseases. Many of the common non-infectious diseases, including obesity, diabetes, cancer and cardio-vascular diseases, impair the body’s immune response. These chronic conditions lower barriers to successful pathogen spillover from animals to humans, and subsequent pathogen transmission between people. Similar to other infectious diseases, COVID-19 disproportionately affects those with poor nutritional status and underlying health issues.

2 Impact of Zoonotic Infectious Diseases on Food Security

2.1 Direct Impacts

Large disease outbreaks disrupt overall mobility, the workforce and the supply chain (Wageningen University and Research 2020). Both the disease itself and the measures implemented to combat the COVID-19 pandemic hindered or disabled part of the workforce and continue to do so. Such disruptions in the workforce affect food supply and, in many cases, workers' income or the economic viability of businesses in the food system (Egger et al. 2021). In addition, restrictions on travel limit the movement of workers, disrupting harvest and processing operations. Similarly, trade restrictions slow down and limit the movement of goods, affecting supply and demand.

2.2 Indirect Impacts

Cascading effects of the pandemic increase price volatility and disrupt food security and the livelihoods of those dependent on the food supply chain (Zurayk 2020). COVID-19, similar to, for example, past influenza outbreaks, has changed consumption patterns. Combined with travel and trade restrictions, this resulted in, among other things, uncertainties in the food supply chain that led to volatility in producer and consumer prices. These disrupted markets most severely affect vulnerable populations, e.g., low-income families – leaving them unable to acquire nutritious food – or small farm operations. Furthermore, the COVID-19 pandemic is estimated to have put about a third of the jobs in the food value chain at risk (451 million jobs out of ~1.3 billion), disrupting the livelihoods of ~1 billion people (Swinnen and McDermott 2020).

2.3 SARS-CoV-2 and Other Infectious Pathogens in the Food Chain

Zoonotic and other infectious pathogens can be transmitted via many different routes, including water and food products. The main transmission route of SARS-CoV-2 is the respiratory route, but anecdotal evidence is available of detection of SARS-CoV-2 genetic material in frozen products (e.g., ice-cream, fish) (Plowright et al. 2017). Currently, in February 2021, the movement of SARS-CoV-2 through the cold chain is still considered as a possible route of introduction of the pathogen to the urbanized center of Wuhan, China, from where it spread across the world.

The presence of pathogens in food systems may trigger interventions to stop pathogen spread. Although we focus on zoonotic pathogens here, animal and plant diseases and pests should be kept in mind. Similar to zoonotic pathogens, the range and outbreak frequencies of these disruptors of the food supply chain and health are expected to change due to the effects of climate change. Interventions to mitigate zoonotic and notifiable animal and plant pathogens, including transport bans, the destruction of crops, and culling, directly impact the food chain and the businesses and livelihoods of those relying on it.

3 Adapting the Agri-Food System to Limit Pathogen Risk

Reducing the likelihood of spillover and onwards transmission risks of pathogens can be achieved through (i) reducing the need for natural habitat disruption, (ii) smart management of both sides of the interface between natural ecosystems and the agri-food system, and vigilance at the human- animal interface within the agri-food system, and (iii) improving overall human, animal and environmental health.

3.1 Decreasing Habitat Disruption Through the Sustainable Intensification of Land Use

Sustainable intensification of land use could aid in limiting contact between humans and livestock with natural ecosystems and wildlife. To continue to meet the growing demand for food, further acreage expansion by conversion of natural habitats into agricultural lands is expected in several regions of the world. The pressure on natural ecosystems, caused by the expanding agri-food system, tends to negatively affect biodiversity and the resilience and health of wildlife, and increases the frequency of human, domestic animal and wildlife contact. These factors all contribute to increasing the chance of spillover occurring (Plowright et al. 2017). Hence, there is a clear need to reduce natural habitat disruption. Acknowledging that the demand for food will continue to grow, reducing habitat disruption may be achieved by using and encouraging sustainable intensification practices, and by reducing food waste and promoting the consumption of products with a smaller resource use foot print.

3.2 Smart Management and Vigilance at the Interfaces Through Surveillance and a Readiness to Intervene

Risk assessments should inform surveillance and readiness strategies to optimize pathogen detection and intervention. Over the past decades, we have created an increasingly connected network in which pathogens can spread, with the agri-food system being an integral part of this conduit (Bakalis et al. 2020). Here, the domains of food security, food safety and animal, environmental, plant and human health clearly overlap: from hunting practices to livestock farming, from butchering practices at home to slaughterhouses, from trade of live animals in markets and unsafe food preparation practices to contaminated food products in supermarkets, and the length and scale of parts of the global food system.

Detection efforts aimed at preventing pathogen spillover and spread throughout these highly connected networks can be optimized by mapping and assessing the risk, specifically, at the human and domestic animal-wildlife interface and in the transport (cold) chain. Regulation, targeted sampling and surveillance throughout the system, complemented by appropriate hygiene and biosecurity measures, form the first steps to preventing shocks to the food system and health.

Optimized surveillance at the human-domestic animal-wildlife interfaces may enable early detection of (re)emerging pathogens and unexplained disease symptoms (e.g., undiagnosed pneumonia in the case of SARS-CoV-2). This early detection provides the opportunity for early interventions and a re-design of the system. Importantly, clear communication with producers and the public about biosecurity measures and a rapid and strong unified response are needed to prevent and control potential outbreaks.

3.3 Improving Overall Human, Animal and Environmental Health – A Global One Health Approach

The current pandemic presents opportunities for positive change (Monti 2021). This is the time for governments, the private sector and society as a whole to create more resilient food production and trade systems that put less strain on the environment and insulate vulnerable populations from shocks – instead of amplifying their vulnerability (as is happening with COVID-19).

Food security is essential to human health and wellbeing, and a healthy human population is less susceptible to pathogens (e.g., by reduced undernutrition, obesity, and resulting diseases). Governmental actions can lead the way to providing food security, by ensuring the functioning of the food supply chain and food systems (e.g., minimizing disruption in the trade of goods, providing employment services to migrant workers), and by communicating clearly to avoid mass panic and disproportional consumer behavior during disease outbreaks (PAHO 2021). The private sector can weigh their impact on health and the environment, considering that their supply chain may be disrupting natural habitats and that unknown pathogens may emerge at their farms, be transported in their cold chains, or disproportionately affect their staff. These actions, serving the global and national good, should be governed through global institutions to ensure governance of the food system and health for all. We, humans should also recognize the impact of the consumption choices that we make on a daily basis.

The interconnectedness of environmental, human and animal health can be leveraged in food systems to find unconventional opportunities to improve health (Fasina et al. 2021). Further research and an improved understanding of the role of food systems in the context of Global One Health may provide additional entry points via the food system for sustainable, culturally acceptable and economically feasible interventions.

4 Towards Food System Resilience

Resilient systems allowing for rapid recovery are needed to minimize direct and indirect health effects of shocks to the food system. Shocks, small and large, will continue to disrupt food systems, although efforts to prevent and minimize shocks (as described above for zoonotic infectious diseases) may reduce the frequency and severity of shocks.

Management of the interdependencies between health and food systems to improve health for all presents many challenges, including the need for a change in mindset. Nevertheless, the elements that connect the food system with environmental, animal, plant and human health, as well as human health systems, are becoming more visibly connected in global, regional and national initiatives (Berthe et al. 2018). The 2021 UN Food Systems Summit is one example of such an initiative using an interconnected approach to set the stage for global food system transformation to achieve the Sustainable Development Goals by 2030. Another example is the September 2020 initiative to create a One Health High-Level Expert Council by UN Environment, FAO, OIE and WHO to address risks at the human-animal-environment interface. Furthermore, there is the materiality matrix in corporate sustainability reports, wherein stakeholder interests and a company's social, economic, and environmental impact are weighted. Also, the European commission is moving towards a code of conduct for participants in the food supply chain. Such a code of conduct could be considered at a global level. When consumers, producers and governments combine their efforts and take a Global One Health approach to re-designing the agri-food system, significant steps can be made towards food system resilience and better health.

References

Bakalis S, Valdramidis VP, Argyropoulos D, Ahrne L, Chen J, Cullen PJ, Cummins E, Datta AK, Emmanouilidis C, Foster T, Fryer PJ, Gouseti O, Hospido A, Knoerzer K, LeBail A, Marangoni AG, Rao P, Schlüter OK, Taoukis P, Xanthakis E, Van Impe JFM (2020) Perspectives from CO+RE: how COVID-19 changed our food systems and food security paradigms. Curr Res Food Sci 3:166–172. https://doi.org/10.1016/j.crfs.2020.05.003

Berthe FCJ, Bouley T, Karesh WB, Le Gall FG, Machalaba CC, Plante CA, Seifman RM (2018) Operational framework for strengthening human, animal and environmental public health systems at their interface. World Bank Group, Washington, DC. (English). http://documents.worldbank.org/curated/en/703711517234402168/Operational-framework-for-strengthening-human-animal-and-environmental-public-health-systems-at-their-interface

Egger D, Miguel E, Warren SS, Shenoy A, Collins E, Karlan D, Parkerson D, Mobarak AM, Fink G, Udry C, Walker M, Haushofer J, Larreboure M, Athey S, Lopez-Pena P, Benhachmi S, Humphreys M, Lowe L, Meriggi NF, Wabwire A, Davis CA, Pape UJ, Graff T, Voors M, Nekesa C, Vernot C (2021) Falling living standards during the COVID-19 crisis: quantitative evidence from nine developing countries. Sci Adv 7(6):eabe0997. https://doi.org/10.1126/sciadv.abe0997

FAO and CELAC (2020) Food security under the COVID-19 pandemic. FAO and CELAC, Rome. https://doi.org/10.4060/ca8873en

FAO, IFAD, UNICEF, WFP and WHO (2020) The state of food security and nutrition in the world 2020. Transforming food systems for affordable healthy diets. FAO, IFAD, UNICEF, WFP and WHO, Rome

Fasina FO, Fasanmi OG, Makonnen YJ, Bebay C, Bett B, Roesel K (2021) The one health landscape in Sub-Saharan African countries. One Health 13:100325. https://doi.org/10.1016/j.onehlt.2021.100325

Monti M (2021) Chaired Independent Commission of WHO-Europe: Pan-European Commission on Health and Sustainable Development. Report: drawing light from the pandemic – a new strategy for health and sustainable development. https://www.euro.who.int/__data/assets/pdf_file/0015/511701/Pan-European-Commission-health-sustainable-development-eng.pdf

PAHO (2021) Food security in a pandemic. Retrieved January 28, 2021, from https://www.paho.org/disasters/index.php?option=com_docman&view=download&category_slug=tools&alias=533-pandinflu-leadershipduring-tool-7&Itemid=1179&lang=en

Plowright RK, Parrish CR, McCallum H, Hudson PJ, Ko AI, Graham AL, Lloyd-Smith JO (2017) Pathways to zoonotic spillover. Nat Rev Microbiol 15(8):502–510. https://doi.org/10.1038/nrmicro.2017.45

Swinnen J, McDermott J (2020) COVID-19 and global food security. International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.133762

Wageningen University & Research (2020) The effects of COVID-19 on food systems: rapid assessments. https://www.wur.nl/en/Research-Results/Research-Institutes/centre-for-development-innovation/Our-Value-Propositions/Guiding-Sector-Transformation/The-effects-of-COVID-19-on-food-systems-rapid-assessments.htm

Zurayk R (2020) Pandemic and food security. J Agric Food Syst Community Dev 9(3):17–21. https://doi.org/10.5304/jafscd.2020.093.014

How Could Science–Policy Interfaces Boost Food System Transformation?

Etienne Hainzelin, Patrick Caron, Frank Place, Arlène Alpha, Sandrine Dury, Ruben Echeverria, and Amanda Harding

1 Introduction

There is broad agreement—both among and between researchers and policymakers—on the need to transform food systems to make them more healthy, sustainable and resilient. Countries have committed to this effort in the declaration on the "Future We Want" and the 2030 Agenda for Sustainable Development. Behind this agreement, however, are disagreements about what exactly needs to be transformed, the pathways to transformation, and the role of technology in the transformation process as we pursue food systems that work for the poor as well as the wealthy. First, although the transformation challenge is global, food systems are hugely diverse, context- and culture-specific, and embedded in a very complex world that is facing growing

E. Hainzelin (✉)
The French Agricultural Research Centre for International Development (CIRAD), University of Montpellier, Montpellier, France
e-mail: etienne.hainzelin@cirad.fr

P. Caron
High-Level Panel of Experts (HLPE) of the United Nations Committee on World Food Security and CIRAD, Vice president for International Affairs, University of Montpellier, Montpellier, France

F. Place
Institutions, and Markets, International Food Policy Research Institute (IFPRI), Montpellier, France

A. Alpha · S. Dury
CIRAD, University of Montpellier, Montpellier, France

R. Echeverria
International Food Policy Research Institute (IFPRI), Montpellier, France

A. Harding
Convene, Paris, France

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_47

uncertainties. Thus, a solution that is viable for one context may not work in another; solutions must be custom-fit for specific situations, constraints, and the capacity to change of the stakeholders involved. Second, scientists and policymakers are only two groups among a complex set of actors involved in food system transformation. Within and across each set of actors—scientists, policymakers, private sector entities, civil society organizations, and so on—there is a wide diversity of viewpoints and visions, as well as diverging values, interests, strategies, and power (Resnick et al. 2018; OECD 2021a). In this complex setting of science—society relations, science—policy interfaces play a key role. Policymakers receive information from different constituencies, scientists being one of them; what distinguishes scientists is that, when they disagree, which is common, they have the capacity to say, from a scientific point of view, what is commonly accepted, what is known, where consensus is lacking, and why.

Since the seventeenth century Age of Enlightenment, science has been viewed as the driver of progress for humanity. Scientists' and policymakers' roles were well defined: scientists would think rationally so as to understand the world and, in some cases, to define and solve problems, and would then provide input for decision-makers. Today, however, the dialogue between science and policy has become more complex (Von Braun 2018). First, the categories of actors are not clear-cut. For example, in many advanced countries, private agricultural research (R&D) is pre-eminent in the food sector; as a result, the private sector is, simultaneously a strong business stakeholder, a powerful scientific actor, and an active political lobby. Second, in practice, scientists and policymakers have different rules and rhythms, and different kinds of accountability to society. Their roles are evolving rapidly, especially in this era when the credibility of and trust in science is subject to increasing scrutiny by politicians and society as a whole. The participation of both citizens and the private sector further muddle science—policy interfaces. Citizens increasingly question food-system-related science, asking scientists to be accountable, and participate more in governing local food systems (Laforge et al. 2016; Andrée et al. 2019).

In this renewed and pluri-actors context, the roles of scientists and policymakers must evolve to meet expectations for their contributions to food system transformation. Science—policy interfaces are currently both bottlenecks to change, when they do not function well, and potential powerhouses for food system transformation when they are active and effective.

This chapter describes the wide diversity within the science and policy spheres and the multifaceted nature of science—policy interfaces. It argues that enhancing the powerful leverage of science—policy interfaces requires that both researchers and policymakers go beyond conventional roles to do "business as **un-**usual." These recommendations draw heavily from the synthesis of the high-level event **Bonding Science and Policy to Accelerate Food Systems Transformation,** held on

February 4, 2021,[1] to contribute to the upcoming United Nations Food Systems Summit (UNFSS), with the participation of the Summit's organizers. With over 40 presenters and 600 delegates from more than 60 countries representing decision- and policymakers, international organizations, civil society, the private sector, think tanks, and academics, this event put out a strong call to action for both the science and policy communities (Hainzelin et al. 2021).

1. A wide variety of scientists and policymakers

2 On the Science Side

Science is a very broad concept, and scientific research, or "science in the making," is one central factor in permanent transformation (Latour 1987). Indeed, scientific institutions have a specific mandate to produce certified knowledge, applying rigorous methods backed by credible theories. Scientists use specific tools (experimental methods, statistical analysis, conceptual modeling, and so on) to establish and test the robustness of their results. However, although scientific researchers follow common rules, the ways in which they work and produce new knowledge are very diverse and embedded in different frameworks. The issues and scientific questions they choose to study are shaped by the objectives of the institutions they work for (public/private research centers, universities), the kind of funding they rely on (public, private), and also their personal values and beliefs. Scientific communities and their priorities are thus shaped by the society they belong to and depend on (Merton 1942).

Moreover, scientific research is not the only source of knowledge and evidence; it is one among various "knowledge producers," and global centers of expertise, such as HLPE/CFS[2] and IPBES,[3] now recognize the importance of local and lay knowledge.

Within the scientific world, there is a polarity—and sometimes tension—between "research-driven" (fundamental knowledge, mostly disciplinary approaches, exploration of the unknown, longer-term perspective) and "demand-driven" or "policy-driven" research (applied to problems to be solved, shorter-term perspective, mobilization of available knowledge through expertise). These research approaches relate to the policy world in different ways, but they clearly inform each other: the former provides fundamental knowledge and tools and the latter works for their integration

[1] Organized by Montpellier University of Excellence (MUSE, University of Montpellier) and its members (CIRAD, INRAE, IRD) and partners, in particular, CGIAR, under the high patronage of the French Government, with support from the French Development Agency (AFD) and Agropolis International.

[2] High-Level Panel of Experts on Food Security and Nutrition of the UN Committee on World Food Security.

[3] Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services.

across disciplinary communities. To ensure synergy between the two approaches, both science policies and institutional support are needed.

Scientific communities are thriving in both private and public settings, but with different objectives, programming, incentives, and rewards. The private sector is focused on short- and long-term profits and aligns its research accordingly. If profits are affected by how companies conduct their affairs (for example, by possible positive or negative social, nutritional, environmental impacts) due to consumer awareness and response or due to government policy, companies will orient more of their research toward those objectives. But otherwise, sustainable and equitable food systems will likely be neglected by private sector researchers and left to the public sector to address.

Research operates within a very competitive world. Fierce competition among institutions, research units, labs, and countries can be a motor for better science, even though cooperation is claimed as a necessity for tackling complex challenges. This competition is not only about funding, but also ideas, prestige, and influence, and thus plays an important role in science—policy interactions. The framing of the problems to be solved (Merton 1973) affects the legitimacy of research questions, and hence the taxpayer money invested in them. There is rivalry among disciplines; all scientific visions are not equal in terms of legitimacy or political influence (for example, the attention paid to economics- "the science of the princes" - *vs* other social sciences). The same holds true for scientific methods (qualitative vs. quantitative, multidisciplinary vs. transdisciplinary, and so on). There is also competition between public and private research; in agrifood system research, in which the private sector is significant and sometimes predominant, the question of legitimacy becomes very complex. In a quest for "excellence," the widespread adoption of bibliometric tools to measure science quality has sometimes generated a bias that affects the integrity, credibility, and legitimacy of scientists, which further muddles science—policy interfaces.

Finally, there is a common, albeit not explicit, theory of change about the role of scientific knowledge or evidence in the emergence of change. Because scientists' expectations can be naive when disconnected from the policy world, they sometimes expect that outstanding results, high-level publications, or breakthrough technologies should naturally flow to policymakers to shape their decisions. This is clearly not the case.

3 On the Policy Side

Of the variety of public actors working at different scales, only a fraction is effectively in charge of "making policies." Political actors, for example, have a specific and eminent role in shaping a future vision and propositions and eventually governing, with their constituents giving legitimacy to their mandate. Their role is distinct from that of public actors in policymaking. In addition, as emphasized by the concept of governance, policymaking refers to coordination processes that involve a plurality of actors, both public and private, not just a centralized executive authority.

Food system policies are closely linked with health, land, and environmental, territorial and social policies. Their implementation is therefore dispersed across various ministries, government bodies, and administrative levels, and their coordination is an inherent challenge in advancing transformational objectives. In addition, some emerging food system challenges or problems require new thinking. For example, hunger has been understood largely as a phenomenon of poverty and poor productivity (and associated with conflict); but obesity, while also a nutritional problem, is a different issue altogether. Tackling multiple objectives at once, namely, making diets and food systems healthy, inclusive, and sustainable, presents an even greater challenge for both scientists and policymakers.

Many policies are informed to some extent by scientific knowledge, including not only laws, regulations, guidelines, and standards, but also incentives for education, research, infrastructure, development, public procurement, and others. Most of these translate into budget allocations. Their scientific basis can be a key element for policy accountability, although policymakers may also have simplistic expectations of science, expecting basic, clear-cut guidance. However, science and policy are not hermetic compartments: some policymakers have a strong scientific education and background, and likewise, some scientists have experience in policymaking. The difficulty of bridging and integrating the two sides may be more about differences in the rules of the game and constraints to research and policymaking than about misunderstanding each other's worlds.

2. Interfacing science and policy at different scales, in different formats

4 A Relation of Supervision: Science Is Governed and Influenced by the State

A key science—policy interface is formed by "science policy"—the rules, institutions, and budgets that governments set to govern and shape science and innovation systems. Because of the nature of scientific research, there is constant negotiation between scientific institutions and governments to find an acceptable balance among command, control, the necessity to find solutions, and the demand for creativity and freedom to explore new ideas. Balance must also be achieved in science policy among principles of intellectual freedom and property rights, open access, fairness and the protection of indigenous knowledge and human subjects, inter alia, while fostering a thriving science system (UNESCO 2018). In addition, scientific advances have opened the possibility of research in contentious areas such as genetic engineering, around which countries must make decisions. Governments have responded with various policies, strategies, plans, directives, institutional arrangements, and budget allocations to address these concerns.

In agrifood innovation systems, the significant and growing role of private sector research must be recognized. Private sector spending on agricultural R&D accounted for 25% of all global research spending in 2014 (Beintema et al. 2020); when food research is also considered, the share of the private sector is even greater. In rich countries, private sector R&D accounted for more than half of all agrifood research in 2011, and the share of private sector R&D in middle-income countries doubled (from 19% to 37%) between 1980 and 2011 (Pardey et al. 2016). Although much of this growth is self-driven by companies, governments can and have promoted private research through tax rules, patent policies, public—private partnerships, and strategic allocations. Private sector research focuses mainly on development of proprietary technologies, leaving many other key aspects, like environmental or social effects of the food system, for public researchers. Private foundations, which also provide significant funding for public research institutions, represent a wider range of interests, including social and environmental impacts. Identifying priority food system topics for publicly funded research in this complex environment is a critical issue for governments and other stakeholders.

Public R&D in the agrifood sector is typically carried out by public institutions and universities, funded through autonomous public sources, government ministries and offices, and foundations. However, the increasing competition for funding blurs the distinction between public and private money. The public and private sectors also interface with research organizations and researchers from outside their country; science policy plays a role here as well, for example, in enabling the transfer of technology, recognition of testing performed elsewhere, and so on. Smaller states and low-income countries may also find it beneficial to rely heavily on regional or global innovation systems or patent offices (Graff and Pardey 2020) as a more efficient approach to meeting demand for science.

Several key challenges in the governance of science emerge from a set of OECD country reviews of national innovation policies (OECD 2021b): a lack of updated overall science, technology, and innovation strategies to guide research and development; a high level of fragmentation among both providers of science and sources of funding, rendering coordination around priority research difficult; funding levels and funding models insufficient to maintain high-quality institutions and individuals; and inadequate generation of scientists through national educational systems.

5 Growing Structuration and Complexity of Science—Policy Interfaces[4]

At national and local levels, numerous organizations and initiatives link governments and scientific institutions, reflecting a global effort to link science and society (Chabasson et al. 2016; Van der Hove 2007). These include scientific or collective

[4] UNEP definition: "Science–policy interfaces can be defined as institutions that aim to improve the identification, formulation, implementation and evaluation of policy to render governance more

expertise committees on specific issues, tasked with providing knowledge for government policies at the legislative and executive levels. In addition, many countries have installed chief scientists at the cabinet level or have expanded experimental projects involving policymakers and scientists together, such as living labs, sometimes extending to multistakeholder platforms. The increasing number of district- and country-level mechanisms to link science and policy offer a means to share accountability.

At the international and multilateral level, there is a growing effort to build collective expertise to formulate state-of-the-art scientific knowledge about specific global problems in order to identify legitimate, efficient, and consensus-based political actions to be implemented at the global level. Similar to IPCC[5] and IPBES in the climate and biodiversity domains, the experience of the HLPE/CFS offers an opportunity to mobilize scientific communities and knowledge to contribute to decision-making. Although each of these panels operates through specific modalities,[6] they are similar in the way they develop negotiation processes about critical, emerging, and controversial issues: they all bring together thousands of scientists from different disciplines and regions; they all rely on consultation and peer review processes; and they are all articulated to multilateral political arenas that relate in one form or another to the United Nations. Convening thematic teams of world-class scientists, the HLPE/CFS has been recognized as a fundamental tool for building a scientific consensus on problem formulation and elements of solutions in the food security and nutrition domain (CFS 2018; Gitz and Meybeck 2011). HLPE scientific reports feed into a process of multilateral negotiation led by the CFS and involving different stakeholders, including member-state policymakers, and are eventually reflected in policies. There are also a number of flourishing scientific panels,[7] some of which interact with civil society, that explicitly aim to use scientific knowledge to influence policies, a number of them playing a clear advocacy role. With their well-communicated reports and recommendations, these panels are able to shape the public debate on global food system reform.

---

effective by: defining and providing opportunities for processes which encompass interrelations between science and policy in a range of domains; assigning roles and responsibilities to scientists, policy-makers and other relevant stake- and knowledge-holders within these processes; and guiding and coordinating their interactions" (UNEP 2017).

[5] Intergovernmental Panel on Climate Change.

[6] The HLPE/CFS, for example, exclusively responds to CFS requests. Its reports are not approved by governments, a fact that has both positive and negative consequences, but are the basis for an intergovernmental negotiation process. The level of financial resources differs from one panel to another, as does their political anchorage in UN institutions.

[7] For example, the Global Panel on Agriculture and Food Systems for Nutrition "works with international, multi-sector stakeholders, to help governments in low- and middle-income countries develop evidence-based policies that make high-quality diets safe, affordable and accessible"; the International Panel of Experts on Sustainable Food Systems (IPES-Food) "is an independent panel of experts with a mission to promote transition to sustainable food systems around the world"; and the EAT Forum is "dedicated to transforming our global food system through sound science, impatient disruption and novel partnerships."

6 Mechanisms at Play and Emerging Issues in These Interfaces

On the whole, in recent history, science has strongly shaped the way challenges are perceived and understood. This is true in many domains (climate, environment, biodiversity, and more), but particularly true in the food system domain. More specifically, science has informed the process of policymaking through various formal channels, including collective expertise, particularly consultation and scientific evaluation mechanisms instituted through legal formulation processes. Informal channels, such as the media and civil society advocacy campaigns, have also played a role when they convey solid scientific diagnostics and results.

For example, research by several scientific teams showed the importance of interventions in domains other than nutrition in reducing the burden of malnutrition. Specifically, the idea of nutrition-sensitive agriculture, promoted by Ruel in the journal *Lancet*, has been very influential in forming consensus views on this topic. Based on a growing quantity of published scientific evidence, many development agencies, together with governments and NGOs, launched new "nutrition-sensitive agriculture" initiatives and redesigned their logical frameworks to take nutrition outcomes into account. In follow-up, researchers tracked these initiatives, documented their outcomes—positive and negative—and raised new questions (Ruel et al. 2018). Outstanding discoveries on the linkage between nutrition and health, intestinal microbiota, the impact of agriculture on biodiversity and soil and water health, the carbon footprint of food, and the quantity of food waste and loss are other examples of the way scientific results drastically change public awareness and, therefore, the orientation of policies.

Yet, there is a gap between the rigorous scientific process of producing evidence on a specific question on the one hand and the complex process of policymaking on the other hand, the latter of which must balance empirical information and scientific evidence with management of trade-offs, political agendas, and societal acceptability (Gluckmann 2016). This points to the limitations of the notion of "evidence"[8] in policymaking (Rycroft-Malone et al. 2004; Saltelli and Giampietro 2017); evidence is not independent of power balances (Loconto et al. 2019). Moreover, there is sometimes confusion between evidence and certainty that can affect policymaking; evidence that scientists perceive to be most convincing is often the most complex and the least easily digested by policymakers. There is also a potential for bias in the choice of evidence to legitimize a specific policy ex post, with possible political manipulation of the research (Soussana et al. 2021). Hence, it is important to appraise the evidence, including its limitations, using guidelines and procedures to assess quality in terms of credibility and legitimacy (for example, in the health domain, WHO guidelines).

[8] With regard to health, Lomas et al. (2005) define evidence as "findings from research and other knowledge that may serve as a useful basis for decision-making in public health and health care." This definition was adopted by The Health Evidence Network (EVIDENT).

Many analyses show the extent to which scientific evidence is framed by social and political debates. For example, the reform of Europe's Common Agricultural Policy in the 1990s was fueled by "economic" models from INRA.[9] These "scientific models" were attractive because they also converged with other stakeholders' interests (Fouilleux 2000, 2004).

As mentioned above, policymakers and scientists are not the only players. Many other stakeholders play an explicit or implicit, visible or invisible role in science—policy interfaces (OECD 2021a). Sometimes, the concept of governance, when it involves other stakeholders (such as public—private partnerships or voluntary guidelines), becomes so broad that its legitimacy can be questioned in view of the potential for a strong imbalance in the actors' powers, privatization of public goods, and betrayal of the common good. Strengthening civil society involvement in food system governance is presented by some as part of the solution (IPES-Food 2021), and its absence as a step backwards (Canfield et al. 2021). However, the ambiguity of these relations can frustrate both scientists and policymakers and highlights the need to build capacities on both sides.

7 Asymmetries Within and Among Countries in Terms of Scientific Capacity

Applied scientific research is context-specific, and some developing countries are lacking the scientific capacity to tackle their most burning challenges (for example, climate or SDG roadmaps, UNFSS dialogues) (Beintema and Stads 2017). These countries often rely on knowledge generated elsewhere, generally in wealthier countries. Sharing such knowledge is certainly advantageous when it is done through respectful, inclusive, and balanced partnerships, but there are obvious risks to relying heavily on international research to build national policies (Soussana et al. 2021). Scientific capacity is an essential driver of development (US NSTC 1999; CIRAD 2017); dependence on science produced elsewhere decreases a country's sovereignty over its own transformation and can affect the framing of national challenges, the design of development and transformation pathways and, ultimately, the relevance of solutions and citizen adherence to policies.

In food systems, there will be a range of science providers driven by different interests and funding mechanisms; this could be a source of strong asymmetries due to power relationships. A critical challenge for governments is to coordinate and guide this diverse innovation system toward their respective country's agreed-upon strategies and plans. Building such strategies and plans is just the first step; maintaining coherence over the years may be a challenge, as changes in political leadership bring different visions.

[9] Institut national de la recherche agronomique (French public research institute).

3. Recommendations to go beyond conventional roles

These recommendations draw heavily from the synthesis of the February 2021 high-level science—policy event (Hainzelin et al. 2021). Enhancing the powerful leverage of science—policy interfaces requires engagement from both sides and a balance of power in their interactions.

8 Science Should Move Beyond Sounding Alarms and Supplying Knowledge

Science is and will be of foremost importance in supporting the sustainable transformation of food systems. Scientific institutions have the mandate to produce certified knowledge, using rigorous methods backed by solid theories. Yet, the role of science is far greater than simply providing evidence or transferring knowledge that will help in designing solutions, as scientists are well placed to convene and collaborate with key food system actors, especially managers, political actors, and policymakers, to jointly build plausible change scenarios based on their different bodies of knowledge. Scientists cannot pose as an external arbiter to decide what should or should not be done, but they should reinforce their role as knowledge brokers.[10]

When considering a specific food system in a specific territory, scientific institutions should address solution-oriented research questions in collaboration with other actors based on a common vision of the needed changes. This engagement should build the capacity to mainstream knowledge and solutions into a wider picture of territorial development, with links to different relevant sectors, such as health, education and infrastructure (Caron et al. 2017). The diversity and complexity of interconnected pathways and dynamics of change in food systems also imply an epistemic rupture in the way most research is doing its business; rather than prescribing and transferring turnkey packages, researchers should be designing, constantly learning, contributing expertise, promoting collective intelligence, and brokering coalitions of change.

Science is expected to help in exploring and designing plausible futures, including desirable and undesired disruptions, using foresight tools such as modeling and scenario building. To anticipate and facilitate responses to shocks, monitoring and early warning systems should be put in place that quickly assess vulnerabilities across several food system dimensions and proactively dialogue with decision-makers. When change pathways are integrated at higher scales—national, continental, or

[10] Knowledge brokers are "organizations or individuals who serve to facilitate interactions between researchers and policymakers, supporting both groups to better understand the goals and professional culture of the other, creating better links and partnerships, and ultimately leading to improved evidence for informed policymaking" (Knight and Lyall 2013). Knowledge brokers also support researchers by translating and adapting findings to the local context (Norton et al. 2016).

global—common constraints or challenges appear to be in the way of desirable transformation. Science must also be instrumental at these scales and contribute to transformation by facilitating agreement on a shared vision of desired changes and formulation of explicit pathways to achieve them. This means understanding the change processes (Béné et al. 2020), their patterns, power dynamics, consequences, and obstacles, and their impacts on the management of shock responses and risk and uncertainty. This includes offering science-based insights into trade-offs across stakeholders, sectors, spatial levels, and timeframes, and identifying lock-ins that create path dependencies, including the issue of why scientific evidence is not being used. Science should also be able to provide a spatiotemporal perspective of these trade-offs that integrates views from across the natural, technical, and social sciences.

9 Policy Should Make Effective Use of Knowledge for Decision-Making

As most food system innovation is context-specific and takes place within complex environments, action-oriented knowledge transfer is not a straightforward linear process. Innovation must be specifically tailored to local contexts for effective brokerage and collaboration among multiple stakeholders. Consequently, it is essential that scientists participate in multisectoral transformation arrangements, for example, commissions involving key actors—policymakers, civil society, and the private sector—and recommend policy actions through transparent, solution-based deliberative dialogue processes.

Given overlapping challenges and sometimes contradictory expectations, political actors and policymakers should not expect single solutions that meet all their criteria. They should strive to benefit from scientists' contributions by collaborating with the science community to ensure relevant and timely research. Novel incentives and institutional mechanisms should be explored to stimulate and strengthen dialogue and action toward positive outcomes in complex contexts. These mechanisms should be conducive to coordinated engagement of science and policy actors, while remaining open to a range of stakeholders throughout the process.

Policymakers should support the decision-making process by putting forward explicit demands for the science community to identify obstacles to food system transformation, to develop technological, institutional and policy innovations that will promote the desired transformation, and to design progress metrics that account for the complexity of this transformation, along with the trade-offs and impacts. This will help build the dialogue process across scientific disciplines, as well as between scientists and policymakers, and identify different possible, plausible and tailored transformative pathways in a long timeframe that buffers possible shifts arising from any change in political leadership.

This mutual engagement also implies capacity-building for policymakers to gain further insight into complex science-based solutions, the trade-offs, the extent of uncertainty, and the nature of scientific evidence. Scientists must also acknowledge the political dimension of scientific research and have a clearer understanding of the policymaking process, as well of the constraints of political timeframes, divergent interests, and power asymmetries.

Enhanced science–policy interfaces founded on these principles could better ensure that knowledge—as a public good—is a keystone of food system transformation that contributes to sustainable development.

10 "Business as Un-Usual" to Boost Food System Transformation

There is no single science—policy interface, but many, at different scales, for different functions, addressing different challenges. These interfaces need to be strengthened, connected, and streamlined to ensure the consistency of food system transformation. Working with existing interfaces, rather than creating new ones, is likely the best way forward.

To meet the challenges, scientists and policymakers will have to interact in new ways: designing together, rather than transferring and applying knowledge, and fostering dialogues, co-learning, and convergence, rather than confrontation and polarization. This "business as ***un***-usual" would rely specifically on four pillars:

- Generating actionable knowledge, data, and metrics in a collaborative way to move beyond obstacles and to address trade-offs and barriers to change, including power asymmetries, path dependency, conflicts of interest, and risk and uncertainty.
- Articulating models, knowledge and place-based innovation to design, implement and assess specific transformative pathways: this requires specific arrangements, dialogues and approaches, including scientific approaches.
- Connecting expertise mechanisms to address multisectoral and multiscale processes toward sustainable development; at the international level, the joint mobilization of IPCC, IPBES, and HLPE/CFS is necessary to address the interconnected challenges of climate, environment and food systems.
- Strengthening scientific cooperation through major challenge-oriented alliances and programs, spanning public and private researchers that address priorities for food system transformation.

Without effective science—policy interfaces, transformation is hampered at a time when urgent action is crucial to design and implement healthy, equitable and sustainable food systems. The COVID-19 pandemic has shown that a tailorable science—policy interface can be beneficial. The key challenge today is to develop effective mechanisms for actively connecting scientific knowledge with policy actions through deliberative dialogue. Examples of effective interfaces are reason for optimism. But new thinking and flexible funding models, at national and global levels, are also required to enable science to respond to short-term policy needs without diverting funds from longer-term research. Strengthening scientific capacity is a critical longer-term objective requiring commitment from national governments, as well as more strategic and coordinated approaches from the global scientific community, especially in view of cross-country imbalances in scientific capacity.

Now is the time to learn from and make effective use of these interfaces, while connecting them, boosting their impact, and innovating to build a desirable future. Science—policy interfaces can play a decisive role if they are able to dovetail divergent views and overcome polarized debates and sectoral fragmentation. They must also help us to look ahead and to bridge local and global processes and actions.

References

Andrée P, Clark J, Levkoe C, Lowwitt K (eds) (2019) Civil society and social movements in food system governance, Routledge studies in food, society and the environment, Taylor & Francis, 216 p

Beintema N, Stads G-J (2017) A comprehensive overview of investments and human resource capacity in African agricultural research. IFPRI. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/131191/filename/131402.pdf

Beintema N, Nin Pratt A, Stads G-J (2020) ASTI global update 2020. ASTI Program Note, International Policy Research Institute, Washington, DC

Béné C, Fanzo J, Prager SD, Achicanoy HA, Mapes BR, Alvarez Toro P et al (2020) Global drivers of food system (un)sustainability: a multi-country correlation analysis. PLoS One 15(4): e0231071. https://doi.org/10.1371/journal.pone.0231071

Canfield M, Anderson MD, McMichael P (2021) UN food systems summit 2021: dismantling democracy and resetting corporate control of food systems. Front Sustain Food Syst 5:103

Caron P, Valette É, Wassenaar T, Coppens DE, Papazian V (2017) Living territories to transform the world. Editions Quae, 274 pp

Chabasson L, Rankovic A, Bonnel A (2016) Fonder les politiques publiques sur les sciences et la connaissance. Regards sur la terre. Iddri/AFD

CIRAD (2017) CIRAD strategic vision and ambition 2018–2028. https://collaboratif.cirad.fr/alfresco/s/d/workspace/SpacesStore/42149ae0-af9f-4432-981b-2d8574acd0ed/2018-2028%20Strategic%20vision.pdf

Committee on the world Food Security (CFS) (2018) Evaluation – implementation report. CFS_BurAG_2018_07_23_03b_Evaluation_Implementation_Report.pdf (fao.org)

Fouilleux E (2000) Entre Production et institutionnalisation des idées, La réforme de la Politique Agricole Commune. Revue française de science politique 50:277–305

Fouilleux E (2004) CAP reforms and multilateral trade negotiations: another view on discourse efficiency. West Eur Polit 27(March (2)):235–255

Gitz V, Meybeck A (2011) The establishment of the high level panel of experts on food security and nutrition (HLPE). Shared, independent and comprehensive knowledge for international policy coherence in food security and nutrition. ⟨hal-00866427⟩. Federal Reserve Bank of St Louis

Gluckmann P (2016) The science-policy interface. Science 353:6303

Graff G, Pardey P (2020) Inventions and patenting in Africa: empirical trends from 1970 to 2010. J World Intellect Prop 23:40–64

Hainzelin E, Caron P, Echeverria R, Harding A, Enriquez M, Broin M (2021) Bonding science and policy to accelerate food systems transformation. Synthesis and recommendations. High level event Science policy February 4th 2021. https://www.agropolis.org/pdf/news/recommendation-february-4.pdf

IPES-Food & ETC Group (2021) A long food movement: transforming food systems by 2045. www.ipes-food.org/pages/LongFoodMovement

Knight C, Lyall C (2013) Knowledge brokers the role of intermediaries in producing research impact: the role of intermediaries in producing research impact. Evid Policy 9(3):309–316

Laforge JL, Anderson CR, McLachlan SM (2016) Governments, grassroots, and the struggle for local food systems: containing, coopting, contesting and collaborating. Agric Hum Values 34: 663–681

Latour B (1987) Science in action: how to follow scientists and engineers through society. Harvard University Press

Loconto A, Desquilbet M, Moreau T, Couvet D, Dorin B (2019) The land sparing – land sharing controversy: tracing the politics of knowledge. Land Use Policy (Elsevier) 2019:96pp. https://doi.org/10.1016/j.landusepol.2018.09.014

Lomas J, Culyer A, McCutcheon C, McAuley L, Law S (2005) Conceptualizing and combining evidence for health system guidance. Final report. Canadian Health Services Research Foundation, 44 p

Merton RK (1942) The normative structure of science. In: Storer NW (ed) The sociology of science. University of Chicago Press, Chicago, pp 267–278

Merton RK (1973) The sociology of science: theoretical and empirical investigations. University of Chicago Press, Chicago

Norton TC, Howell C, Reynolds C (2016) Exploratory study of the role of knowledge brokers in translating knowledge to action following global maternal and newborn health technical meetings. Public Health 140:235–243

OECD (2021a) Making better policies for food systems. OECD Publishing, Paris. https://doi.org/10.1787/ddfba4de-en

OECD (2021b) OECD reviews of innovation policy. Accessed at https://www.oecd.org/sti/inno/oecd-reviews-of-innovation-policy.htm on April 21, 2021

Pardey P, Chan-Kang C, Beddow J, Dehmer S (2016) Shifting ground: food and agricultural R&D spending worldwide, 1960–2011. International Science and Technology Practice and Policy (InSTePP) Center at the University of Minnesota

Resnick D, Haggblade S, Babu S, Hendriks SL, Mather D (2018) The kaleidoscope model of policy change: applications to food security policy in Zambia. World Dev 109(2018):101–120. https://doi.org/10.1016/j.worlddev.2018.04.004

Ruel MT, Quisumbing AR, Balagamwala M (2018) Nutrition-sensitive agriculture: what have we learned so far?. Glob Food Sec 17:128–153

Rycroft-Malone J, Seers K, Titchen A, Harvey G, Kitson A, McCormack B (2004) What counts as evidence in evidence-based practice? J Adv Nurs 47:81–90. https://doi.org/10.1111/j.1365-2648.2004.03068.x

Saltelli A, Giampietro M (2017) What is wrong with evidence-based policy, and how can it be improved? Futures 91(2017):62–71

Soussana J-F, Weill C, Caron P, Chotte JL, Joly P-B, Aggarwal P, Whitmee S (2021) International science foresight workshop: global challenges and research gaps. The Royaumont process. INRAE (France), 25 p. https://doi.org/10.15454/m3k7-j656

UNESCO (2018) Recommendation on science and scientific researchers. United Nations Educational, Scientific and Cultural Organization, France

United Nations Environment Programme (UNEP) (2017) Strengthening the science-policy Interface: a gap analysis. United Nations Environment Programme (UNEP), Nairobi, 125 p

US NSTC (National Science and Technology Council) (1999) Annual report. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/nstc99annualrpt_0.pdf

Van den Hove S (2007) A rationale for science–policy interfaces. Futures 39(7):807–826

Von Braun J (2018) Global institutions: governance reform for food, nutrition, and agriculture. IFPRI: International Food Policy Research Institute

The Transition Steps Needed to Transform Our Food Systems

Patrick Webb, Derek J. Flynn, Niamh M. Kelly, and Sandy M. Thomas

1 Introduction

The United Nations (UN) Food Systems Summit and N4G meetings in 2021 reflect a growing international recognition that the policies that fed the world in the twentieth century are no longer fit for purpose. Urgent reform is essential to achieve the goal of universally accessible and affordable healthy diets delivered by food systems that are environmentally, economically and socially sustainable.

On behalf of the Global Panel on Agriculture and Food Systems for Nutrition:
John Beddington – Former UK Chief Scientific Adviser, Senior Adviser to the Oxford Martin School and Professor of Natural Resource Management at Oxford University
Agnes Kalibata – President, Alliance for a Green Revolution in Africa (AGRA)
Akinwumi Adesina – President of the African Development Bank
Celso Moretti – President, Brazilian Agricultural Research Corporation (Embrapa)
Emmy Simmons – Senior Adviser, Non-resident, to the Center for Strategic and International Studies Global Food Security Project
Rachel Kyte – Dean of The Fletcher School at Tufts University
Rhoda Peace Tumusiime – Former Commissioner for Rural Economy and Agriculture, African Union Commission
Tom Arnold – Former Director-General, Institute of International and European Affairs (IIEA)
Shenggen Fan – Chair Professor of China Agricultural University
K. Srinath Reddy – President, Public Health Foundation of India
Qu Dongyu – Director-General, Food and Agriculture Organization of the United Nations (FAO)

P. Webb (✉)
Friedman School of Nutrition Science and Policy, Tufts University, Medford, MA, USA

Global Panel, London, UK
e-mail: Patrick.Webb@tufts.edu

D. J. Flynn · N. M. Kelly · S. M. Thomas
Global Panel, London, UK

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_48

Today's food systems are asked to nourish the world's growing population in ways that do no harm to either human or planetary health. However, the growing problems facing food systems now amount to a twofold crisis. First, global progress in addressing malnutrition in all its forms (including undernutrition, obesity and micronutrient deficiencies) and reducing diet-related diseases has stalled. Food systems are failing to provide affordable healthy diets for three billion people (FAO, IFAD, UNICED, WFP W 2020). This affects their health, the mental and physical development of children, and the earning potential of those children throughout their lives. Those affected risk being locked into lifelong inequality. Second, food systems are in a spiral of decline with environmental systems (Global Panel on Agriculture and Food Systems for Nutrition 2020a): they are a major cause of worsening degradation of soil, water and air quality, biodiversity loss and climate change. Moreover, although food systems have generally responded to the challenges posed by COVID-19, the pandemic has highlighted just how fragile and precarious the world's food systems have become.

Without decisive action, the situation is set to worsen in the future due to a multitude of factors: population growth and climate change, increasing competition for land, water and other natural resources, and emerging diseases, conflict and economic volatility. The stakes could not be higher, not just for the health of the world's population and the planet, but also for the delivery of most of the Sustainable Development Goals (SDGs), such as those relating to hunger and nutrition, growth, equality, education, wellbeing, and sustainable cities and communities (Global Panel on Agriculture and Food Systems for Nutrition 2017a).

Minor adjustments on the margins of today's food systems will be inadequate. All stakeholders involved in food systems, including government policymakers, donors, businesses, non-governmental organisations, and civil society, should be encouraged to adopt a much more radical approach. They need to rethink the ways in which food systems are currently managed, governed and used, and at the most fundamental level, they must decide what food systems need to deliver and how the performance of those systems is assessed. Reshaping food systems to respond simultaneously to nutritional, health, economic, and environmental issues presents considerable challenges, but also great opportunities for actions that would yield considerable benefits to countries (see Box 1).

However, it is not enough merely to have a vision for future transformed food systems. Policymakers need to chart a way forward to achieve them through a practical and pragmatic plan for the specific transition steps[1] that need to be taken, and how they would be funded, implemented, and managed. Developing such a plan, and implementing it effectively, presents massive challenges that must cut through the complexity of food systems and competing priorities. It will need to navigate a path through powerful forces and vested interests that might favour the

[1] In this chapter, the term 'transition' refers to the process of changing from one state of a food system to another, and it typically involves a number of specific 'transition steps.' A 'transformed' food system refers to the end state of the transition process.

status quo and impede policy change. It must also be affordable at a time when countries are still grappling with the economic catastrophe of COVID-19. The transition needs to be viewed with realism, rather than being an abstract ideal. Against this background, the following sections of this chapter set out the steps of the transition process that need to be taken on the road to a fundamental transformation of food systems.

1.1 What the Transition Process Needs to Achieve

A series of steps must be urgently planned, discussed, financed, and enacted to allow the world's food systems to transition from their current sub-optimal state to one in which they fully support the dietary patterns needed to maximise human and planetary health. The following are five key outcomes that broadly map onto the original UN Food Systems Summit Action Tracks and could usefully be considered within the Summit's deliberations:

- Food systems need to deliver universal access to healthy diets. This means moving beyond merely addressing hunger to addressing all forms of malnutrition, in part, by ensuring improved diets for all. Nonetheless, there is a global shortfall in the production of the range of nutrient-rich foods required to achieve this. For example, only 34% of fruits and vegetables needed for everyone to access a healthy diet are being produced (Dias et al. 2018). Healthy diets are currently also unaffordable for three billion people worldwide.
- Consumer demand needs to be harnessed as a significant driver of change. Consumers must be able to make informed choices and be encouraged to select nutrient-rich food options, and to play their part in reducing waste. The latter is especially important in view of projected increases in the global population, combined with increasing stresses in environmental systems essential for food production such as land, soils and water.
- Food systems must become fully environmentally sustainable, thereby operating within planetary boundaries. This is one of the three 'pillars' of the SDGs, and it is essential for both the future health of the planet and the future viability of food systems to nourish the world. Policymakers need to adopt a perspective that considers the environmental footprint of all parts of food systems, from farm to fork. This perspective needs to encompass greenhouse gas emissions, as well as the effect of food systems on biodiversity loss, changing land use and deforestation, water use, and more. Substantial reduction in losses throughout the food chain, of foods and the nutrients that they contain, needs to be a priority.
- The transition needs to be a 'just' rural and urban process, so that it reduces inequality and inequities of all kinds, rather than increasing them. No one must be left behind.
- The transition needs to deliver transformed food systems capable of operating at two speeds, i.e., responding to immediate needs and short-term shocks, but also

able to address the long-term restructuring of food systems needed to respond to climate change, population growth, and urbanisation. Governments have been too slow to act on climate change and biodiversity loss, despite warnings over many years. More recently, COVID-19 has exposed the profound fragility of food systems and their potential to exacerbate instability and conflict, for example, through food riots.

Box 1: The Potential Benefits of Transformed Food Systems

Sustainable[2] healthy diets that are accessible and affordable for all would help to drive much-needed progress across most of the SDGs. Potential benefits include:

- Elimination of a major cause of inequality for the three billion people today who cannot access a healthy diet (Bommer et al. 2018; IPBES 2019).
- A substantial reduction in levels of stunting, which, in 2019, affected 144 million children under five, and wasting, which affects 47 million pre-school children. This would lead to benefits in terms of cognitive development and educational attainment for children, and a more productive workforce.
- A substantial reduction in the prevalence of diet-related non-communicable diseases (NCDs). Without action, health costs linked to mortality and the health impacts of NCDs could reach US$2.5 trillion per year globally by 2030 (Bommer et al. 2018).
- A reduction of 41–74% in food system greenhouse gas emissions, while boosting resilience to climate shocks. This would also greatly contribute to addressing biodiversity loss. Agriculture is the largest contributor to the latter – the global annual loss of pollinating insects alone is estimated to cost US$235–577 billion (IPBES 2019).
- A substantial reduction in the economic drag presented by inadequate nutrition, which ranges from 2% to 3% of GDP in some countries and up to 11% of GDP in Africa and Asia each year. This would engender progress on poverty reduction, education and equality (The World Bank and Nutrition 2019).

[2] In this chapter, the term “sustainable” in “sustainable, healthy diets” or “sustainable food systems” refers to environmental sustainability. It is used if the contribution of a place’s food system (which delivers locally produced, but also imported and marketed, foods) can be continued without undermining the ability of the natural environment to function in the long term, i.e., the system does not drive biodiversity loss, pollution, soil degradation, or climate change. It is acknowledged that other dimensions of sustainability are also important, notably, economic and social sustainability, although detailed consideration of these is beyond the scope of this chapter.

2 Planning the Transition Steps

Food systems are complex, dynamic, and comprise many different interacting subsystems, but food system policies often fail to recognise this. Too often, a narrow approach is adopted that focuses on specific parts of the food system; for example, when setting production targets for specific food commodities. The reality is that the diverse parts of food systems are in constant flux, with the many parts influencing each other in a web of relationships. Production, trade, food prices and consumer demand are notable examples. Policymakers need to think in terms of food systems as a whole and as interacting dynamic systems, rather than individual isolated components in equilibrium.

The choice of initial transition steps should be informed by a comprehensive analysis of existing policies and private sector investments, to help identify priority outcomes (defined in holistic human and planetary dimensions) and barriers to change. A food system assessment of all public funding and institutional mandates can distinguish those that could be repurposed to help cover the costs of transition phase actions. Similarly, a review of existing food system functions, challenges and benefits would determine where best to target actions to increase the availability of nutrient-rich foods in particular, and to improve the efficiency of food value chains overall.

The complexity of food systems presents a challenge for policymakers trying to decide the first steps of the transition process. This is because of the myriad possible actions, policies and interventions. The following subsections outline how the necessary choices could be navigated.

2.1 New Priorities and Principles to Guide Transition Choices

New metrics of 'success' in the process of food system transition are needed to frame and monitor policy decisions. For example, the failure to properly account for the value of human health and the natural environment in policy decisions related to food systems is both a market failure and a widespread institutional failure. Unless addressed at the outset, this fundamental flaw will continue to distort or impede progress in food system transition.

More generally, decisions involved in planning the transition of food systems will require a new approach that should adhere to the following principles: at every stage of the transition, ensure that inequality does not increase, and that the poor are able to access and afford healthy diets; avoid closing off options for the future; invest in strengthening institutions and capacity-building; ensure transparency to engender trust and 'buy-in'; base decisions on evidence and transparent expectations; and establish feedback mechanisms for adjustment. This last point is particularly relevant to actions that may be under-explored in some contexts. Limited trials of different options with wide societal engagement and transparency of intent will help to start the transition process, and inform subsequent wider rollouts.

A priority should be to ensure a 'just' transition in which all classes of society benefit, and in which inequality at all scales (international, national, and local) is reduced rather than increased. This is important, since low- and middle-income countries (LMICs) are likely to be least able to resource the transition of their food systems, and the poor in any country will be inadequately placed to cope with fluctuations in food prices that might occur during the process. Coordination among high-income countries (HICs), LMICs and the donor community will be needed to support transition agendas.

Policy decisions across government also need to be aligned with national food-based dietary guidelines (FBDGs). FBDGs are now available in roughly 100 countries across the world and are designed to inform consumer choice (FAO n.d.). However, much greater use should be made of them to inform policy decisions in all relevant areas of government, from trade to infrastructure development, health and the environment. Without this common approach, different parts of government risk pulling in different directions, rather than working together towards a common agenda of food system transition. FBDGs also need to be reassessed and updated to reflect the latest science, and to embody issues of sustainability, as well as dietary health.

2.2 *Placing Poor and Marginalised People at the Heart of the Transition*

The transition of food systems has the potential to address societal inequalities in several ways. By ensuring access to diets that are affordable, healthy and sustainable, it has immediate benefit for the three billion who cannot afford healthy diets today (FAO, IFAD, UNICED, WFP W 2020). At a stroke, access to healthy diets for pregnant women and children will address the lifetime inequalities related to health and mental development that malnutrition can cause. Consequential increases in productivity and lifetime earnings would further help to lift families out of poverty, thereby helping to open up wider opportunities.

However, a key challenge for policymakers is to ensure that the transition reduces inequality rather than increasing it. At the country level, the latter is a real threat: LMICs are likely to be less able to resource the necessary transition steps, and thus they risk falling further behind HICs. For individual families, the poorest will be least able to afford nutrient-rich food alternatives if they are more expensive, and less able to cope with fluctuations in food prices that might occur as food systems change. The effects of the transition of jobs and livelihoods needs to be managed particularly carefully, recognising the vital importance of the food sector as a major source of employment for the poor across the world.

If the transition of food systems is to reduce inequality, then policymakers must commit to specific actions at both the international and national levels:

- Disruption to trade in general, and through protectionism in particular, must be avoided. Trade is a vital tool for minimising food prices and maintaining food security, particularly at times of stress and price volatility.
- Governments need to promote growth that is specifically inclusive and pro-poor. This is a vital component in a strategy to address affordability.
- Donors need to specifically focus their attention on protecting the poor from price fluctuations that may occur during the transition.

Planning the transition of their food systems is likely to be a particular challenge for those LMICs that are heavily resource-constrained. It is suggested that governments in LMICs should give particular consideration to the following:

- Repurposing existing expenditure across government, recognising that sustainable healthy diets can contribute to multiple policy agendas, including health, economic growth and education.
- Giving particular focus to actions that are, to first order, cost neutral; for example, rebalancing production (terrestrial and aquatic food systems of all kinds) subsidies and research, taxes and regulation. Influencing consumer dietary choices is potentially low cost, but has considerable potential to drive change throughout food systems.
- Leveraging the considerable resources of the private sector by forging a partnership to work together on a common agenda.
- Focusing attention on actions that simultaneously produce multiple wins.
- Using reviews to prioritise where to focus actions within food systems, and using the best science, evidence, and modelling to help choose the most cost-effective actions.

2.3 Tackling Trade-Offs and Compromises Head On

The need to resolve competing policy and investment priorities operates at many scales and contexts. It is a daily reality in governments when resources are constrained and actions need to be prioritised, in private companies when making investment choices regarding product portfolios or retail strategies, and in households when making day-to-day food-purchase choices (Global Panel on Agriculture and Food Systems for Nutrition 2020b; Webb 2010; Global Panel on Agriculture and Food Systems for Nutrition 2017b).

Policymakers seeking to transition food systems need to think through how to navigate difficult trade-offs that may lie entirely within the food system, but equally may involve wider areas of policy. Examples include how to balance resource expenditure among fostering education, stimulating economic growth, and investing specifically in food systems, how to allocate scarce resources for addressing different forms of malnutrition that may affect a population simultaneously, including undernutrition, micronutrient deficiencies, or overweight and obesity, how to strike a balance between investing in agriculture and fisheries versus other sectors in rural communities, and how to balance avoiding coronavirus-led debt default in the short-term with investing in food system transition to achieve longer-term health and economic benefits.

Trade-offs may usefully be approached through mapping out existing policies in relation to new goals and likely trade-offs, developing a clear understanding of the costs and benefits of alternative actions, transparently defining who pays and benefits from alternative strategies, taking a longer-term perspective, and ensuring affordability as a priority (FAO, IFAD, UNICED, WFP W 2020; Herforth et al. 2020).

2.4 Ensuring That the Transition Process Is Appropriately Resourced

The transition of food systems will inevitably incur costs before the benefits can be realised. These costs will likely manifest in all domains of the system, from production through to trade, food processing, retail, and consumption. It is therefore necessary that the distribution and impacts of these costs are identified, understood, and managed effectively. Put simply, it is essential to have clarity from the outset about how the transition steps would be resourced. This will be doubly important, not only to ensure that reform can move beyond political aspiration, but also so that the transition does not further widen the gap between HICs and LMICs. Much can be achieved by repurposing (see Sect. 4) or refocusing existing resources (for example, shifting subsidies and realigning taxes and incentives), and through negotiating more equitable trade agreements. Identifying actions that produce multiple benefits (win-wins) may also help. However, the following non-governmental actions also need to be considered:

- **Incentivise the private sector to realign its resources to help support national agendas of delivering healthier diets in a sustainable manner.** The public sector cannot deliver transformed food systems on its own; rather, it needs to work in partnership with the private sector. However, many commercial actors too often act in ways that are not conducive to health or to the sustainability of food systems. This is incompatible with the necessary transition agenda and needs to change. It is important for governments to incentivise businesses to make a much wider range of nutrient-rich foods affordable to the entirety of 'bottom of the pyramid' families. More generally, a comprehensive framework for food industry engagement needs to be established.
- **Establish a dedicated global financing facility for food system transition**. Such a facility would mobilise multilateral resources to support and incentivise

increased allocations of domestic resources towards making food systems more resilient and diets both more sustainable and healthier. A particular priority for such a facility would be to assist LMICs in their transition, recognising the severe financial constraints in which many operate. It also has the potential to catalyse reform where there is a mismatch between the actors who need to resource change and those who stand to benefit.

- **Realign donor policies towards supporting actions that promote the achievement of both human health and planetary goals**. A particular priority should be the protection of the poor during the transition by refocusing social protection policies so that they will be able to cope with fluctuations in the availability and price of foods that may occur during this time.

3 Incentivising and Supporting Actions

Given the diverse benefits that would result from achieving sustainable, healthy diets for all, the limited actions taken by countries across the world in recent decades (Global Panel on Agriculture and Food Systems for Nutrition 2020a) represent a huge missed opportunity. The reasons for this are many and varied, but include insufficient policy focus by governments on improving diet quality and nutrient-rich foods (as opposed to the provision of staples).

A further issue concerns the private sector. Despite playing a major role in feeding the world, the private sector too often develops and promotes foods that are not conducive to healthy diets, or which rely on food production systems that over-exploit natural resources. The benefits mainly accrue to private sector stakeholders, while the costs (population-wide ill health, ecological degradation, etc.) are mainly borne by the public sector and wider society. This mismatch has impeded progress in the past and must be addressed as part of the transition.

Many factors also affect the pace of change. Global food systems involve powerful business interests with considerable investment in the status quo: revenues of the global food system are estimated to reach US$8 trillion in 2021 (Statista 2020; Van Nieuwkoop 2019). The implementation of policy change may also be constrained by limited resources, particularly in LMICs, and especially in a post-COVID-19 world. Major shifts in policy may incur political risks, and decision-makers typically assign more weight to these compared with the risks associated with maintaining the status quo (The World Bank and Nutrition 2019). Moreover, at the level of the consumer, dietary choices may be heavily conditioned by evolving cultural or religious norms (Monterrosa et al. 2020; Alonso et al. 2021). However, three systemic issues stand out within the policy environment. Addressing these at the outset of the transition is essential.

3.1 The Misalignment Between the Complexity and Interconnectedness of Food and Environmental Systems, and How They Are Managed Today

Policy actions on food, health, agriculture and fisheries, and climate are typically managed in isolation, in an organisational approach that is inherently unsuited to managing complex food systems. The need for 'joined up' policy is a cliché, but remains widely relevant. This important issue can be addressed through a combination of measures: initiating training and sensitisation of policy leads in all relevant sectors to the urgency of the transition, encouraging leadership at the highest levels of government, convincing relevant policymakers across government of the critical importance of sustainable, healthy diets to their respective policy agendas, embedding these objectives into their own plans and strategies so that all parts of government drive change within a common transition agenda, and establishing targets for actions that improve food system functions in ways that deliver multiple benefits simultaneously.

3.2 Inadequacies in Science and Evidence for Policy Development

Trusted, high-quality science and evidence are essential to give policymakers the confidence to make the bold decisions that are required. There is a need to address major gaps in the evidence base, particularly in LMICs, where evidence of 'what works' is often limited, establish a common science base that is recognised as independent, widely trusted, and freely available to all countries, and develop consensus around contentious areas of policy.

The idea for creation of an IPCC-like organisation for sustainable food systems (an 'International Panel for Food System Science, (IPFSS)) has been mooted in recent years and offers one way to help deliver the necessary improvements. This idea is now gathering support from major stakeholders.

An important role of the IPFSS would be to engender trust in the science and evidence in two distinct communities. In the case of policymakers, it would engender confidence and provide support in justifying difficult or controversial decisions. However, trust in the underlying science is equally critical for citizens who can exert considerable influence throughout the food system through their individual and collective food choices (Global Panel on Agriculture and Food Systems for Nutrition 2020a). The vast amounts of misinformation circulating on the internet and social media concerning climate change, and now vaccinations, collectively illustrate how false information can dangerously mislead consumers.

3.3 Metrics for Monitoring, Tracking, and Adjusting the Transition Process

Effectively measuring what policymakers and businesses manage is key to identifying what works and what is most cost-effective, as well as for supporting transparency and accountability (The World Bank 2021). As such, the transition steps in food system reform must be carefully based on appropriate evidence where it is available (International Food Policy Research Institute 2021), and should promote making evidence available where it is not (Global Panel on Agriculture and Food Systems for Nutrition 2020a). For example, it remains difficult to compare diets (what people actually eat) across geographies and over time. This gap in appropriate measurement and monitoring continues to impair the prospect of reaching a global consensus on what elements should be included to define healthy or high-quality diets, and how to ensure the planetary sustainability of the food systems that underpin them.

What is urgently needed is open-access portals for data not just on diets, but on all elements of food system functions, including information access, market prices, and the nature and quality of food environments, all of which are needed in forms that can be effectively linked with global trade and climate change models to better inform policy choices.

4 Who Needs to Act: Priorities for Transitioning Food Systems to Protect Human and Planetary Health

The transition of food systems requires global leadership with a long-term focus and the delivery of a coherent set of commitments and actions that place both people's and the planet's health at the centre. For the next decade, the structure of the SDGs will help to provide a coherent framework for action. Global leadership, such as that expected to emerge more fully from the UN Food Systems Summit, will help to provide the continuity needed, as well as mechanisms for periodic reassessment and reorientation.

However, global leadership must be supplemented with and supported by national, regional, and local level initiatives that bring together public, private, and civil society actors around the priorities that are most urgent, feasible and essential for food system transformation. The Global Panel's recent Foresight report sets out detailed recommendations for different classes of stakeholder, and different parts of the food system, recognising that such actions will usually need to be tailored to individual circumstances. However, the following priorities are generally applicable:

International

1. **Leaders and decision-makers should capitalise upon upcoming global fora to agree to new commitments for making food systems more resilient and diets that are healthy and sustainable.** Both the Nutrition for Growth (N4G) Summit and the UN Food Systems Summit are important opportunities to explore the creation of a dedicated global financing facility for food system transformation and secure national endorsements for change, including much improved capacity for research and evidence to better support policy decisions. A new vision for sustainable food systems delivering healthy diets for all must be supported through the best science and evidence of what works, as informed by practical evidence.
2. **Policymakers must build on existing global development targets (such as the SDGs and the Paris Agreement on Climate Change) so that they embody the goal of sustainable, healthy diets for everyone as a shared objective.** These targets need to recognise the central importance of sustainable, healthy diets as a key enabler for progress on diverse agendas; for example, those related to inequality, economic growth, climate change, environmental degradation, and livelihoods and job creation.

Governments

3. **Food systems and the policies that govern them need to be people-centred**. This means ensuring that healthy diets are available to all people irrespective of class, religion, gender and age. It means recognising the vital role that food systems play in providing livelihoods for countless millions, particularly for poor and marginalised groups. Moreover, it means ensuring that policymakers understand and recognise the central importance of healthy diets for physical and mental development, as a foundation for health, prosperity and wellbeing.
4. **Policymakers in relevant government departments must address planetary and dietary challenges simultaneously, because they are fundamentally interlinked.** The approach to date, in which these issues were tackled piecemeal and in silos, simply will not work.
5. **Governments in countries at all stages of development must resolve policy distortions that could fundamentally impede change, or even drive food systems in the wrong direction.** Examples include taxation and regulation, subsidies, and food-related research and development. The aim is to give much greater weight to the importance of nutrient-rich foods and better support measures that further both human and planetary health simultaneously.
6. **Relevant ministries (e.g., agriculture, fisheries, health, transport infrastructure, environment) need to work together to implement policies for realigning production systems so that they support healthy diets in sustainable ways.** Food systems today do not produce enough nutrient-rich foods to meet current needs, let alone projected demand over coming decades, nor are they producing most foods sustainably. Narrow targets related to productivity need to be replaced with broader measures valuing efficiency and sustainability.

7. **Relevant government departments need to prioritise building the resilience of food systems, as COVID-19 has highlighted their current deficiencies and vulnerabilities**.[3] A broad approach is required that addresses the causes of the lack of resilience within food systems, the root causes of the threats, and mitigation measures that may be needed during times of stress.
8. **Governments in all countries should creatively target actions that can create multiple 'wins' across health and sustainability**. Opportunities need to be sought throughout food systems, from farm to fork. Major projects in sub-Saharan Africa and China have already shown that this is possible, creating substantial and lasting benefits in terms of jobs, equality, and the development and prosperity of individuals and regions (Fu et al. 2011; Lü et al. 2012; Deng 2014; Goffner et al. 2019). Technological innovations across food systems, from production through processing, storage, and retail, hold considerable promise.

Donors

9. **Donor agencies must support LMICs to ensure that the transition of food systems is socially and ethically just**. They have an important role to play in ensuring that the poorest are protected during and after a period of food system transition.

Companies Operating in the Food System

10. **Major transnational businesses and local SMEs must work closely with governments on more clearly articulated common agendas to deliver sustainable, healthy diets**. A comprehensive framework for food industry engagement is needed: it is essential that the public and private sectors work together on common agendas and share the costs of implementing them. The private sector must spell out specific, measurable responsibilities for improving diet quality and the sustainability of food systems and be willingly held accountable.

Civil Society

11. **Civil society advocacy groups and citizens need to play their part. The former have a major role in leveraging change in businesses operating across food systems and holding policymakers to account, and the latter have considerable influence to drive change through their purchasing power**. However, shifts in demand in favour of sustainable, healthy diets will need encouragement and empowerment through information from trusted sources.

[3] The Global Panel is producing a separate science chapter on the relationship between food systems and the COVID-19 pandemic, and the implications for building resilience.

References

Alonso S, Aderu S, Bekele TH, Bishaw Z, Brouwer ID, Brown LR, et al (2021) Background paper. Transforming Ethiopian food systems: better diet quality, prosperity, and sustainability in a changing climate

Bommer C, Sagalova V, Heesemann E, Manne-Goehler J, Atun R, Bärnighausen T et al (2018) Global economic burden of diabetes in adults: projections from 2015 to 2030. Diabetes Care. 41(5):963–970

Deng X (2014) Restoration and development of the degraded Loess Plateau, China. Springer, tokyo, pp 215–231

KC KB, Dias GM, Veeramani A, Swanton CJ, Fraser D, Steinke D, et al. When too much isn't enough: does current food production meet global nutritional needs? PLoS One. 2018.13(10).

FAO (n.d.). Home | Food-based dietary guidelines | Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/nutrition/education/food-dietary-guidelines/en/

FAO, IFAD, UNICED, WFP W (2020) The state of food security and nutrition in the world: transforming food systems for affordable healthy diets. FAO, Rome

Fu B, Liu Y, Lü Y, He C, Zeng Y, Wu B (2011) Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecol Complex. 8(4):284–293

Global Panel on Agriculture and Food Systems for Nutrition (2017a) Healthy diets for all: a key to meeting the SDGs, Policy Brief No. 10. Global Panel on Agriculture and Food Systems for Nutrition, London

Global Panel on Agriculture and Food Systems for Nutrition (2017b) Urban diets and nutrition: Trends, challenges and opportunities for policy action, vol 9. Global Panel on Agriculture and Food Systems for Nutrition, London

Global Panel on Agriculture and Food Systems for Nutrition (2020a) Future food systems: for people, our planet, and prosperity. Global Panel on Agriculture and Food Systems for Nutrition, London

Global Panel on Agriculture and Food Systems for Nutrition (2020b) Rethinking trade policies to support healthier diets, Policy Brief. Global Panel on Agriculture and Food Systems for Nutrition, London

Goffner D, Sinare H, Gordon LJ (2019) The Great Green Wall for the Sahara and the Sahel initiative as an opportunity to enhance resilience in Sahelian landscapes and livelihoods. Reg Environ Chang. 19(5):1417–1428

Herforth A, Bai Y, Venkat A, Mahrt K, Ebel A, Masters WA (2020) Cost and affordability of healthy diets across countries. Technical Background Paper for SOFI 2020: The State of Food Security and Nutrition in the World, 2020

International Food Policy Research Institute (2021) 2021 Global Food Policy Report: Transforming Food Systems after COVID-19. IFPRI, Washington, DC

IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Population and Development Review, Bonn

Lü Y, Fu B, Feng X, Zeng Y, Liu Y, Chang R et al (2012) A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. PLoS One. 7(2):e31782

Monterrosa EC, Frongillo EA, Drewnowski A, de Pee S, Vandevijvere S (2020) Sociocultural influences on food choices and implications for sustainable healthy diets. Food Nutr Bull. 2020.41. Available from: https://doi.org/10.1177/0379572120975874

Statista (2020) Food – Worldwide | Statista Market Forecast. Available from: https://www.statista.com/outlook/cmo/food/worldwide

The World Bank (2021) World development report 2021: data for better lives, A World Bank Flagship Report. The World Bank Group, Washington, DC
The World Bank and Nutrition (2019). Available from: https://www.worldbank.org/en/topic/nutrition/overview
Van Nieuwkoop M (2019) Do the costs of the global food system outweigh its monetary value? World Bank. Available from: https://blogs.worldbank.org/voices/do-costs-global-food-system-outweigh-its-monetary-value
Webb P (2010) Medium- to long-run implications of high food prices for global nutrition. J Nutr, Available from 140(1):143S–147S. https://doi.org/10.3945/jn.109.110536

Engaging Science in Food System Transformation: Toward Implementation of the Action Agenda of the United Nations Food Systems Summit

Joachim von Braun

1 Introduction

The Secretary-General's **"Chair Summary and Statement of Action on the UN Food Systems Summit"** strongly emphasizes the role of science in the transformation of food systems. It states, for instance:

- "Progress will require local and global communities of practice and stakeholders coming together with national governments... In particular, support to enhance implementation through financing, data, science and innovation, governance and trade."
- "Global initiatives to reinforce the ambition of science-based solutions will be key to deliver on the 2030 Agenda."
- "Collaborating with the High-level Panel of Experts (HLPE) of the CFS at global level, support strengthening the science-policy capacities and interfacing at local and national levels."

The purpose of this chapter is to outline a concept for constructive contributions of science towards providing evidence-based insights for national, regional, and global level implementation of the UNFSS Action agenda.[1]

The "**Science ecosystem of support"** is part of the envisioned support structures for the "FS Follow-Up Coordination Hub" and "Country Level Platforms led by the Government" (see Fig. 1). The science ecosystem of support is understood to be the community of science and knowledge organizations of relevance for food systems.

[1]The implementation of the UNFSS agenda can draw on the rich material developed by the Scientific Group and its partners compiled in the "Science Reader" for the UNFSS https://sc-fss2021.org/wp-content/uploads/2021/09/ScGroup_Reader_UNFSS2021.pdf

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_49

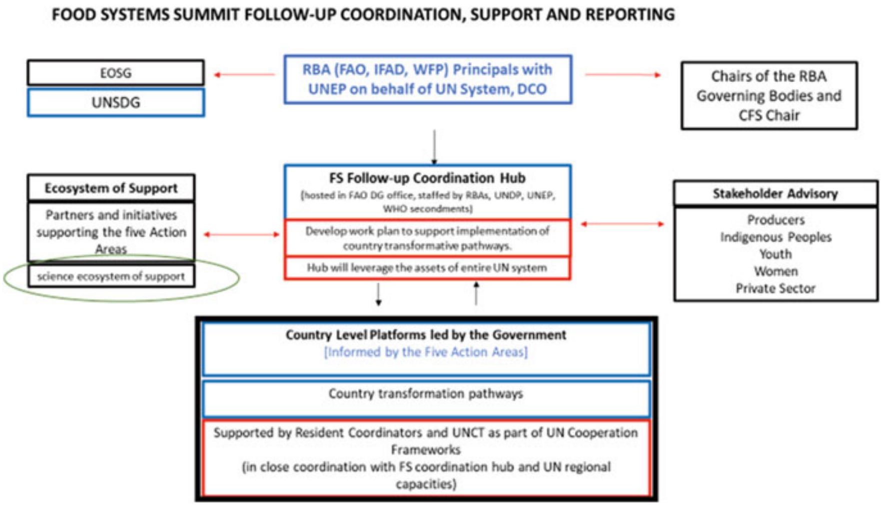


Fig. 1 The Deputy Secretary-General's presentation to the UNFSS Advisory Group in October 2021 on Summit follow-up

Its support functions include providing evidence for setting coherent national targets of food system transformation; supporting, through science, the translation of targets into action, understood as implementation research; and strengthening related capacity-building for national systems when needed. While we note the terminology of "Science ecosystem of support," in this chapter we refer simply to the **food systems-relevant science landscape (FSSL)**.

Food systems embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and disposal (loss or waste) of food products that originate from agriculture (incl. livestock), forestry, fisheries, and food industries, and the broader economic, societal and natural environments in which they are embedded (building on definitions by FAO (2018), HLPE (2014) and others) (von Braun et al. 2021a). Production includes, of course, farming communities, but also pre-production actors, for example, input industries that produce fertilizers or seeds. The range of actors importantly includes science, technology, data, and innovation actors. They are partly integral to food systems, and partly outside, but hold strong influence, for instance, being embedded in life science and health systems research. In food industries' processing, foods and non-foods result from interlinked value chains. Other relevant food system actors include, for example, public and private quality and safety control organisations.

2 Mobilizing the Science and Knowledge Community for Implementation of UNFSS Actions

The Scientific Group has developed a set of seven science-driven priorities of innovations to support the transformation of food systems to achieve the Food Systems Summit goals (von Braun et al. 2021b, c):

1. Innovations to end hunger and increase the availability and affordability of healthy diets and nutritious foods: this bundle partly draws on the six science and innovation actions below.
2. Innovations to de-risk food systems and strengthen resilience, in particular, for negative emission farming, drawing on both advanced science and traditional food system knowledge.
3. Innovations to overcome inefficient and unfair land, credit, labor, and natural resource use arrangements, and facilitate the inclusion, empowerment and rights of women, youths and Indigenous Peoples.
4. Bio-science and digital innovations for improving people's health, enhancing systems' productivity, and restoring ecological well-being.
5. Innovations to maintain – and, where needed, regenerate – productive soils, water and landscapes, and protect diversity of the agricultural genetic base and biodiversity.
6. Innovations for sustainable fisheries, aquaculture, and the protection of coastal areas and oceans.
7. Engineering and digital innovations for the efficiency and inclusiveness of food systems and the empowerment of youths and rural communities.

Furthermore, the Science Group and its partners have published the set of **strategic papers of relevance for national and global level UNFSS actions**, assembled in the "Science Reader for the UNFSS."[2] All of these together provide insights into the actions required to enable food system transformation to achieve the UNFSS goals.

Science–policy interfaces that serve national, regional and global implementation activities to enable food system transformation should be further explored (von Braun et al. 2021b; Hainzelin et al. 2021). A roundtable format with representatives of the main sets of organizations from the science landscapes could initiate this exploration.

Merely mobilizing science and pushing a supply of scientific findings will not be sufficient for science to play its conducive role in the design of food system transformations. The policy and stakeholder communities need to articulate the **demand for science-based insights**, and even respect uncomfortable findings that may contradict conventional wisdom. It is greatly helpful when government departments cooperate with each other in policymaking for food system innovations, and when they, along with stakeholders from the private sector and civil society, agree to be

[2] See Scientific Group https://sc-fss2021.org/wp-content/uploads/2021/09/ScGroup_Reader_UNFSS2021.pdf

guided by factual information. Taking the time and effort to consider complex analyses and findings from modelling is part of mutually constructive engagement between policy and science.

1. **Mobilizing the science and knowledge communities at the country level**

We applaud the active participation of UN member states in the Summit: 165 countries participated, with almost 100 of these represented by heads of state. Furthermore, 69 member states noted the salience of science and innovation in the transformation of food systems. About 230 commitments were registered in regard to action areas, made by a diverse group of players ranging from small NGOs to multinational institutions to member-states. A number of coalitions have emerged from the Action Tracks, and member states have the opportunity to engage with coalitions.

The science and knowledge communities must continue to mobilize in each country for national-level implementation of the UNFSS action proposals (Webb et al. 2021). In this context, the fields of science and the scientific and innovative priorities that are critical for shaping sustainable food systems are important to consider. Accordingly, the landscape would comprise, among others:

- Universities' related institutes
- Academies of sciences
- Agricultural, forestry, land, water, and climate research institutions,
- Health and nutrition research centers,
- Indigenous and traditional knowledge carriers,
- Others (incl. Corporate and start-up research and innovation communities, National think-tanks, private sector research institutions, etc.)

The national-level science landscape would engage in national level implementation under the leadership of national governments, and the UN, where applicable (in some countries, possibly augmented by regional science organizations), and in consultation with other stakeholders (corporate, civil society, farmer and consumer orgs). Figure 2 below depicts this science support framework in national contexts.

The key initial task would be to **design details and typologies for countries' science landscapes and science-policy interfaces.** This would entail mapping the FSSL in all countries, considering its regional and international linkages, and communicating it to national implementation actors. Such a mapping exercise mandates action from both the government and the scientific communities, who should jointly map out this landscape (see Fig. 2).

The table in Annex 1a can serve as a guideline in this regard.

As a service, mapping of all of the materials from the Scientific Group and partners that may be of relevance for national concerns can be considered (i.e., relate all of the papers and briefs from the Scientific Group's website to countries' and regional contexts). An important early task could be **modelling national issues in regional and global contexts:** thematic areas of focus could include trade, hunger, healthy diets, ecology, climate, food safety and health, innovations, etc.

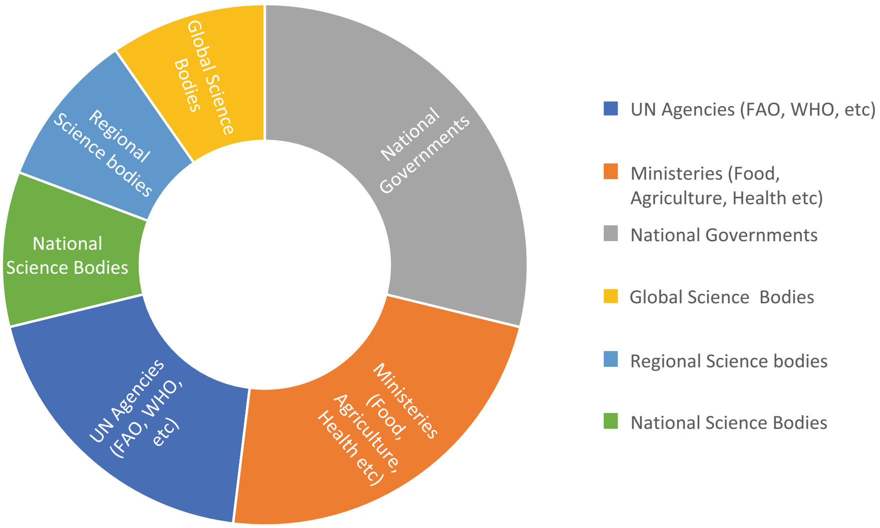


Fig. 2 Science support framework in national governance contexts

In cases when the science and knowledge community may not have critical mass at the country level, systems of scientific support can be considered at the sub-regional level.

2. **Mobilizing the science and knowledge communities at regional levels**

To operationalize the task, national UNFSS focal points need to be made aware of related regional and international organization scientific bodies that could serve their purpose, with information and analyses as input for options on implementation of the UNFSS Action Agenda. Thus, at **regional levels**, the food system-related organizations of sciences that could be mobilized to address trans-national issues could include, among others:

- Regional academies of sciences
- Regional research and innovation institutes
- Regional think-tanks
- Regional scientific bodies and forums
- Regional private research organizations

A tabulated presentation is presented in Annex 1b.

3. **Mobilizing the science and knowledge communities at the global level**

Similarly, the international science and knowledge communities spanning all of the sciences relevant to food system transformation need to continue to mobilize and engage in international public goods issues that impact the implementation of the UNFSS actions, such as trade, food safety, climate resilience, peace and security, trans-boundary water, equity and inclusion, science and knowledge transfers, and many others. Food system-related organizations of sciences that could be mobilized at the global level could include, among others:

- Academies (InterAcademy Partnership, IAP)
- International food, agricultural, health and food system-related research institutes (Incl. CGIAR, HLPE of CFS, Science and research entities in food system-related UN agencies, etc.)
- Think-tanks
- Scientific associations (incl. associations related to soil science, agronomy, food technology, agricultural economics, etc., the International Advisory Council on Global Bioeconomy (IACGB), the Inter-American institute for Cooperation on Agriculture (IICA),
- Others (incl. private sector research institutions, civil society organizations, **Indigenous** peoples/traditional knowledge carriers, etc.)

A tabulated presentation is presented in Annex 1c.

We acknowledge the InterAcademy Partnership's recommendation and others that further consideration be given to options for strengthening the science-policy interface,[3] and, in particular, we suggest that an exploration be undertaken for options for an **inclusive global science-policy interface,** serving a sustainable food system and evidence-based follow-up to the Summit (Fears and Canales 2021). This exploration can draw on experiences with the comparable national and international science processes, e.g., the IPCC Science Policy Interface model and related considerations about an "IPFood," as discussed in various fora, such as the InterAcademy Partnership (IAP) and the Science Days of the Scientific Group with FAO in 2021.

3 Pathways for Broadly Engaging Networks of the Science and Knowledge Communities

Science systems in many countries are weak, and particular attention will need to be paid to **strengthening local research capacities**, as well as improving data, methods, models and tools. Modalities for expanding collaboration among public and private research and indigenous systems will need to be explored, along with modalities for building or sharing research infrastructure (FAO 2021). Beyond investing in capacities to undertake research, it will also be important to invest in the capacities of policymakers and practitioners to demand, use and act upon research.

Networking among national, regional and global science bodies will be critical for this task. The current level of such networking capacities is deficient. Investing in that capacity at national levels will be of tremendous benefit for many countries' efforts to build their evidence-based priority-setting tools and

---

[3] Letter from InterAcademy Partnership Co-Presidents to UN Secretary General, November 4 2021 (https://www.interacademies.org/sites/default/files/2021-11/Letter%20to%20Secretary%20General%20of%20the%20UN_final.pdf).

mechanisms, considering synergies and trade-offs of actions and implementation. This would help to achieve two goals:

1. **Raise the engagement** of science and knowledge communities at national, regional and global levels for food system transformation in the five action areas as identified by the UN SG in his UNFSS statement.
2. **Connect national science and knowledge communities with regional and global communities** to also address the above-mentioned international public goods issues that are critical for food systems' functioning.

To fully tap the potentials of science, **funding mechanisms** (Díaz-Bonilla 2021) for the science ecosystems of support at national, regional and global levels should be developed. The public funding of food systems science in particular needs to expand, and we reiterate our **call for governments to allocate at least 1% of their food systems-related GDP to food systems science and innovation**. Private sector science also has important new opportunities to scale up its engagement, particularly in partnership with the public sector, to address public goods in food system innovations. There must be room to develop innovative finance approaches to not only support science at scale, but also to contribute to an overall sustainable financing of food system transformation.

4 Concluding Remarks

The Scientific Group for the UN FSS completed its mandate by the end of 2021. Thereafter, the Hub will handle any follow-up tasks with mechanisms to be defined. Consideration may be given to holding a series of consultations, under the auspices of the Hub, with and among the science and knowledge institutions mentioned above with regard to fostering science-policy interfaces at national, regional, and global levels to develop effective science-policy interfaces.

Consideration may also be given to **continuing with Science Days for follow-up**. It will be important to continue to include diverse food system-related science and knowledge communities at the country, regional and global levels in scientific discourses informing the evidence base for implementation of actions to achieve the FSS goals. Science Days should remain in the format of the independent science community partnering with FAO, which has shown its value in the Food Systems Summit processes. This format may be considered for future follow-up activities to the UNFSS 2021, possibly before assessments of progress that the UN Secretary General envisages.

Science has an important role to play in the appropriate and effective implementation of the action agenda of the UNFSS at national, regional, and global levels, and it is important to continue to invest in undertaking and using science and knowledge at all of these levels.

Acknowledgements Helpful comments on an earlier draft by members of the Scientific Group and research support by Sundus Saleemi and Heike Baumüller (both at ZEF) are gratefully acknowledged. The author is grateful for the comments by external peer reviewers.

Annexures

Annex 1a: National-Level Framework for Identification of a Science Ecosystem of Support

Category of Science Stakeholders in the country					
Country Name					
Universities (Related institutes)	Academies of Sciences	Agricultural, Forestry, Water, Land and Climate Science Research Institutions	Health and Nutrition Research Institutions	Indigenous & Traditional Knowledge carriers	Other (Corporate & Start-up Research & Innovation Groups, Think-tanks, Private Research Organizations)

Annex 1b: Regional-Level Framework for Identification of a Science Ecosystem of Support

Region	Regional Academies of Sciences	Regional Research & Innovation Institutions	Regional Think-Tanks	Regional Science Bodies and Forums	Regional Private Research Organizations
Northern Africa					
Sub-Saharan Africa					
Latin America and the Caribbean					
Northern America					
Central Asia					
Eastern Asia					
South-eastern Asia					
Southern Asia					
Western Asia					
Europe					
Oceania					

Annex 1c: Global-Level Framework for Identification of a Science Ecosystem of Support

	Global Academies of Sciences	**Food, Agricultural, Health and Food System-Related Research Institutes**	**Think-tanks & Policy Advisory Institutes**	**Science Associations**	**Others (Private sector research institutes, Civil Society, Traditional Knowledge Carriers, etc.)**
	Inter-Academy Partnership (IAP)	CGIAR	World Resource Institute (WRI)	International Advisory Council on Bioeconomy	Global Alliance for Improved Nutrition (GAIN)
		CFS-HLPE	Chatham House		
		Science in Food and Agricultural Organization of the UN (FAO)	Center for Development Research (ZEF)	Inter-American Institute for Cooperation on Agriculture (IICA)	
		Science in World Health Organization (WHO)	Global Panel on Food, Agriculture for Nutrition		
		Research unit in UNICEF			
		Global Crop Trust			

References

Díaz-Bonilla E (2021) Financing SGD2 and ending hunger. In: Food systems summit brief prepared by research partners of the scientific group for the food systems summit. https://doi.org/10.48565/scfss2021-ba75

FAO (2021) The White/Wiphala Paper on indigenous peoples' food systems. Rome. https://doi.org/10.4060/cb4932en

Fears R, Canales C (2021) The role of science, technology and innovation for transforming food systems globally. In: Food systems summit brief prepared by research partners of the scientific group for the food systems summit. https://doi.org/10.48565/scfss2021-q703

Hainzelin E, Caron P, Place F, Alpha A, Dury S, Echeverria R, Harding A (2021) How could science–policy interfaces boost food system transformation? In: Food systems summit brief prepared by research partners of the scientific group for the food systems summit. https://doi.org/10.48565/scfss2021-4y32 von Braun J, Afsana K, Fresco L, Hassan M, Torero M (2021a) Food system concepts and definitions for science and political action. Nature Food. https://rdcu.be/cxPxJ, https://sc-fss2021.org/wp-content/uploads/2021/06/Food_Systems_Definition.pdf

von Braun J, Afsana K, Fresco L, Hassan M (2021b) Food systems: seven priorities to end hunger and protect the planet. Nature 597:28–30. https://doi.org/10.1038/d41586-021-02331-x. https://www.nature.com/articles/d41586-021-02331-x

von Braun J, Afsana K, Fresco L, Hassan M (2021c) Science for transformation of food systems: opportunities for the UN food systems summit. https://sc-fss2021.org/wp-content/uploads/2021/07/Scientific-Group-Strategic-Paper-Science-for-Transformation-of-Food-Systems_August-2.pdf

Webb P, Flynn DJ, Kelly NM, Thomas SM (2021) The transition steps needed to transform our food systems. In: Food systems summit brief prepared by research partners of the scientific group for the food systems summit. https://doi.org/10.48565/scfss2021-hz63

Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit

Joachim von Braun, Kaosar Afsana, Louise O. Fresco, and Mohamed Hag Ali Hassan

1 Introduction

Food systems (von Braun et al. 2021a) at the global level, and in many countries and regions, are failing to end hunger, provide adequate nutritious foods for healthy diets, or deliver safe foods. Between 720 million and 811 million people face hunger and are undernourished – that is, every tenth person – 150 million children under 5 years of age are stunted (short for their age), and two billion people are overweight or obese. These numbers have been high and/or growing for a number of years now, and with COVID-19 disproportionately impacting poor and food-insecure populations, they are continuing to rise, with an estimated 118 million more people facing hunger in 2020 than in 2019 (FAO et al. 2021; Klassen and Murphy 2020). About 600 million people fall ill each year due to the consumption of contaminated or unsafe foods (WHO 2020). We are losing ground on the progress that we have already made, and we face the prospect of severely compromising the achievement of the SDGs and the 2030 Agenda.

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

K. Afsana
James P Grant School of Public Health, BRAC University, Dhaka, Bangladesh

L. O. Fresco
Wageningen University and Research, Wageningen, The Netherlands

M. H. A. Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), Trieste, Italy

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_50

Besides escalating hunger and all forms of malnutrition (micronutrient deficiencies, underweight, overweight/obesity and related NCDs), poverty and inequalities between and within countries are widespread and becoming entrenched. For many people, engaging in activities in the food system would seem to offer the most viable opportunities to escape poverty, yet they are being left out of earning their fair share of the benefits from engaging in food systems, and are condemned to jobs that do not provide livable wages and decent working conditions and livelihoods. Fundamental human rights to food, health, safe water and sanitation, and education continue to be violated. Ending poverty and gross inequalities remains essential for achieving the SDGs.

Food systems relate to the three basic dimensions of sustainability: social, economic, and environmental (Dury et al. 2019; FAO 2018). Many food systems are based on production and distribution systems that are simply not sustainable. Scientific assessments indicate that many aspects of current food production systems drive the degradation of land and soil, water, and climate, as well as biodiversity loss (IPBES 2019; HLPE 2017). Climate change is increasingly adversely impacting food security. The global food system emits about 30% of global greenhouse gases, contributes to 80% of tropical deforestation, and is a main driver of soil degradation (Food and Land use Coalition 2019) and desertification, water scarcity, and biodiversity decline. Climate change, along with soil and environmental degradation, is partly caused by – and has negative impacts – on the food system. It is very clear that how we produce and consume food has profound implications for the health of people, animals, plants, and the planet itself (Bron et al. 2021).

The Food Systems Summit took place in the midst of the COVID-19 pandemic, which has revealed the close intertwining of food, ecological, and health systems (Webb et al. 2020a). The pandemic is having a significant impact on the global commodity markets and trading systems, economic growth, incomes, and poverty levels, with disproportionate burdens on vulnerable communities in both urban (Moustier et al. 2021) and rural areas. This is likely to worsen inequalities and undernutrition, including child undernutrition, which can have life-long consequences. Modeling projects that COVID-19 could result in an additional 9.3 million children wasted (low weight for height) and 2.6 million children stunted (low height for age) by 2022 (Osendarp et al. 2020). COVID-19 further increases food insecurity and poverty, which may become much more serious if comprehensive policy responses – especially equitable global vaccination coverage – are not implemented in a timely and evidence-based manner (von Braun et al. 2020).

Science needs to explore the root causes of emerging zoonotic diseases and closely engage with policy innovations, including those related to land use and animal production. Going forward, it is abundantly clear that more attention will need to be paid to how to make food systems more resilient to health shocks and pandemics, associated economic shocks and slowdowns, and violent conflicts and other crises, just as more attention is now being paid to how to make food systems more resilient to extreme weather events and other stressors induced by the changing climate (Webb et al. 2020b; Mushtaq et al. 2020). This will require integrated approaches that create greater synergy across government efforts to deal with health and other social services, as well as food system failures, in rural areas and other marginal communities (Allen et al. 2014; Wouterse and Badiane 2019).

The changing state of the art of science and innovation and the important lessons that they offer for food system transformation, need to be recognized. As noted earlier, science has at least two important roles in food systems: first, science generates new breakthroughs that can become innovations in food systems (e.g., genomics, plant nutrition, animal production and health, bio-sciences, earth sciences, social sciences, remote sensing, AI and robotics, digitization, big data, health and nutrition science, behavioral research, etc.); and second, science helps to inform and shape decisions, investments, policies and institutions, and can also be involved in the design, implementation and monitoring of actions needed to learn and draw lessons for impact at scale (Hainzelin et al. 2021). This also includes science that focuses on knowledge gaps, risks, uncertainties, and controversies. Many approaches, from discovery research to implementation research, and including both primary research and modeling techniques, can contribute valuable evidence.

2 Opportunities for Science and Innovation

Science and research are fundamental drivers of innovation. All three – science, research, and innovation – are essential for accelerating the transformation to healthier, more sustainable, equitable, and resilient food systems (Fears and Canales 2021). To enable the full inclusion of poor and marginalized populations – including smallholder communities (Diao et al. 2021) – in the process of and benefit from food system transformation, investments in technology-based innovations must be accompanied by institutional innovations (including social, business and policy innovations), underpinned by science: basic sciences and applied sciences, natural sciences and social sciences. The Scientific Group underlines not only its respect for Indigenous Peoples (von Braun et al. 2021a) knowledge systems, but also recommends investing more in programs that explore mutual learning and innovation across traditional and modern knowledge and science systems, considering both on equal footing. This may include documenting this knowledge and jointly studying it scientifically.

We highlight the need for systems innovations, rather than merely single-issue innovations, and call for enhanced collaboration between and among different disciplines of sciences for this purpose. We suggest a focus on seven science-driven innovations to catalyze, support, and accelerate food system transformation to achieve the SDGs, and SDG2 in particular. These innovations emerge from our conceptual framework and the building blocks and linkages therein (see Box). We hasten to emphasize that technology-based innovations and policy and institutional innovations are in synergy among each other: in other words, many technology-based innovations need policy and institutional innovations to fully realize their potential (for instance, innovative financing mechanisms), and, similarly, many policy and institutional innovations need technology-based innovations to be properly implemented and monitored (for instance, information systems). Further, in many instances, food system innovations must be place-based, adapted to the local contexts and capacities. We provide *examples of science-based innovations in the seven action areas below, identifiable in cursive format*. Alignment of technological change with sustainability concerns certainly requires attention and joint engagement by researchers from all areas of the food system-related sciences (including social sciences) guiding innovation arrangements.

2.1 Innovations to End Hunger and Increase the Availability and Affordability of Healthy Diets and Nutritious Foods

More than three billion people cannot afford healthy diets, and more than 1.5 billion people cannot even afford a diet that only meets the required levels of essential nutrients (FAO et al. 2021; Masters et al. 2021). The contribution of science and innovation here relates to identifying optimal context-specific investment opportunities and their implementation. Broadly speaking, the investment opportunities include productivity enhancement, people's skills and empowerment, agricultural research, social protection, nutrition programs, etc. (Center for Development Research (ZEF) of the University of Bonn in cooperation with the Food and Agriculture Organization of the United Nations (FAO) 2020). Policy innovations are needed to *repurpose subsidies towards related supportive investments that facilitate a sustainable food system* (Hendriks et al. 2021a).

Food Is Undervalued The value of food from the cultural, social and economic perspectives needs revisiting. An important role of science here is also to identify the indirect effects of these perspectives, while efforts must be made to embrace the true value of food (Hendriks et al. 2021b). External costs associated with climate change (Hansen et al. 2019), biodiversity loss, and adverse health effects need to be considered. The current costs of environmental and health externalities of food systems are estimated to range within 4–11 trillion USD and 3–39 trillion USD, respectively. Compared to the current total global food consumption of nine trillion USD, the true cost of food, including environmental, health and economic externalities, is 19.8 trillion USD.[1] *True-cost accounting* approaches are to be pursued throughout the whole food system, and related capacities built up in the corporate and public sectors. Capacities for internalizing such externalities are limited.[2]

[1] https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf

[2] It should be noted that lower food prices – if they come about in the short term – might have adverse income effects for producers and discourage them from investing to protect the ecosystem, especially if ecosystem services related to food systems are not incentivized, but more relevant is the avoidance of extreme price volatility, because that reduces incentives to invest and hurts farm households.

Cautious approaches are warranted to develop price and non-price instruments, including regulatory-based instruments, to help deal with such externalities. Fostering positive externalities of the food systems, such as through carbon farming and biodiversity-enhancing land use, should be considered and tested where justified (Miller et al. 2016). Nonetheless, if food prices were to reflect true costs, healthy diets may become unaffordable for low-income consumers, and social safety nets would need to be put in place.

Healthy Diet Concepts Benefit from a Strong Scientific Basis Measures that incentivize the production and market supply of fruits and vegetables and related innovations enhance consumption and can increase the income of smallholders (Zilberman et al. 2019; Zarnowiecki et al. 2020). However, rising incomes for consumers do not automatically lead to the increased consumption of healthy diets: even when accessibility and affordability are not constraints, the consumption of healthy diets is not assured, as people may still not change their consumption behavior. Approaches to creating demand for healthy diets and nutrition must be explored. At the same time, we have to be careful not to put all of the blame for poor nutrition on consumer behavior (Herrero et al. 2021a). Considerably more science is needed to understand the drivers in the processing, marketing and food environments. Science-intensive and promising opportunities such as *scaling up sustainable cold chain technology* to make perishable foods (especially fruits and vegetables, e.g., potatoes) more available and affordable (Harris et al. 2021) and, at the same time, reduce food loss and waste must be pursued, along with complementary *investments in infrastructure to reduce transportation and other related costs*, and thereby reduce food prices (van Zutphen et al. 2021).

Nutrition Science – Like All Science – Is Conflicted, and much of our real understanding of these nutrition issues is only starting to emerge. More research is needed to identify the most adequate healthy diets and their affordability and environmental sustainability across different contexts (Hirvonen et al. 2020; Headey and Alderman 2019). *Dietary targets* elaborated by the World Health Organization (WHO) – such as those related to adequate fruit and vegetable consumption, sweeteners, etc. – should be considered accordingly. There is a lack of scientific consensus on the dietary recommendations for animal-sourced proteins (ASF); these are nutrient-rich, but some are evidenced to increase the risk of diet-related chronic diseases if consumed at high levels. Plant-based diets have been evidenced to lower the risks of non-communicable diseases, and meet protein and adult micronutrient requirements. Changes in the consumption of ASF – reducing consumption, in particular, of processed forms of meat in communities where current levels are high and increasing consumption among vulnerable groups – can ensure a sustainable livestock sector while retaining the positive nutritional impact of ASF (Herrero et al. 2021b). Plant- and insect-based meat alternatives and protein sources can substitute for ASF without compromising its nutritional benefits. Improvements in the scientific assessment's methods regarding the health-related, environmental and socioeconomic impacts of reduction in ASF are needed. A potentially very significant contribution to deepened insights around the health-related aspects of diets is *the "Periodic Table of Food Initiative (PTFI),"* a global effort to create a public database of the bio-chemical composition and function of the food that we eat using the latest mass spectrometry technologies and bioinformatics.[3] If then combined with the *micro-biome science of human nutrition* (Kau et al. 2011), the perspectives on healthy diets may further shift and related health and information actions can become more concrete, including for the prevention of obesity.

We need to better understand how to *design and implement policies that enable healthy food environments, especially for children*, such as through taxes on foods whose excessive consumption should be avoided, limitations on advertisements of unhealthy foods, information through *educational food labeling,* prohibition of trans-fats, and regulation of the use of high-fructose corn syrup. Sound implementation of nutrition education is likewise required. Information about health properties from the industrial fortification and biofortification of certain foods should also be considered (Zilberman et al. 2019; Zarnowiecki et al. 2020; Downs and Demmler 2020). Research on the costs of action versus no-action regarding the key drivers of diets and food system change and the impact of these changes is required for effective decision-making.

2.2 Innovations to De-Risk Food Systems and Strengthen Resilience

In particular, for negative emission farming, and drawing on both advanced science and traditional food system knowledge (Mirzabaev et al. 2021). As food systems become more global, dynamic, and complex, they also become more vulnerable to new, challenging, and systemic risks, as evidenced by the food price crisis in 2008, the ongoing COVID-19 pandemic (Sperling et al. 2020), and the performance of these systems during armed conflicts (Kemmerling et al. 2021). The implementation experiences of *triple nexus approaches of the humanitarian-peace-development nexus* should be accompanied by evidence-seeking social science (Barakat and Milton 2020). Science-based responses to catastrophes require preparedness. The capacity to understand, monitor, analyze, and communicate vulnerabilities, crises, and risks must be strengthened (Bhutta et al. 2013; Hidrobo et al. 2018; Ruel et al. 2013). Opportunities to expand and *improve food security forecasting and monitoring with web-based approaches* must be seized. Local *meteorological capacities must be expanded*, as accurate weather forecasting is of critical importance to farming communities. Food systems can be de-risked through *solar powered*

[3] See at https://foodperiodictable.org/about/

small-scale irrigation and affordable *smart phones with location-specific soil and weather data*, concrete innovations that can be scaled.

Food prices currently show fast upward movement and increased volatility. Such tendencies, on top of the income losses due to COVID-19, add to food security dangers for the poor. Care must be taken to avoid erratic policies, especially trade policies. While *strategic food reserves can play a role* in ensuring resilience to supply shocks, open rule-based trade – both international and interregional – can provide a more economical option for dealing with localized extreme weather events. Ensuring *free and rule-based open food trade* will require a rejuvenation of multilateral trade negotiations. In addition, to avoid panic-induced world price spikes, transparent information on production, stocks and government interventions around the world are critical and must be made widely available. The Agricultural Market Information System (*AMIS) is an important step* in this direction (Zimmermann and Rapsomanikis 2021).

Climate change is the defining issue of our time (Hodson et al. 2021; Hertel et al. 2021). Agriculture, deforestation and related land use change are the single largest drivers of multiple environmental pressures, and major contributors to greenhouse gas emissions. The livestock sector is also a major contributor of greenhouse gas emissions (Herrero et al. 2016). Significant improvements in livestock production productivity in terms of land use and reduction of GHGs have been made; however, the adverse environmental impact of the expansion of the sector has continued to rise (Herrero et al. 2021b). While the sector is part of the overall climate change problem, it must also be part of the solution. Reducing consumption of ASF, particularly of red meat, can potentially benefit the environment. Good resource management practices for soil and water that contribute to promoting sustainable food systems must be rewarded, with *payments for ecosystem services* as an option (Daily and Polasky 2019; Rahman and Hickey 2019). In some countries, there is a need to reduce the over-use of chemical fertilizers that leads to significant environmental pollution and climate change. Boosting nature-based solutions (Jensen et al. 2020) and nature-positive production calls for *transforming soil management, farm input use, agronomy* (Neufeld et al. 2021; Lal 2017), and livestock and aquatic food systems in ways that sustainably boost production to meet current and future food demands, *protecting and using biodiversity through biophysical and ecological practices* (van Zonneveld et al. 2021), rapidly reducing the use of pesticides in intensive crop production, similarly reducing the use of antibiotics and steroids, and protecting the agriculture- and forest-related genetic base (Schmitz et al. 2021). Adopting circularity in the livestock sector can fulfill a significant part of the human protein need and lower the adverse environmental impacts. Alternatives to the current inputs for the livestock sector, including recycled feed and *superfeeds* and feeds from protein sources such as protein rich insects, woody plants, algae and seaweed, need further research and exploration before being expanded at scale (Herrero et al. 2021b; Van Zanten et al. 2019). Of critical importance in this context is the *rapid reduction of the use of antibiotics and steroids in livestock and aquatic food* production systems. Greater emphasis must also be given to the development of green technologies that deploy ecologically suitable trees and indigenous perennial species to boost nature-positive production, and the reduction of large monocultures (Niggli et al. 2021; Snapp et al. 2021). Similarly, *organic fertilizers and bio-stimulants from land and marine sources that can replace chemical fertilizers in promoting soil plant growth* and increasing yields can be further explored (Alae-Carew et al. 2020). *Novel insurance products* and *efficient social protection programs* that include job creation and a variety of nutrition programs, including school-feeding programs, strengthen resilience (Bundy et al. 2018).

Future scientific and technological developments can increase the portfolio of bioproducts developed from local biodiversity, in keeping with a *circular bio-economy* approach (Trigo et al. 2021). Accelerating the reduction of food waste and loss calls for developing *food processing, refrigeration, storage and warehouse technologies* (Dobermann et al. 2021). It also calls for *modifying consumption behaviors, lifestyle choices*, and the perverse incentive to buy much more than needed. A rapid move towards climate-positive and climate-resilient food systems should employ *carbon pricing at appropriately high levels* and incentives for technologies that facilitate adaptation and mitigation (Zilberman et al. 2019; Zarnowiecki et al. 2020). Initiatives for *carbon farming* (growing carbon in soil and trees as a tradable commodity) and related payment schemes should be explored. Climate finance for adaptation has important ecological opportunities in the food system and is also pro-poor. It only currently accounts for a very small proportion of climate finance, and it needs to be increased (Van der Ploeg et al. 2019).

Food systems need to become more prepared for and resilient to not only extreme weather events and climate shocks, but also market and inflationary shocks, health shocks, natural disaster shocks, political/governance shocks, cyber shocks, and other emerging shocks. The characteristics, scale and impact of risks continue to evolve (World Economic Forum 2021), and food-related crises are rising in likelihood and severity. Science also has a growing role in developing a common language to converge multiple knowledge systems and shared goals under emerging risks and uncertainties and how to prepare for and manage them. Rigorous implementation research is needed to strengthen the fit-to-context design and delivery of such programs, and thereby strengthen the resilience of chronically vulnerable communities and their food systems.

2.3 Innovations for Overcoming Inefficient and Unfair Land, Credit, Labor, and Natural Resource Use Arrangements, and Facilitating Empowerment of Women, Youths and Indigenous Peoples

Poverty and hunger are interlinked, and reducing extreme poverty directly impacts the elimination of hunger and malnutrition. Among the effective ways to sustainably eradicate poverty and inequality is boosting the opportunities and capacities of the poor and those living in situations of vulnerability, through ensuring more equitable access to resources, i.e., to natural resources and economic assets. *Providing and protecting the land rights* of smallholders – especially female smallholders, and Indigenous Peoples – is critical in this context, as is overcoming exploitative share tenancy. *Inclusive approaches are more possible, affordable and controllable through block chain ledgers of land ownership and credit.*

Ensuring decent work is a key area, and calls for regulation and value chain transparency. The potential for significantly expanding green jobs within food systems must be vigorously pursued. *Pro-poor asset sharing investments and programs that empower poor people to build their asset base* offer promise. Nonetheless, eliminating poverty alone will not make healthy diets affordable for all. Changing food systems need to ensure that people with low incomes can access a healthy diet by *enabling them to earn living wages and have access to social safety nets.*

The roles of **women** are very important for productive, healthy and sustainable food systems (Schmitz et al. 2021). Many food systems are unequal or breed inequalities through land and other asset ownership and market power relationships, whereby power imbalances are a common phenomenon. Besides gender inequalities, overall inequalities across classes, regions, rural-urban contexts, and social groups also influence whether food systems will transform so as to be healthier, more sustainable, and equitable. Women's voices being included in policymaking – as they are cognizant of the needs and wants of women and societal norms and issues – is critical.

The situation of the **young**, as well as the elderly, deserves particular attention. Key innovations include policies for transforming land tenure in equitable ways, providing more and better education investments that enable and empower youths and women and allow them unfettered access to knowledge and information, facilitating job training and education programs, providing affordable financial services, and including youths more fully and meaningfully in policymaking processes. *Vocational training with multi-faceted curricula relevant to rural economic space and food systems need to be scaled up.* Youths have the right and responsibility to learn about food system dynamics and to be fully engaged in opportunities to transform the food systems that they will inherit. The inclusive transformation of smallholder farming will be imperative for youths. Smallholders are not a homogenous group, and transformation of the small farm economies around the world will call for different policies to address the heterogeneity of smallholders.

2.4 Bio-science and Related Digital Innovations for People's Health, Food Systems' Productivity and Ecological Well-being

Specific scientific opportunities for innovations here include *genetic engineering, genome editing, alternative protein (including more plant-based and insect-derived protein) sources* (van Vliet et al. 2020) *and essential micronutrient sources, cell factories, microbiome/soil and plant health technologies, plant nutrition* *technologies* (Jensen et al. 2020), *and animal production and health technologies*. These advances in science and technology have great potential to meet food system challenges such as restoring soil health and functionality (Lal 2017), improving the resource efficiency of cropping systems (Pretty et al. 2018), breeding orphan and underserved crops (Padulosi et al. 2019), and re-carbonizing the terrestrial biosphere. *Modern plant breeding techniques that allow plants to capture nitrogen from the air reduce the need for fertilizers and improve nutritional qualities.*

However, it must not be neglected that there are potential risks associated with science-based innovations that need to be considered within the science systems and through societal dialogues around transparency, ethical standards and reviews, and biosafety measures, and – where needed – through regulatory policies. Adopting the *One Health approach*, i.e., the health of soil, plants, animals, people, ecosystems and planetary processes, being one and indivisible, would be an important contribution (Lal 2020a).

Translating bio-science innovations into reality does not happen automatically: property rights, skills, and data are key for the translation and management of scientific innovations in practice (Webb et al. 2021). However, b*io-sciences increasingly benefit from digital innovations and artificial intelligence* (Benfica et al. 2021). Nonetheless, these technologies sometimes run the risk of exclusion through the creation of monopolies that need to be prevented through anti-trust regulations. Hence, *innovations in governance structures* are needed to ensure that access to bio-science and digital technologies is not hindered. Furthermore, developing these bio-science and digital innovations and ensuring that they – especially the potentially controversial technologies – contribute to sustainability is not sufficient; rather, it will be important to *adapt them to local conditions*, make them accessible and affordable to farmers, especially smallholders, and use them to enhance local and traditional knowledge. It will also be important to have open information-sharing so that users are aware of the opportunities, costs and benefits of new innovations and are able to better use the available technology and implement innovations (Thornton et al. 2019). To ensure that poor communities are not left behind, governments of countries in the global South need to invest in the *creation of capacities and expertise for developing and utilizing bio-sciences and digital technologies, receiving support for that from development partners.* It is important that Indigenous Peoples and local people in general receive the benefits of the innovations that result from their interactions and information-sharing with scientists.

2.5 Innovations to Keep and Regenerate Soils, Land, Coastal Areas and Water, Including Oceans, and Protect the Agricultural Genetic Base and Biodiversity

One-third of global land area is degraded (Le et al. 2016). Soil degradation is being exacerbated by climate change, along with land misuse and soil mismanagement (IPCC 2019). Water is becoming increasingly scarce and polluted (Ringler et al.

2021). Ecosystem services of land, forests, and water cycles are being undermined (Mirzabaev et al. 2019). The livestock sector needs particular attention in this regard; it is a major user of land and water and has significant negative impact on the environment. One-third of the global land suitable for crop production is used to produce livestock feed (FAOSTAT 2018). The sector has contributed, and continues to contribute, to global biochemical cycles that cause a loss of biodiversity (Herrero et al. 2021b). Resource protection and enhancement of terrestrial resources must not exclude coastal areas and their links to the oceans. Technology-based innovations are needed to support sustainable soil, agricultural, and water management, protect natural resources from degradation and restore degraded resources, and maintain and even increase biodiversity in agricultural settings (Shukla 2019; Smith et al. 2019). This underlines the need to advance knowledge of plant genetic diversity and microbial diversity, taking local climate variability into account (Guerra et al. 2020). *Harnessing soil microbes to add to depleted soils for the purpose of improving structure, carbon capture and yields is a promising innovation opportunity.* The use of *modern hand-held digital devices for in-field measurement* and *remote sensing measurement of soil carbon* can become a significant opportunity for both climate policy and productive plant nutrient management. These examples highlight the interconnectedness of technological and policy innovations, because the technologies can facilitate the increased feasibility of payments for ecosystem services. Similarly, agro-ecology and other regenerative *practices for resilient landscapes* at scale promise opportunities. They need long-term accompanying science. An integrated approach for sustainable soil management should be considered and incentivized. Locally adapted sustainable intensification of existing agricultural systems, including the livestock sector, is also needed (Bernard and Lux 2017; Pretty et al. 2018; HLPE 2019). In the livestock sector, production of dual-purpose crops, improved feeding practices, agroforestry and pasture intensification have potential for scaling up.

Primary forests are over-exploited, including due to the non-sustainable expansion of agriculture. Conversion of intact ecosystems, including carbon-dense, biodiverse forests for livestock production, is a major environmental concern. *Innovations in agroforestry* with trees and bushes and in landscape contexts can contribute to large-scale productive land use, combined with ecological and climate-positive ecosystem services (Olsson et al. 2019). Wild foods (e.g., berries and fruits) are important for food security and nutrition for both smallholder farmers and Indigenous Peoples (Angelsen et al. 2014). Traditional food and forest systems – including Indigenous Peoples' food systems – need to be better understood and protected when designing policies (Azam-Ali et al. 2021).

2.6 Innovations for Sustainable Fisheries, Aquaculture, and Livestock

Science-based innovations for the livestock sector that ensure the availability and affordability of sustainably produced, high quality protein need support and scaling up. These include the sustainable intensification of livestock systems. Ensuring the availability of key inputs and services, as well as the development of associated value chains and market integration, is a prerequisite for widespread adoption of sustainable practices. Improving livestock productivity can help mitigate the negative environmental impacts and reduce GHG emissions. Replacing currently used animal feed with microbial protein from sewage and *superfeeds* like algae and grass and using organic anti-methanogenic compounds can reduce the cropland area used for the production of feed and decrease methane emissions. GPS devices, robotics and sensors can also be effectively used for controlled grazing, surveillance, and precision feeding. Alternatives to animal-based protein, including insect-based proteins, cultured meat, algae and seaweed, should also be explored. Institutional innovations, including true-cost accounting methods, may be used to discourage the consumption of meat and dairy products in regions where consumption levels are high.

Given the tremendous current and future potential of wild and farmed seafood and seaweed to help assure healthy diets, it is critical to broaden the understanding of food systems to more fully include the aquatic food systems (Leape et al. 2021). The livestock sector poses challenges due to its salience as the key provider of high-quality nutrition (esp. protein) and an income source for farming communities, while being a key contributor of global GHG emissions.

Institutional innovations are needed to overcome the misuse of oceans as commons: We are approaching tipping points in regard to harvesting from nature, and unless we *stop treating the oceans as commons that can be exploited* for perpetuity, we will accelerate species extinction, among other irreversible changes. Ecological science perspectives and global cooperation and institutions are needed to bring the harvesting of oceans to sustainable levels and protect biodiversity.

Science-based innovations for sustainable aquatic foods that protect and harness oceans and coastal areas can play a growing role in reducing hunger and malnutrition and building healthy, nature-positive and resilient food systems (Costello et al. 2019). Innovations must support aquatic foods "to increase nutritional diversity, reduce waste, address environmental change and management failures, improve livelihoods of fishing and coastal communities, and capitalize on opportunities to sequester carbon in the marine environment." (International Food Policy Research Institute 2020) Of critical importance are innovations in fish-feeding systems: *insect rearing and the use of oil rich modified legumes as fish feed in improved aquaculture to avoid depletion of oceans are potential options. Enhancing the use of organisms of lower trophic levels for human consumption, e.g. micro-algae and seaweed, can lead to their evolution as foods.*

2.7 *Engineering and Digital Innovations for Efficiency and Inclusiveness of Food Systems*

Digital innovations and engineering that hold much promise for making food systems more efficient, productive, and sustainable are touching on all components of food systems. Examples include *artificial intelligence, big data analysis, remote sensing and robotics* (Taylor et al. 2021), *mechanization, sub-surface drip irrigation with conservation agriculture, precision agriculture, vertical farming, indoor farming, and digitized food processing* (Lal 2020b). The use of *sensors to monitor the origin and quality of products and ingredients all along the food chains* can reduce losses, guarantee safety and reduce unnecessary "in-transparencies."

The ways in which digital innovations can be put to work to optimize agricultural production processes include using *drones and advanced analysis of image data to identify pests and diseases in real time*. With improved access to biotic (pests and diseases) or physical (meteorological, SAT early warning systems) information and remote sensing, producers can use their mobile phones to strengthen their agricultural practices and make better use of inputs and resources.

Digitization in the food system does not necessarily enhance equity, and it may even benefit large-scale farming and processing at the expense of smallholder farming. Thus, appropriate *governance structures* are needed to ensure that access to digital technologies is not hindered and that data collected from smallholders are appropriately protected so that smallholders are not "data-exploited." Inequitable access to digital technologies could significantly impede the transition to equitable food systems. Easing information access for women is particularly important. Strengthening the *e-commerce ecosystem* could transform rural livelihoods, providing *platforms* to reach the last-mile households and better connect them to the wider economy.

The growing role of *digital innovations in science and technology processes* that serve bio-chemical sciences and engineering of relevance for food systems is also noteworthy.

It is of note that digitization itself facilitates decentralized organization of science and research that produces technological, policy and institutional innovations that are context-specific, and thereby offers extraordinary new opportunities to re-organize how science is undertaken, delivered, and used in participatory ways.

Further development to make digital technologies affordable and accessible for small- and medium-sized farmers is essential to avoid even further reducing their competitiveness (Malabo Montpellier Panel 2019). In this context, revisiting and reinvigorating *agricultural extension services with digital options* is called for. Attention to employment effects is also called for, as well as attention to ethical considerations of data use and data ownership. Investments are also needed to scale up universal access to digital technologies and key infrastructure, in particular, access to rural electrification, wherever possible based on renewable energy sources.

3 Modeling Synergies and Trade-Offs Between Actions in Food Systems

The sets of innovations and actions mentioned above are connected, and there are synergies and trade-offs among them. Understanding these synergies and trade-offs is critical to maximizing the effectiveness of innovations and actions. A convincing game-changing action in one food systems domain may cause adverse effects in another. For example, a fertilizer subsidy that increases income and reduces hunger may have an adverse environmental effect if this leads to excessive nitrogen use. To avoid such unintended consequences, food system modeling is essential.

Furthermore, food systems do not operate in isolation. Innovations go beyond food systems and are connected to transformations in health systems (“One Health”), energy and environmental systems (climate), economic systems (trade), and evolving science and knowledge systems. Strengthening the interactions among scientists specializing in food systems, health, climate, and energy will make it possible to generate the required expertise. Furthermore, researchers and users of research need to work together to increase the chances of achieving food systems-related SDGs. Supporting local innovations and creating knowledge, participatory science, and living labs should be explored at scale.

A recent review of the advanced quantitative global modeling (Valin et al. 2021) found **strong synergies between SDG2 and other related SDGs**. These synergies and trade-offs are illustrated in Fig. 1. In particular, SDG1 (no poverty) is central for food security and can unlock many additional benefits across the SDGs. SDG2 is closely integrated with SDG3 (good health and well-being) due to the close link between malnutrition and maternal and child health, as well as deaths associated with poor diet. Other socioeconomic SDGs – including SDG4 (education), SDG5 (gender equality), SDG8 (decent work and economic growth), SDG10 (reduced inequality), SDG11 (sustainable cities and communities), SDG16 (peace, justice and strong institutions), and SDG17 (partnership) – are key enablers for SDG2. These potential synergies merit greater attention in regard to accelerating food system transformation.

The importance of trade-offs must also be recognized. Agricultural production substantially contributes to global warming, nutrient pollution, the degradation of water quantity and quality, biodiversity loss, and soil degradation. Climate action (SDG13) requires curtailing greenhouse gas-intensive products (meat, dairy, rice). Achieving biodiversity on land (SDG15) requires limiting deforestation associated with agriculture expansion and establishing new conservation areas. Achieving environmental water flows (SDG6) requires reducing water withdrawal for irrigation. Quantitative assessments show more efficient production systems and technologies and the pricing of externalities. Additionally, integrated resource management can mitigate some of these trade-offs, although it is unlikely to succeed in addressing them altogether.

Forward-looking analyses indicate that, to achieve the SDG2 targets and other goals, deeper transformation of food systems at the global level will be required,

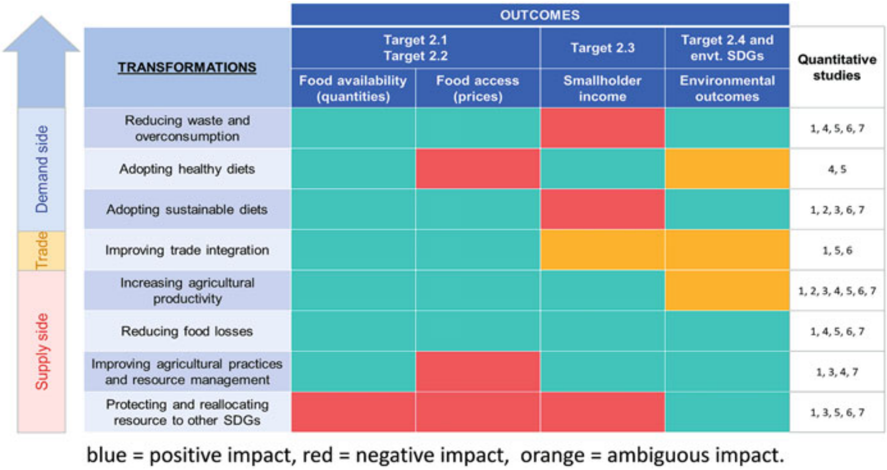


Fig. 1 Key transformations implemented in global analyses and their typical impact for relevant indicators (Valin et al. 2021)

combining supply- and demand-side measures. Such transformation entails new supply-side investments, effective trade and markets, and modified consumer behavior, with a fast transition towards more sustainable and healthy diets and sharp reductions in food loss and food waste. SDG12 (responsible production and consumption) is a key goal for the successful transformation of global food systems to achieve SDG2.

With an integrated modeling framework, Laborde and Torero (this volume) model six individual interventions similar to those presented in Fig. 1 with respect to their impact on food systems, the prevalence of undernutrition, ecological effects in terms of GHG emissions, land and energy use, and the use of chemical inputs. Given the synergies and complementarities between these scenarios, the authors assess them as a package. The sensitivity to the results is also assessed under different governance principles, such as land use policies.

The scenarios are listed in Laborde and Torero (this volume) and organized around three main pillars: achievement of a more *efficient* and *inclusive* system, allowing consumers and producers to make *better choices*. The results of the different scenarios are consistent with the baseline of *The State of Food Security and Nutrition in the World 2020***,** namely that, in 2019, there were 690 million undernourished people in the world and healthy diets were unaffordable for almost three billion people. The findings confirm that ending chronic hunger at a 5% level is feasible by 2030 with the appropriate balance of interventions. While no intervention alone could solve the problem, key interventions to increase the efficiency of food systems – through increased *farm productivity* and a reduction of *food loss and waste* – will reduce the number of people in chronic hunger by 314 million by 2030.

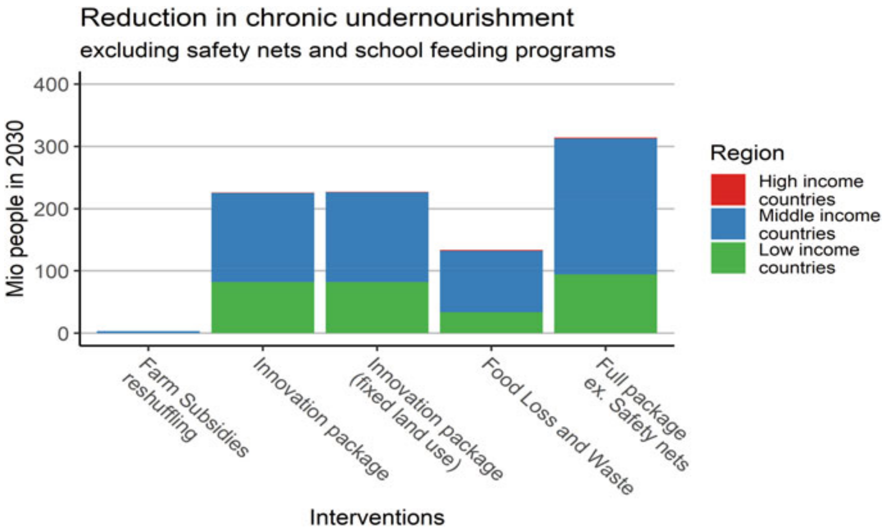


Fig. 2 Number of people (mio) removed from a state of chronic undernourishment in 2030. (Source: Preliminary results based on Laborde and Torero, 2021)

Beyond hunger, 568 million people will be able to afford healthy diets. To target the remaining population, *safety nets* and targeted programs like *school-feeding* interventions are required. When adding such safety nets into the model, it is possible to cover the 2.4 billion remaining people without access to healthy diets (Fig. 2).

Achieving the end of widespread hunger requires significant *resource mobilization*, representing 8% of the size of food markets.[4] The actions – referred to as "better choices," including *consumer incentives* and *farm subsidy re-purposing* – do not contribute to the total costs, because they are designed to be cost-neutral for the government and producers (farm subsidies), as well as consumers (food tax/subsidies), in each country. The cost structure is dominated by the large investment in innovations for productivity, in people, who impact the value chains and national economies (45%), and in the social safety nets (36%).

Clearly, the two main items are different, since the latter involves recurrent spending every year and will have to be managed and financed by governments alone. Since the needs are unevenly distributed globally, a significant solidarity effort is required for global coordination, especially to support the transformation of food systems in low-income countries.

As previously shown, no single intervention can end malnourishment. The actions modeled will generate trade-offs in greenhouse gas emissions (emissions from agricultural production and net emissions from agriculture, forestry, and other

[4] 2030 spending and food market values, as estimated by the model to guarantee full consistency.

land use, or AFOLU), chemical inputs (increased use of chemical inputs per hectare), biodiversity (reduction of forest habitat and agricultural land) and energy consumption.

The effects indicate environmental improvement as a consequence of reducing food loss and waste. However, when it comes to net agricultural emissions and AFOLU, the effect is negative, as is the case for forest land. This highlights the need for policies that can stimulate investments in innovation for carbon farming – growing carbon in soil and trees as a tradable commodity – and related payment schemes for ecosystem services, as indicated in Sect. 2.5 concerning the science and innovation actions above.

4 Enabling Food System Transformation

Transformation of food systems that are under way do not guarantee that the food-related SDGs – especially SDG2 – will be achieved. There are fundamental conditions that are essential to enable and leverage food system transformation to achieve the desired objectives, including *facilitating peace and security and conflict resolution, full inclusion of marginalized and vulnerable populations, gender equity, sound governance at all levels, from community to local to regional to national and international,* and *supportive global and national policies for public goods* (Global Panel on Agriculture and Food Systems for Nutrition 2020; International Food Policy Research Institute (IFPRI) 2020). We highlight below the required additional actions in the follow-up to the UNFSS 2021 in the fields of finance, capacity, and governance.

Finance Enabling food system transformations requires constant investment in science that has the potential to produce positive change in systems. In 2018, the world science “output” in terms of peer-reviewed publications was 4.04 million, and of these, 14% were related to agricultural and biological sciences (about 298,000) and environmental sciences (about 273,000).[5] Thousands of potentially game-changing insights are generated by the world’s scientific communities every year. More attention is needed to identify actionable insights for innovations, and that requires strengthening capacity and innovative financing.

Science systems have been decimated in many countries, especially in the global South. To tap the potentials of science, the public funding of food system science and related research partnerships needs to expand. Governments need to change their low levels of spending on food system-related research and innovation. We call on governments – especially in the global South – to review the level of their investments in food system science and allocate at least 1% of their food system-related GDP to food system science and innovation with a perspective to substantially

[5] Scimago journal and country rankings for 2018.

exceed this target. LDCs should be assisted in quickly reaching the equivalent of this target. About 20 years ago, African ministers responsible for science and technology had already committed to increase public expenditures on research and development to at least 1% of GDP per annum.[6] As basic sciences – for instance, *bio-chemical and nutrition and health sciences* – are becoming increasingly relevant for food systems, the investment in these must also be accelerated and systems for sharing the sciences related to food systems expanded (Beintema et al. 2020; von Braun 2020). There are important new opportunities for engaging private sector science to address public goods in food system innovations, particularly in partnership with the public sector (Herrero et al. 2020). The private sector here is a broad concept, ranging from semi-subsistence farmers to large corporations. It is often overlooked that the former are also proven innovators (Tambo and Wünscher 2017). The knowledge of Indigenous Peoples is another important component of local food systems' innovation landscape. Intellectual property rights protection issues require revisiting so as to align them with sustainability expectations, especially for scientific opportunities that address overcoming hunger and malnutrition (Zilberman et al. 2019; Zarnowiecki et al. 2020). New institutional arrangements may be discussed for sharing intellectual property that could directly reduce hunger and address sustainability concerns.

The follow-up to the Food Systems Summit needs to consider how the investments in the identified priority actions may be financed, and that is where innovative finance approaches that economics research can explore shall be considered. Research suggests that mobilizing the necessary financial resources may include a combination of actions, such as (1) provision of additional – actually double the current amount – international development funds (ODA) for agricultural and rural development, food and nutrition security; (2) reallocation of agricultural subsidies towards investment in sustainable development and the scaling up and redesigning of social safety nets; (3) initiation of a new dedicated "end hunger" fund, perhaps through expanded IDA; and (4) possibly the financing of innovative financial mechanisms such as "End Hunger Bonds" through support from incremental special drawing rights (SDRs) (von Braun et al. 2021b; Díaz-Bonilla 2021). The private sector should be part of this resource mobilization, expecting long-term returns from a more prosperous society. Research shall identify what combinations of finance may contribute to the sustainable financing of food system transformation.

Capacity Of particular importance are investments in *improving data, methods, models and tools for all food system components* and actors, as well as building or *enhancing (shared) research infrastructures related to (research) data, modeling platforms, observation and monitoring networks* to support the required advances in research and innovation, especially in the global South (Inter-Academy Partnership 2018). Integrated *global food system models* are needed, as existing models do not have consistent global coverage and are not designed to assess the impacts of all

[6]Declaration of the first NEPAD Ministerial conference on Science and Technology, 7 November 2003, Johannesburg, South Africa https://sarpn.org/documents/d0000614/index.php

elements of food systems (Webb et al. 2020b). Besides global foresight work, strengthening national and – where possible – subnational/local policy scenarios and foresight work is also necessary. More attention needs to be paid to strengthening local research capacities, *expanding research collaboration among public and private sector research and indigenous systems*, sharing research infrastructure and data, developing more inclusive and equitable science partnerships and follow-up mechanisms, systematically learning what works and what can be scaled up and translating that knowledge into action, improving the efficiency in the way knowledge is generated and shared, and *addressing intellectual property rights issues when they hinder innovations* that can serve food and nutrition security, food safety, and sustainability goals (Hendriks et al. 2021b). With the increased recognition of their central role in achieving many development goals, food systems will be expected to perform a more complex set of activities, and this requires new and more appropriate holistic metrics. Protection of the freedom of science to innovate and experiment while adhering to ethical standards needs to be continually reinforced.

Because significant components of food systems are local, the Summit has to ensure that its outcomes and deliverables turn into positive local actions. This requires science to align with national and local agendas for the implementation actions. The proximity of science to decision-making is important to connect the timeliness and relevance of science to policy where and when it is needed. Similarly, the development of national and local infrastructure and expertise to effectively link science to decision-making is important. The science underpinning food system transformation becomes more inter- and trans-disciplinary, more open to a wide range of innovations and their diverse stakeholders, and more appropriately configured and scaled to different contexts. Relatedly, it would be important to innovate and *improve the methods for analyzing the performance of food systems* (e.g., analyzing their impact on health, nutrition and sustainability goals) at different levels (local, national, global).

Transformation is not possible without science, and in many instances, citizen participation in research and implementation can be very supportive for the transformation of farming, the application of new technologies, the shift to healthy diets, and other key elements of successful food system transformation. Citizen science has an important role to play in inclusive food system transformation, especially with farmers as co-designers directly participating in the development of innovations and with scientists being more open to and collaborating on fair terms with start-ups. Indigenous Peoples knowledge systems should be partnered with in such approaches.

The international sharing of science and the participation of science in the follow-up to the Food Systems Summit as part of implementation agendas is vital. Proposals for international collaboration include supporting low- and middle-income countries in building and sustaining capacities to acquire and deploy technologies through joint research, education and training programs. Beyond investing in capacities to undertake research, it will be important to also invest in capacities to act upon research: in other words, to put to effective use the knowledge and innovations that already exist (e.g., traditional and indigenous knowledge) or that are generated from new research. This calls for investing in *strengthening the skills of all food system actors*, especially in emerging economies, where these skills tend to be more limited. In many instances, what is lacking is actionable knowledge that may contribute to systemic changes, which requires supporting local innovations and encouraging and facilitating the co-creation/co-design of knowledge. In support of this, *leading research organizations from world regions could form networks (or alliances)* to share science and develop actionable knowledge that supports food system transformations.

Governance and Science-Policy Interface In contrast to other subjects of global concern that were agreed upon at the Earth Summit in Rio in 1992, agriculture, food security and nutrition do not have an international agreement or convention to consolidate actions. Climate, biodiversity and desertification have their dedicated conventions and ensuing subsidiary bodies, secretariats and further protocols. Fueled by regular meetings of the conference of parties and underpinned by a solid science-policy interface, they have made enormous progress. Thus, we believe that the time has come to consider such a set of agreements and mechanisms for the complex area of food systems, obviously fully recognizing existing efforts and agents. The UNFSS may wish to consider opening a process for *exploring a treaty on food systems*. In a related manner, food system science and policy need a stronger scientific framework for constructive and evidence-based interaction that will allow it, too, to move ahead for the long term (von Braun 2018). At the national level, coherent national food systems research policies need to be better integrated into national development policies, such that countries develop their own context-specific food systems policies and strategies. At the international level, some have proposed strengthening the contribution of science to policymaking for transformational food systems with an Intergovernmental Scientific Advisory Panel, while others advocate strengthening and better connecting existing mechanisms (Hendriks et al. 2021a; Inter-Academy Partnership 2018; von Braun and Kalkuhl 2015). We suggest exploring options for an inclusive, global science-policy interface (SPI) for a sustainable food system that connects national and global food systems concerns and will assist in an evidence-based follow-up to the proposed Summit actions and for the long term. This proposition is based on three considerations: (1) the growing complexity of food value chains from resource use to human nutrition and their increasing globalization, which urgently requires a new integrated approach that draws on all related science for sustainable agriculture, food and nutrition systems; (2) the absence of a comprehensive and timely system to collect, analyze and assess data on the diagnosis and technical, economic and social solutions for creating long-term sustainable, affordable, nutritious and safe food systems; and (3) the limited or non-existent translation and traceability of scientific data and experiences into evidence-based policy that precludes the application of experiences across countries and regions (Hendriks et al. 2021c; Hodson de Jaramillo et al. 2021; Moughan et al. 2021; Fan et al. 2021; Serova et al. 2021; Gulati et al. 2021). Addressing these considerations requires a global mechanism that mobilizes the leading food systems scientists worldwide and across disciplines to support the SPI through co-production, open access, and communication of knowledge. The effective and independent participation of research communities from low-income countries and emerging economies in the SPI must be strengthened to enhance credibility, relevance and legitimacy. We call upon governments and UN agencies to *initiate a process to explore options – those already existing*[7] *as well as new – for a global SPI* for a sustainable food system. As such, this would be a concrete outcome of the UNFSS.

Science and policy have a lot to gain from cooperation, but the independence of science to address policy and institutional opportunities and failures with evidence-based insights must not be compromised. Nonetheless, science that produces new insights also needs to constantly earn the trust of society, and in view of the cultural sensitivity of all matters related to food, policies and rules must assure confidence in scientific endeavors. Anti-science sentiments exist in parts of society. While pursuing new insights and truths, there are many issues upon which scientists themselves do not agree, which sometimes irritates policymakers and practitioners. Adhering to responsible and ethical principles, science must collaborate with a broad range of stakeholders. The improved quality and timeliness of science translation and communication for policymakers and non-technical audiences are helpful, along with attention to ethics, peer review, scientific integrity and excellence, transparency and declarations of interest in science.

In closing, science, innovation, and technologies play critical roles among the measures to achieve food system transformations. All sciences – natural sciences and social sciences, basic sciences and applied sciences – in collaboration with diverse traditional knowledge systems must deliver innovations and make significant contributions for the necessary food system transformation in order to achieve the SDGs, especially SDG2, and the complete 2030 Agenda.

Acknowledgments The authors developed this chapter in close collaboration with the Scientific Group of the UN Food Systems Summit, which has engaged extensively with scientific communities around the world, including the partners and contributors of more than 40 reports and briefs prepared specifically for the Scientific Group's evidence-based contributions to the Summit. The authors thank the participants of Science Days in 2021 for their thoughtful input and comments on the draft paper, as well as all others who shared comments and suggestions.

[7] Including the CGIAR (https://www.cgiar.org/), the Global Forum on Agricultural Research and Innovation (GFAR) https://www.gfar.net/), the High Level Panel of Experts on Food Security and Nutrition (HLPE) (http://www.fao.org/cfs/cfs-hlpe), and the InterAcademy Partnership (IAP) (https://www.interacademies.org/).

References

Alae-Carew C, Nicoleau S, Bird FA, Hawkins P, Tuomisto HL, Haines A et al (2020) The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. Environ Res Lett 15(2):023002. https://doi.org/10.1088/1748-9326/ab5cc0

Allen S, Badiane O, Sene L, Ulimwengu J (2014) Government expenditures, health outcomes, and marginal productivity of agricultural inputs: the case of Tanzania. J Agric Econ 65(3):637–661

Angelsen A, Jagger P, Babigumira R, Belcher B, Hogarth NJ, Bauch S et al (2014) Environmental income and rural livelihoods: a global-comparative analysis. World Dev 64:S12–S28. https://doi.org/10.1016/j.worlddev.2014.03.006

Azam-Ali S, Ahmadzai H, Choudhury D, Goh EV, Jahanshiri E, Mabhaudhi T et al (2021) Marginal areas and indigenous people–priorities for research and action. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/fd4f-rk35

Barakat S, Milton S (2020) Localisation across the humanitarian-development-peace nexus. J Peacebuild Dev 15:2. https://doi.org/10.1177/1542316620922805

Beintema N, Pratt AN, Stads G-J (2020) Key trends in global agricultural research investment. ASTI Program Note. https://www.asti.cgiar.org/sites/default/files/pdf/Global-update-ASTI-note.pdf

Benfica R, Chambers J, Koo J, Nin-Pratt A, Falck-Zepeda J, Stads GJ, Arndt C (2021) Food system innovations and digital technologies to Foster productivity growth and rural transformation. In: Food systems summit brief prepared by Research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-6180

Bernard B, Lux A (2017) How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. Reg Environ Chang 17:1279–1290. https://doi.org/10.1007/s10113-016-1027-y

Bhutta ZA, Das JK, Rizvi A, Gaffey MF, Walker N, Horton S, Webb P, Lartey A, Black RE (2013) Evidence-based interventions for improvement of maternal and child nutrition: what can be done and at what cost? The Lancet 382(9890):452–447

Bron GM, Siebenga JJ, Fresco LO (2021) In the age of pandemics, connecting food systems and health: a global one health approach. In: Food systems summit brief by partners of scientific group. https://doi.org/10.48565/scfss2021-z850

Bundy D, Horton S, Jamison D, Patton G, de Silva N (eds) (2018) Re-imagining school feeding: a high return Investment in Human Capital and Local Economies. DCP3 and WFP. http://www.dcp-3.org/schoolfeeding

Center for Development Research (ZEF) of the University of Bonn in cooperation with the Food and Agriculture Organization of the United Nations (FAO) (2020) Investment costs and policy action opportunities for reaching a world without hunger (SDG 2). http://www.fao.org/documents/card/en/c/cb1497en

Costello C, Cao L, Gelcich S et al (2019) The future of food from the sea. In: Capture fisheries: current status and trends. World Resources Institute, Washington, DC. Available online at www.oceanpanel.org/future-food-sea

Daily GC, Polasky S (2019) How do we stem biodiversity loss? In: Biological extinction: new perspectives. Cambridge University Press, pp 332–357. https://doi.org/10.1017/9781108668675.015

Diao X, Reardon T, Kennedy A, DeFries RS, Koo J, Minten B, Takeshima H, Thornton P (2021) The future of small farms: innovations for inclusive transformation. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Small_Farms.pdf

Díaz-Bonilla E (2021) Financing SGD2 and ending hunger. In: Food systems summit brief prepared by Research Partners of the Scientific Group for the Food Systems Summit. https://doi.org/10.48565/scfss2021-ba75

Dobermann A, Bruulsema T, Cakmak I, Gerard B, Majumdar K, McLaughlin M, Reidsma P, Vanlauwe B, Wollenberg L, Zhang F, Zhang X (2021) A new paradigm for plant nutrition. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/SCFSS2021-HG55
Downs S, Demmler KM (2020) Food environment interventions targeting children and adolescents: a scoping review. Glob Food Sec 27:100403. https://doi.org/10.1016/j.gfs.2020.100403
Dury S, Bendjebbar P, Hainzelin E, Giordano T, Bricas N (2019) Food systems at risk. New trends and challenges. FAO-CIRAD-European Commission, 132 p, ISBN 978-2-87614-751-5, Rome. https://doi.org/10.19182/agritrop/00080
Fan S, Huang J, Zhang F, Zhao W, Song H, Nie F . . ., Cong W (2021) Transforming Chinese food systems for both human and planetary health. https://doi.org/10.48565/scfss2021-vq06
FAO (2018) The future of food and agriculture – alternative pathways to 2050. Summary version, Rome, 60 pp. http://www.fao.org/3/CA1553EN/ca1553en.pdf
FAO, IFAD, UNICEF, WFP, WHO (2021) The state of food security and nutrition in the world 2021. FAO, Rome. http://www.fao.org/3/cb4474en/online/cb4474en.html
FAOSTAT (2018) FAOSTAT food balance sheets. Available at: http://www.fao.org/faostat/en/#data/FBS. Accessed 16 June 2021
Fears R, Canales C (2021) The role of science, technology and innovation for transforming food systems globally. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-q703
Food and Land use Coalition (2019) https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf
Global Panel on Agriculture and Food Systems for Nutrition (2020) Future food systems: for people, our planet, and prosperity. https://www.glopan.org/foresight2/
Guerra CA, Heintz-Buschart A, Sikorski J et al (2020) Blind spots in global soil biodiversity and ecosystem function research. Nat Commun 11:3870. https://doi.org/10.1038/s41467-020-17688-2
Gulati A, Paroda R, Sanjiv P, Narain D, Ghanwat A (2021) Food system in India: challenges, performance and promise. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-b823
Hainzelin E, Caron P, Place F, Dury S, Echeverria R, Harding A (2021) How could science-policy interfaces boost food system transformation? In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-4y32
Hansen J, Hellin J, Rosenstock T, Fisher E, Cairns J, Stirling C et al (2019) Climate risk management and rural poverty reduction. Agric Syst 172:28–46. https://doi.org/10.1016/j.agsy.2018.01.019
Harris J, Piters BDS, McMullin S, Bajwa B, de Jager I, Brouwer DI (2021) Fruits and vegetables for healthy diets: priorities for food system research and action. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-ys30
Headey DD, Alderman HH (2019) The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. J Nutr *149*(11):2022–2033. https://doi.org/10.1093/jn/nxz158
Hendriks S, Soussana J.-F, Cole M, Kambugu A, Zilberman D (2021a) Ensuring access to safe and nutritious food for all through transformation of food systems paper on action track 1. https://doi.org/10.48565/scfss2021-wg92
Hendriks S, de Groot Ruiz A, Acosta MH, Baumers H, Galgani P, Mason-D'Croz P, Godde C, Waha K et al (2021b) The true cost and true price of food. In: Scientific group report for the Food Systems Summit. https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf
Hendriks SL, Bekele E, Chaibi T, Hassan M, Miano DW, Muyonga JH (2021c) The role of science, technology, and innovation for transforming food systems in Africa. https://doi.org/10.48565/scfss2021-a948
Herrero M et al (2016) Greenhouse gas mitigation potentials in the livestock sector. Nat Clim Chang 6(5):452–461. https://doi.org/10.1038/nclimate2925

Herrero M, Thornton PK, Mason-D'Croz D et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1:266–272. https://doi.org/10.1038/s43016-020-0074-1

Herrero M, Hugas M, Lele U, Wira A, Torero M (2021a) Shift to healthy and sustainable consumption patterns. Scientific group report for the food systems summit: a paper on action track 2. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-9240

Herrero M, Mason-D'Croz D, Thornton PK, Fanzo J, Rushton J, Godde C, Bellows A, de Groot A, Palmer J, Chang J, van Zanten H, Wieland B, DeClerck F, Nordhagen S, Gill M (2021b) Livestock and sustainable food systems: status, trends, and priority actions. In: Food systems summit brief by Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/bonndoc-1

Hertel TW, Elouafi I, Frank E, Morakot T (2021) Building resilience to vulnerabilities, shocks and stresses: a paper on action track 5. In: The scientific group for the UN food system summit. https://doi.org/10.48565/scfss2021-cz84

Hidrobo M, Hoddinott J, Kumar N, Olivier M (2018) Social protection, food security, and asset formation. World Dev 101:88–103

Hirvonen K, Bai Y, Headey D, Masters WA (2020) Affordability of the EAT–lancet reference diet: a global analysis. Lancet Glob Health 8(1):e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

HLPE (2017) Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 152 p. http://www.fao.org/3/a-i7846e.pdf

HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf

Hodson de Jaramillo E, Trigo EJ, Campos R (2021) The role of science, technology and innovation for transforming food systems in Latin America and the Caribbean. https://doi.org/10.48565/scfss2021-6w45

Hodson E, Urs N, Kaoru K, Lal R, Sadoff C (2021) Boost nature positive production: a paper on action track 3. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-q794

Inter-Academy Partnership (2018) Opportunities for future research and innovation on food and nutrition security and agriculture. The Inter-Academy Partnership's Global Perspective. https://www.interacademies.org/sites/default/files/publication/iap_fnsa_global_web_complete_28nov.pdf

International Food Policy Research Institute (2020) 2020 global food policy report: building inclusive food systems. International Food Policy Research Institute. - Reshaping Food Systems, Washington, DC. https://doi.org/10.2499/9780896293670

International Food Policy Research Institute (IFPRI) (2020) Global food policy report: building inclusive food systems. https://doi.org/10.2499/9780896293670

IPBES (2019) In: Brondizio ES, Settele J, Díaz S, Ngo HT (eds) Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES Secretariat, Bonn

IPCC (2019) Summary for policymakers. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Jensen ES, Carlsson G, Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev 40(1):5. https://doi.org/10.1007/s13593-020-0607-x

Kau A, Ahern P, Griffin N et al (2011) Human nutrition, the gut microbiome and the immune system. Nature 474:327–336. https://doi.org/10.1038/nature10213
Kemmerling B, Schetter C, Wirkus L (2021) Addressing food crises in violent conflicts. In: Systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-h009
Klassen S, Murphy S (2020) Equity as both a means and an end: lessons for resilient food systems from COVID-19. World Dev 136:105104. https://doi.org/10.1016/j.worlddev.2020.105104
Lal R (2017) Improving soil health and human protein nutrition by pulses-based cropping systems. Adv Agron 145:167–204. https://doi.org/10.1016/bs.agron.2017.05.003
Lal R (2020a) Managing organic matter content for restoring health and ecosystem Services of Soils of India. J Indian Soc Soil Sci 68(1):1–15. https://doi.org/10.5958/0974-0228.2020.00001.8
Lal R (2020b) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Secur 12:871–876. https://doi.org/10.1007/s12571-020-01058-3
Le QB, Nkonya E, Mirzabaev A (2016) Biomass productivity-based mapping of global land degradation hotspots. In: Nkonya E, Mirzabaev A, von Braun J (eds) Economics of land degradation and improvement – a global assessment for sustainable development. Springer, Cham. https://doi.org/10.1007/978-3-319-19168-3_4
Leape J, Micheli F, Tigchelaar M, Allison EH, Basurto X, Bennett A, Bush SR, Cao L et al (2021) The vital roles of blue foods in the global food system, – protect and develop the potential of blue foods to help end malnutrition. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-bg71
Malabo Montpellier Panel (2019) Byte by byte: policy innovation for transforming Africa's food system with digital technologies, Dakar, June 2019. https://doi.org/10.2499/9780896296848
Masters WA, Martinez EM, Greb F, Herforth A, Hendriks S (2021) Cost and affordability of preparing a basic meal around the world. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Cost_of_Basic_Meals.pdf
Miller V, Yusuf S, Chow CK, Dehghan M, Corsi DJ, Lock K, Popkin B, Rangarajan S, Khatib R, Lear SA, Mony P, Kaur M, Mohan V, Vijayakumar K, Gupta R, Kruger A, Tsolekile L, Mohammadifard N, Rahman O et al (2016) Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the prospective urban rural epidemiology (pure) study. Lancet Glob Health 4(10):e695–e703. https://doi.org/10.1016/S2214-109X(16)30186-3
Mirzabaev A et al (2019) Desertification. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/06_Chapter-3.pdf
Mirzabaev A, Olsson L, Kerr RB, Pradhan P, Guadalupe M, Ferre R, Lotze-Campen H (2021) Climate change and food systems. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Climate_Change_and_Food_Systems.pdf
Moughan PJ, Chamovitz DA, Ayyappan S, Tanticharoen M, Lal K, Kim YH (2021) The role of science, technology, and innovation for transforming food systems in Asia. https://doi.org/10.48565/scfss2021-tf41
Moustier P, Holdsworth M, Seck PA, Renting H, Caron P, Bricas N (2021) Priorities for inclusive urban food system transformations in the Global South. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/3xdb-qq20
Mushtaq S, Kath J, Stone R et al (2020) Creating positive synergies between risk management and transfer to accelerate food system climate resilience. Clim Chang 161:465–478. https://doi.org/10.1007/s10584-020-02679-5
Neufeld LM, Jikun H, Ousmane B, Patrick C, Forsse LS (2021) Advance equitable livelihoods: a paper on action track 4. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-tw373

Niggli U, Sonnevelt M, Kummer S (2021) Pathways to advance agroecology for a successful transformation to sustainable food systems. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-wf70

Olsson L et al (2019) Land degradation. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/07_Chapter-4.pdf

Osendarp S, Akuoku J, Black R, Headey D, Ruel M, Scott N et al (2020) The potential impacts of the COVID-19 crisis on maternal and child undernutrition in low- and middle-income countries. Preprint under consideration at a Nat Portfolio J. https://doi.org/10.21203/rs.3.rs-123716/v1

Padulosi S, Roy P, Rosado-May FJ (2019) Supporting nutrition sensitive agriculture through neglected and underutilized species - operational framework. Bioversity International and IFAD, Rome, 39 pp

Pretty J, Benton TG, Bharucha ZP et al (2018) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1:441–446. https://doi.org/10.1038/s41893-018-0114-0

Rahman HM, Hickey GM (2019) What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? Front Environ Sci 7:2. https://doi.org/10.3389/fenvs.2019.00002

Ringler C, Agbonlahor M, Baye K, Barron J, Hafeez M, Lundqvist J et al (2021) Water for food systems and nutrition. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-tg56

Ruel MT, Alderman H, Maternal and Child Nutrition Study Group (2013) Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? Lancet 382(9891):536–551

Schmitz S, Barrios R, Dempewolf H, Guarino L, Lusti C, Muir J (2021) Crop diversity, its conservation and use for better food systems. The crop trust perspective. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-j983

Serova E, Orlova N, Popov V, Petukhova M, Osmakova A, Kobiakov O, . . ., Tolmachev P (2021) Key areas of the agricultural science development in Russia in the context of global trends and challenges. https://doi.org/10.48565/scfss2021-6265

Shukla et al (2019) Summary for policymakers. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Smith P et al (2019) Interlinkages between desertification, land degradation, food security and greenhouse gas fluxes: synergies, trade-offs and integrated response options. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/09_Chapter-6.pdf

Snapp S, Kebede Y, Wollenberg E, Dittmer KM, Brickman S, Egler C, Shelton S (2021) Delivering climate change outcomes with agroecology in low-and middle-income countries: evidence and actions needed. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-2420

Sperling F, Havlik P, Denis M, Valin H, Palazzo A, Gaupp F, Visconti P (2020) Transformations within reach: Pathways to a sustainable and resilient world-Resilient Food Systems. http://pure.iiasa.ac.at/16822

Tambo JA, Wünscher T (2017) Farmer-led innovations and rural household welfare: evidence from Ghana. J Rural Stud 55:263

Taylor B, Tonnang HEZ, Beale T, Holland W, Oronje M, Abdel-Rahman EM, Onyango D, Finegold C, Zhu J, Pozzi S, Murphy ST (2021) Leveraging data, models & farming innovation to prevent, prepare for & manage pest incursions: delivering a pest risk service for low-income countries. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-ty56

Thornton PK, Kristjanson P, Förch W, Barahona C, Cramer L, Pradhan S (2019) Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? Glob Environ Chang 52:37–48. https://doi.org/10.1016/j.gloenvcha.2018.06.003

Trigo E, Chavarria H, Pray C, Smyth SJ, Torroba A, Wesseler J, Zilberman D, Martinez JF (2021) The bioeconomy and food systems transformation. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-w513

Valin H, Hertel T, Bodirsky BL, Hasegawa T, Stehfest E (2021) Achieving zero hunger by 2030 a review of quantitative assessments of synergies and tradeoffs amongst the UN sustainable development goals: a paper from the scientific group of the UN food systems summit. Scientific Group for the UNFSS. https://doi.org/10.48565/scgr2021-2337

Van der Ploeg JD, Barjolle D, Bruil J, Brunori G, Madureira LMC, Dessein J et al (2019) The economic potential of agroecology: empirical evidence from Europe. J Rural Stud 71:46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003

van Vliet S, Kronberg SL, Provenza FD (2020) Plant-based meats, human health, and climate change. Front Sustain Food Syst 4:128. https://doi.org/10.3389/fsufs.2020.00128

Van Zanten HH, Van Ittersum MK, De Boer IJ (2019) The role of farm animals in a circular food system. Glob Food Sec 21:18–22

van Zonneveld M, Volk GM, Dulloo ME, Kindt R, Mayes S, Quintero M et al (2021) Safeguarding and using fruit and vegetable biodiversity. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-rz27

van Zutphen KG, Barjolle D, van den Berg S, Gavin-Smith B, Kraemer K, Musard C, Prytherch H, Six J, Winter S, Woltering K (2021) Secondary cities as catalysts for nutritious diets in low- and middle-income countries. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Secondary_Cities.pdf

von Braun J (2018) Global institutions: governance reform for food, nutrition, and agriculture. Global Food Policy Report, pp 62–71. https://doi.org/10.2499/9780896292970_08

von Braun J (2020) Transforming Food Systems – the challenges of food security, malnutrition, climate change, ecosystems degradation, well-being. In: Presentation at the European Union – FAO Strategic Dialogue (May 06, 2021). https://sc-fss2021.org/wp-content/uploads/2021/05/EU_FAO_JvonBraun_Keynote_6-5-2021.pdf

von Braun J, Kalkuhl M (2015) International Science and policy interaction for improved food and nutrition security: toward an International Panel on Food and Nutrition (IPFN). ZEF Working Paper Series, 142(October)

von Braun J, Zamagni S, Sorondo MS (2020) The moment to see the poor. Science 368(6488):214. https://doi.org/10.1126/science.abc2255

von Braun J, Afsana K, Fresco LO, Hassan M, Torero M (2021a) Food system concepts and definitions for science and political action. Nat Food 2(10):748–750

von Braun J, Bezawit C, Torero MC, Laborde D, Carin S (2021b) Ending hunger by 2030 – policy actions and costs. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-kz31

Webb P, Flynn DJ, Kelly NM, Thomas SM, Benton TG (2020a) COVID-19 and food systems: rebuilding for resilience. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-g940

Webb P, Benton TG, Beddington J, Flynn D, Kelly NM, Thomas SM (2020b) The urgency of food system transformation is now irrefutable. Nat Food 1(10):584–585. https://doi.org/10.1038/s43016-020-00161-0

Webb P, Flynn DJ, Kelly NM, Thomas SM (2021) The transition steps needed to transform our food systems. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-hz63

WHO (2020) Dietary recommendations: nutritional requirements; establishing human nutrient requirements for worldwide application. WHO, Geneva. https://www.who.int/news-room/fact-sheets/detail/food-safety

World Economic Forum (2021) The global risks report 2021. http://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf

Wouterse F, Badiane O (2019) The role of health and educational attainment in agricultural production: evidence from smallholders in Burkina Faso. Agric Econ 50:4

Zarnowiecki D, Mauch CE, Middleton G, Matwiejczyk L, Watson WL, Dibbs J, Dessaix A, Golley RK (2020) A systematic evaluation of digital nutrition promotion websites and apps for supporting parents to influence children's nutrition. Int J Behav Nutr Phys Act 17(1):17. https://doi.org/10.1186/s12966-020-0915-1

Zilberman D, Lu L, Reardon T (2019) Innovation-induced food supply chain design. Food Policy 83:289–297. https://doi.org/10.1016/j.foodpol.2017.03.010

Zimmermann A, Rapsomanikis G (2021) Trade and sustainable food systems. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-zq03