# Research strategies to catalyze agroecological transitions in low- and middle-income countries

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OVERVIEW ARTICLE

# Research strategies to catalyze agroecological transitions in low- and middle-income countries

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**Abstract**
Governments are updating national strategies to meet global goals on biodiversity, climate change and food systems proposed in the Convention on Biological Diversity post-2020 framework and agreed at the United Nation's Climate Change Conference (COP26) and Food Systems Summit (UNFSS). This represents a unique and crucial opportunity to integrate and accelerate food system actions to tackle interconnected global challenges. In this context, agroecology is a game-changing approach that can provide the world's growing population with nutritious, healthy affordable food, ensure fair incomes to farmers and halt and reverse the degradation of the natural environment. Here, we explore agroecological transition pathways in four case studies from low- and middle- income countries and identify catalysts for change. We find that enabling policy and market environments, participatory action research and local socio-technical support each plays a critical role in stimulating transitions towards agroecology. We propose strategies and priorities for research to better support agroecological transitions using these catalysts of change as entry points. Engagement of governments, private sector, civil society, farmers and farm workers in this research agenda is essential.

**Keywords** Agroecology · Sustainable food systems · Food system transformation · Transition pathways

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## Introduction

Our global food systems fail to nourish the world's population (FAO et al. 2020) while causing environmental degradation so severe that it threatens life on earth by surpassing local and planetary boundaries (Gerten et al. 2020). In low- and middle-income countries (LMICs) this is coupled with population growth, urbanization and persistent economic and social inequality. Around the world, people are calling for a transformation to sustainable food systems that provide the world's growing population with nutritious, healthy and affordable food while ensuring fair and stable incomes to farmers, restoring the natural environment and regenerating ecosystem services (Webb et al. 2020).

Agroecology is increasingly seen as an effective means to achieve sustainable food systems. Agroecology means "applying ecological concepts and principles to optimize interactions between plants, animals, humans and the environment [within agricultural systems] while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (FAO 2021a). There is no single farm or food system model that defines agroecology. Agroecology is best interpreted as a set of principles which can be used to guide interventions at farm and food system level. Building on earlier work by FAO (2016), a set of 13 principles has been proposed, positioned around the following three operational objectives: increase resource use efficiency, strengthen the resilience of farming systems and secure social equity and responsibility (HLPE 2019; Wezel et al. 2020). To become operationalizable and meaningful, these objectives and principles need to be prioritized and interpreted for each context.

Here, we attempted the following: (i) clarify what agroecology means in practice, (ii) define plausible agroecological transition pathways for LMICs with contrasting starting points and, (iii) identify strategies for research and development to support these transitions. First, we explore the practices and principles associated with agroecology and clarify how agroecology can complement other approaches to achieving sustainable agriculture. The subsequent section draws on four case studies from Burkina Faso, Vietnam, Cuba and Brazil that reflect distinct starting points and socio-ecological contexts, to demonstrate plausible agroecological transition pathways and evaluate change processes in the context of wider research of how transitions happen. Finally, we propose strategies and priorities for research and development to better support agroecological transitions focusing on three catalysts for change.

## Operationalizing agroecology

Operationalizing agroecology requires interventions in both agroecosystems (at field, farm and agricultural landscape level) and food systems (in markets and along agricultural value chains) to adhere to the High-Level Panel of Expert's (HLPE's) 13 agroecological principles (HLPE 2019; Wezel et al. 2020) (Table 1). Despite the primary focus on principles, the term 'agroecological practices' is nonetheless widely used. Agroecological practices refer to farming practices that seek to regenerate biological functions in line with ecological principles that underly increased resource

**Table 1** Thirteen agroecological principles, from HLPE (2019) and Wezel et al. (2020)

| **Agroecological principle** (short name in bold) |
|---|
| **Principle 1: Recycling**, including closing nutrient and biomass resource cycles |
| **Principle 2: Input reduction**, through reducing or eliminating use of chemicals or environmentally harmful inputs |
| **Principle 3**: Enhancing **soil health** through improving soil biodiversity and use of organic material |
| **Principle 4**: Ensuring **animal health** and welfare |
| **Principle 5**: Enhancing **biodiversity** at field, farm and landscape scales |
| **Principle 6**: Enhancing **synergies** across agronomic or environmental outcomes by strengthening ecological interactions and processes |
| **Principle 7: Economic diversification**, to provide greater financial security to farmers |
| **Principle 8: Co-creation of knowledge**, including empowering farmers as data owners and encouraging farmer-to-farmer knowledge exchange |
| **Principle 9**: Respecting **social values and diets**, including enhancing social cohesion and putting community-driven priorities at the center of decision-making |
| **Principle 10**: Fostering **fairness** including ensuring that all food system actors have respectable and sustainable livelihoods centered on fair trade, safe and dignified labour conditions and fair intellectual property rights |
| **Principle 11**: Increasing **connectivity** between producers and consumers by promoting local markets and short distribution networks |
| **Principle 12**: Strengthening local **land and natural resource governance**, including recognizing and empowering smallholders and indigenous peoples as sustainable land and natural resource managers |
| **Principle 13:** Encourage and facilitate **participation** of food producers and consumers in decision making, including women, youth and minority groups |

use efficiency and stability or resilience of plant communities or (agro)ecosystems (Bommarco et al. 2013; Tittonell 2014a). However, only an assessment of what outcomes are achieved, and how far these adhere to the agroecological principles, determines whether the practices do indeed move a farming system towards agroecology.

In food systems, following the HLPE principles requires policies, investments and non-governmental initiatives that: improve social, environmental and animal welfare outcomes along the value chain; shift consumers towards nutritious, diversified, locally-sourced diets that stimulate farm-level diversification; recognize the value of farmers adopting agroecological approaches and; facilitate co-creation of knowledge, fairness, connectivity and participation (HLPE 2019; Wezel et al. 2020). In agroecosystems, practices such as crop rotation, intercropping, varietal mixtures, organic fertilization, biological control of pests, integration of plant and animal production, management of natural elements in and around agricultural fields, reduced or no tillage, use of cover crops, green manure, agroforestry and other diversification practices, can all contribute to farming systems that adhere to agroecological principles (Altieri 1995; Gliessman 1997; Wezel 2013). Each of these practices can, however, introduce trade-offs among environmental, agronomic and social outcomes and between scales from plot to landscape, which is why agroecology is defined by principles and not practices (Tittonell 2020). Similarly, interventions designed to shift consumers towards nutritious diets, improve market conditions for the poor, or halt poor treatment of animals, can have unintended consequences leading to trade-offs (Mausch et al. 2020). The combined practices, policies, investments and initiatives that lead to farming and food systems that optimize their performance according to agroecological principles is highly context dependent.

Many organizations, including farmers and social networks, are now actively engaged in efforts to make food systems more sustainable. Different groups may share the same broad vision, but advocate for different approaches to achieving this vision, including organic, regenerative, agroecological and nature-based farming (Table 2). The cacophony of terms creates confusion among actors, while in their implementation the different approaches overlap. One key difference is that certified organic farming strictly excludes the use of synthetic fertilizers, genetically modified organisms (GMOs) and certain pesticides (Table 2), whereas other approaches, including agroecology, discourage but do not prescribe strict rules on chemical use (Giller et al. 2021). In contrast, organic farms can include highly simplified farming systems that rely on very intensive mechanization which can compromise environmental outcomes, while most other approaches, including agroecology, explicitly encourage diversification.

The added value of agroecology is its focus extends beyond the farming system to the whole food system, emphasizing that production systems are inseparable from social processes, policies and markets, and calling for fundamental transformation by finding a better balance among large corporations, food producers and consumers. Nonetheless, agroecology should be promoted alongside and not at the exclusion of these other approaches as each has its own value and challenges according to different contexts (Giller et al. 2021). What is important to encourage a shift towards sustainable food systems is that the different groups engaged with improving the sustainability of farm and food systems unify around their shared cause, seeking opportunities to work together and pool their knowledge, expertise and networks to provide a wider variety of context-specific solutions.

Research providing insights into how to operationalize agroecology has gained momentum over the past decade. A Web of Science search for publications with agroecology (or derivatives) in the title, abstract or keyword list, showed 4294 articles and book chapters have been published between January 2005 and December 2021, with 66% of these published since January 2017 (Fig. 1). The search was conducted in Web of Science on 22 February 2022 using the search string "agro*ecolog*". These publications provide evidence that agroecological approaches can be a viable solution for farmers, environment, society and consumers, reducing or removing many of the persistent and fundamental problems associated with our current food systems. They indicate that agroecological principles can be practiced in a wide range of contexts from subsistence or commodity-based smallholder farming systems (Altieri et al. 2012; Tittonell 2014b) to industrialized farming systems (Tittonell et al. 2020).

One comprehensive global synthesis of 5160 original studies showed that, compared to conventional agriculture, crop diversification significantly increases above- and below-ground biodiversity by, on average, 40%, pollination by 32%, pest control by 26%, nutrient cycling by 20%, water regulation by 20% and soil fertility by 19%, while having a neutral effect on yield (Tamburini et al. 2020). Other reviews show that in diversified farms and landscapes (whether organically farmed or not), ecological outcomes improve while effects on yield vary with contextual factors but are most often higher and more stable than on simplified farms (Beillouin et al. 2019; Ponisio et al. 2015; Rosa-Schleich et al. 2019; Sirami et al. 2019). Certain diversified cropping systems significantly increase total yields. For example, a review of cereal–legume intercropping compared to monocrop systems found that land equivalent ratios are 1.32, meaning equivalent yields can be obtained with far less land, due to facilitation and niche complementarity effects (Xu et al. 2020). Greater crop diversity at the national level

**Table 2** Farming approaches that seek sustainable outcomes, in contrast to conventional agriculture. This list is non-exhaustive and aims to capture the dominant lexicon in current use. The scales are adapted from the Dictionary of Agroecology for farming approaches included in the dictionary (INRAE 2022)

| Farming approach | Scale | Definition |
|---|---|---|
| Conventional agriculture | Farm to food system | Energy-intensive, often mono-cropped production systems dependent on external inputs (such as chemical fertilizers, pesticides and herbicides, irrigation, machinery) and optimized for yields (Ethan 2009) |
| Agroecological farming | Farm to food system | "Applying ecological concepts and principles to optimize interactions between plants, animals, humans and the environment [within agricultural systems] while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (FAO 2021a). Thirteen agroecological principles have been proposed to operationalize agroecology at the agroecosystem and food system level (HLPE 2019; Wezel et al. 2020) |
| Biodynamic farming | Farm | A spiritual, ethical and ecological approach to agriculture, developed by Rudolf Steiner (1861–1925). It emphasizes the importance of interplay between cosmic and earthly forces. Steiner ideated a set of preparations for biodynamic farmers to use for soils, compost and plants to support the ecosystem in building up its innate immune system and vital forces |
| Climate-smart agriculture | Farm to food system | Climate-smart agriculture has three objectives: 1) to sustainably increase agricultural productivity, 2) to support farmers and countries to adapt to climate change and 3) to reduce greenhouse gas emissions (Lipper et al. 2014). Climate-smart agriculture seeks locally appropriate agricultural practices that help achieve one or more of these objectives |
| Conservation agriculture | Farm | "A farming system that promotes minimum soil disturbance (i.e. no tillage), maintenance of permanent soil cover and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production." (FAO 2021b) |
| Ecological intensification | Farm and landscape | Making smart use of the natural functionalities that ecosystems offer at field, farm and landscape scales (Bommarco et al. 2013). The aim is to design multifunctional agroecosystems that are both sustained by nature and sustainable in their nature (Tittonell 2014a) |
| Nature-based solutions (broader than agriculture) | Farm and landscape | "Actions to protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016). Nature-based solutions in agriculture include interventions that strengthen or restore ecological functions and processes |
| Organic agriculture | Farm | A production system that seeks to sustain the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, excludes the use of synthetic inputs (inorganic fertilizers and pesticides) and GMOs. Organic Agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and good quality of life for all involved (IFOAM 2021) |
| Permaculture | Farm and landscape | The "conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability and resilience of natural ecosystems. It is the harmonious integration of landscape and people—providing their food, energy, shelter and other material and non-material needs in a sustainable way." (Mollison 2002) |
| Regenerative agriculture | Farm and landscape | A system that, "at increasing levels of productivity, increases our land and soil biological production base. It has a high level of built-in economic and biological stability. It has minimal to no impact on the environment beyond the farm or field boundaries. It produces foodstuffs free from biocides. It provides for the productive contribution of increasingly large numbers of people during a transition to minimal reliance on non-renewable resources" (Rodale 1983). The system draws from decades of scientific and applied research by the global communities of organic farming, agroecology, holistic grazing and agroforestry |

has also been associated with higher temporal stability of crop yields (Renard and Tilman 2019). A synthesis of 172 scientific papers documenting food production and food security outcomes from alternative farming practices (e.g. agroforestry, intercropping, crop rotations and natural pest controls) in 17 developing countries found positive yield and/or economic outcomes for producers in more than half of cases, mainly due to improved soil quality, while also demonstrating an association between higher on-farm species diversity and more nutritious diets (Paracchini et al. 2020). The same study identified lack of access to organic inputs as a major constraint to improving soil health without use of synthetic inputs, and identified financial support, scientific knowledge and increased market value for agroecological products as key factors enabling uptake of agroecology by farmers. Finally, studies by the United Nations

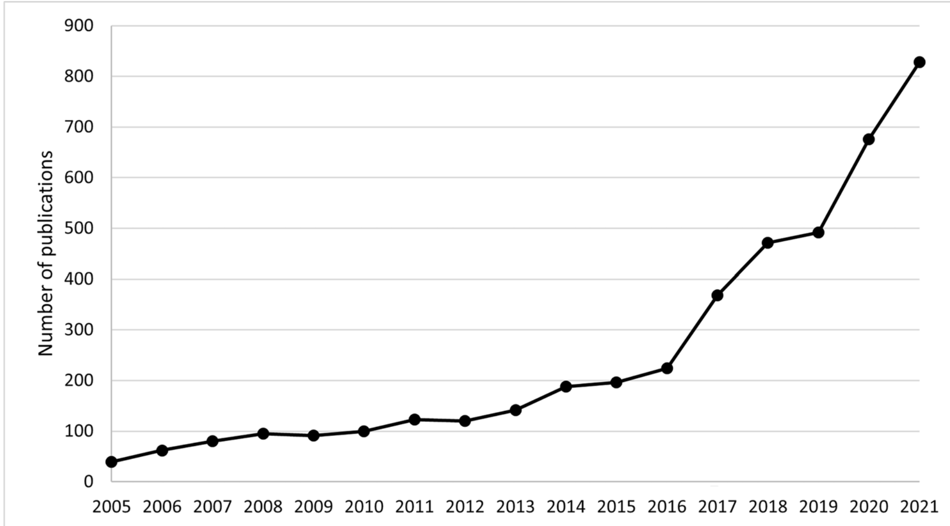


**Fig. 1** Number of academic publications from 2005 to 2021 with agroecology in the title, abstract or keywords, based on a Web of Science search conducted 22 February 2022

Food and Agriculture Organization (FAO) and the Institut National de Recherche pour l'Agriculture (INRA) summarize which market interventions stimulated sustainable agriculture in 15 developing countries (FAO and INRA 2016) and ways to market agroecological produce based on 12 case studies mainly from LMICs (FAO and INRA 2018). These two studies highlight the crucial role of the public sector in legitimizing and structuring markets for agroecological produce, and the importance of both social and technical interventions for scaling agroecology, including strengthening private–public partnerships and engaging civil society.

Implementation of alternative agricultural production systems by farmers needs to accelerate to achieve food security and human wellbeing for a growing population within planetary boundaries (Raworth 2017). Adoption of alternative production systems has increased globally over the last two decades, such as conservation agriculture which increased from 106 Mha in 2008/2009 to 180 Mha in 2015/2016 to cover an estimated 12.5% of global cropland (Kassam et al. 2019). Certified organic systems were estimated to cover 1.5% of agricultural land in 2018, having increased from 0.5% in 2004 (FAO 2021c). Yet synthetic inputs and simplified farming systems continue to dominate food production. For example, pesticide use persists over integrated pest management strategies in many developing countries (Parsa et al. 2014). While the diversity of crops cultivated globally and regionally since late 1970s has increased, there has also been an increase in the dominance of a small number of crop species resulting in increased homogeneity of crops grown around the world (Martin et al. 2019).

## Agroecological transition pathways

Transitioning to sustainable food systems through agroecology is possible from many different starting points but requires systemic change through interventions in agroecosystems and food systems that form part of integrated, long-term strategies (IPES-Food and ETC Group 2021). An 'agroecological transition' refers to a significant temporal and spatial shift in a farm or food system through implementation of the 13 HLPE agroecological principles (building on Marsden 2013).

For research for development organizations, it is particularly important to understand what an agroecological transition means for farmers who may already be implementing agroecological practices yet have low levels of wellbeing and vulnerable livelihoods (Mugwanya 2019), as well as those farmers engaging in more conventional agriculture. Gliessman (2007) proposed that there are five levels of transition towards sustainable food systems, moving from increasing input use efficiency and reducing scarce or environmentally harmful inputs (level 1), to complete changes in the way markets and societies interact with farmers (level 5).

In 2019, the Alliance of Bioversity International and the International Centre for Tropical Agriculture (Alliance) created the "Agroecological Transitions Nexus", bringing together ~ 30 Alliance researchers with multiple academic backgrounds and experiences on agroecology worldwide. Through this safe and open space for reflection, capacity building, dialogue and knowledge exchange we selected four in-depth cases (see inset boxes and Fig. 2) linked to research for development projects in different regions and socio-ecological contexts.

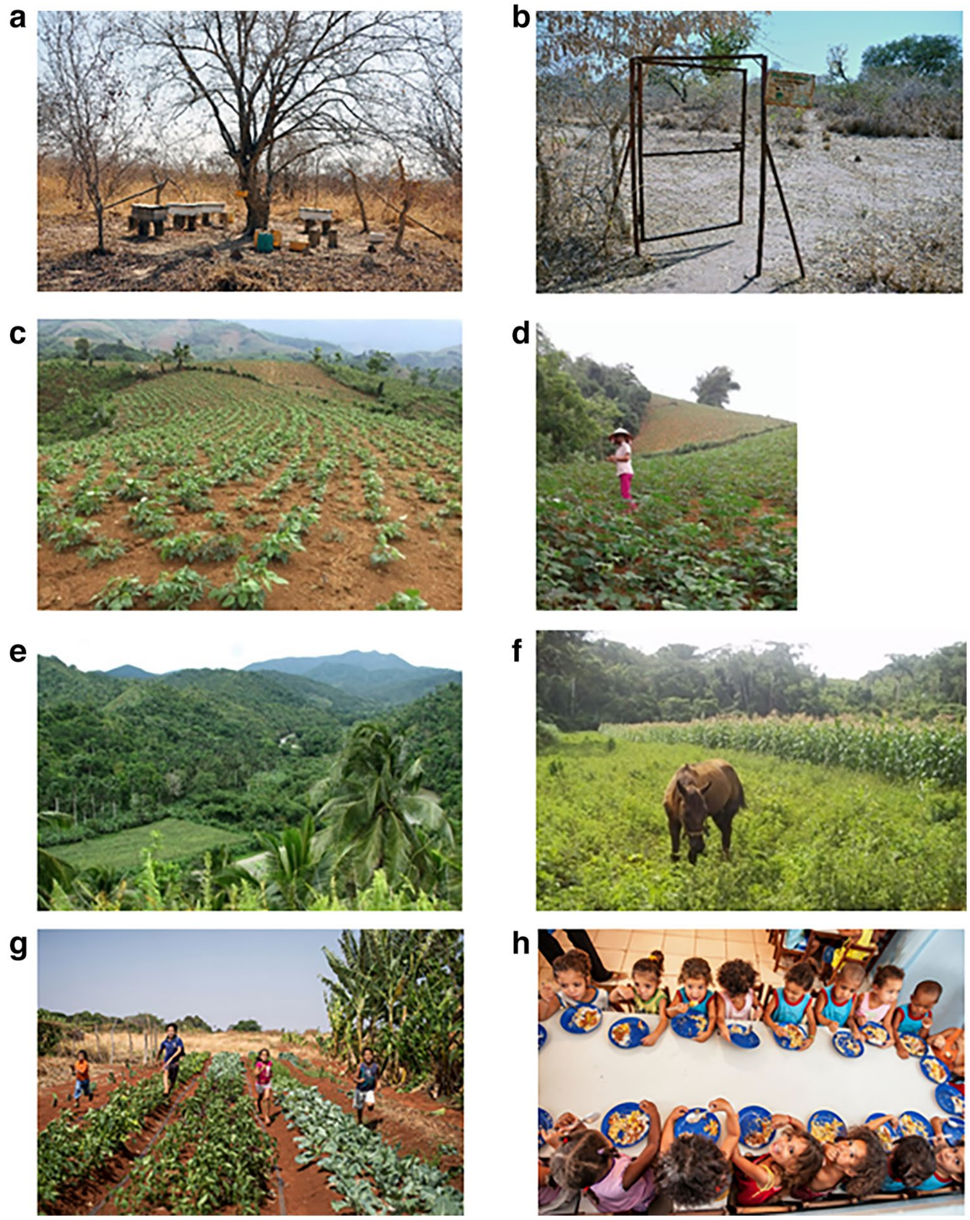


**Fig. 2** Case study sites. Figures show (**a**) bee hives and (**b**) vegetation clearing to control fires, inside fenced plots established by farmers supported by Association Tiipaalga in Central Plateau, Burkina Faso (credit: Barbara Vinceti); (**c**–**d**) cowpea-cassava intercropped in Yen Bai, Vietnam (credit: Didier Lesueur); (**e**) Mosaic agricultural landscape, and (**f**) Cuban family farm, in the Cuchillas del Toa Man and the Biosphere reserve, Cuba (credit: INIFAT); (**g**) diversified family farm that sells agroecological produce at markets in Brasilia (credit: Rafael Zart, Ministry of Social development (MDS)) (h) school meals promoting the use of nutritional species, Federal District, Brazil (credit: Ubirajara Machado, MDS)

**Case study 1: Tree functional traits for nutrition and land restoration in Burkina Faso**

In Burkina Faso, droughts and expansion of cultivated areas have caused significant loss of natural woody vegetation and land degradation in about 19% of the country (MEEVCC 2018). Increasing pressure to produce food on these marginal lands from population growth has led to a spiral of overexploitation and overgrazing reducing plant diversity and associated biodiversity and ecosystem productivity

The country is a member of the regional restoration initiative AFR100, with a commitment to restore 5 Mha of degraded land by 2030 (http://afr100.org/content/burkina-faso). Researchers have been working in partnership with the Association Tiipaalga to help meet this objective, and help improve farmer livelihoods, through creating forest patches on and adjacent to farmland (Vinceti et al. 2020). Motivated farmers with sufficient land to spare from cultivation are provided equipment and technical advice to establish fenced plots of minimum three hectares and set it aside for forest regeneration (Fig. 2a–b). In these plots, farmers favour natural regeneration but also enrich their plots through planting useful tree species, increasing biodiversity and local ecosystem goods and services, including firewood and wild foods. Tree species selection is a critical part in the design of these on-farm restoration efforts to optimize the provision of desired goods and services. In Burkina Faso, a considerable number of tree species provide edible products (fruit, leaves, seeds) that are critical for nutrition security, especially in famine periods. Practitioners can identify the most appropriate tree species and seed sources to recommend to farmers now and under future climate scenarios using the decision support tool called Diversity4Restoration (Thomas et al. 2017), helping promote local and varied tree diversity

Smallholders who establish fenced plots privately manage this land, while the land itself may be owned, borrowed or rented under the customary laws that govern rural land management in Burkina Faso. Farmers joining the scheme earn income from selling forage, produced more abundantly inside the fenced plots which are protected from grazing animals. Many farmers also place beehives inside the fenced areas and produce honey. Researchers work with farmers monitor the diversity inside the plots, the costs and benefits of the new forest for farmer livelihoods and wellbeing and farmers' evolving training needs. Setting aside an area of farmland compromises agricultural production and is challenged by limited revenues in the initial stages, creating critical trade-offs. Overcoming the initial stages is difficult but the household benefits in terms of forest products (honey, fruits, medicinal products) are significant in the long term while forage production generates important immediate revenues and helps farmers persevere through the initial years after fencing. Farmers are recognizing the longer-term benefits and Association Tiipaalga is currently overwhelmed with farmers wishing to participate in the programme. In 2019, Association Tiipaalga was assisting more than 300 farmers with fenced plots and many more households interested in applying agroecological practices in their fields (e.g. production of compost, digging of half-moons and zai pits, displaying stone bunds) (Valette et al. 2019)

**Case study 2: The effect of intercropping on soil biology and rhizobial inoculation of cowpea in Northern Vietnam**

Around the world, including in Vietnam, crop specialization and intensive use of agrochemicals over the past decades has positively influenced crop productivity but negatively affected the environment and substantially depleted soil health (Pahalvi et al. 2021). In Vietnam, soil health is of increasing concern with the emergence of soil-borne pests and diseases such as nematodes which are devastating coffee plantations (Hoang et al. 2020)

Research in one Yen Bai community showed that intercropping of cassava and cowpea results in an increase of soil macrofauna richness and evenness, doubling the richness of soil macrofauna and increasing evenness (Pielou Index) by 20% compared to cassava monocrops (Fouillet et al. 2019). In the same study, a high-throughput sequencing analysis of the microbial community showed that soil microbiota also benefits from intercropping, with bacterial community richness increasing by 10%. However, results showed intercropping does not significantly affect fungal communities and several soil parameters including pH and organic matter. The findings highlighted the potential of native rhizobia inoculation to enhance soil fertility and sustainable agriculture in the Northern mountainous region of Vietnam. Results were presented to over 100 farmers and local authorities at a field day in 2017. Around the same time, local authorities of the Yen Bai province began recommending that farmers intercrop cassava with cowpea as a way to restore soil health (Fig. 2c-d). Initial evidence suggests these policies have been effective; Nguyen et al. (2020) observed a tripling in the number of farmers intercropping cassava with cowpea between 2017 and 2018 in one Yen Bai commune. Cassava-cowpea intercropping provides additional income from cowpea sales at local markets, without reducing the income farmers receive from cassava, which may in part explain farmer willingness to convert

**Case study 3: Participatory guarantee system to stimulate agroecological transition in Cuba**

Cuba has promoted and implemented agroecology for over 30 years, since the fall of the Soviet bloc in 1990, as part of its struggle to sustain national food security, sovereignty and environmental sustainability. The agroecological movement has seen strong support from central government, research institutes and non-state organizations like the National Association of Small Farmers (ANAP) through the Campesino-a-Campesino Agroecological Movement (MACAC). Today, an estimated 300,000 small-scale farmers are practicing agroecology in Cuba. Studies suggest that agroecological approaches are applied on 46–72% of small-scale farms, accounting for about 65% of the vegetables, maize, beans, fruits and pork production on 35% of the total arable land (Rodríguez and González 2018; Rosset et al. 2011)

Despite the large production of organically grown foods, organic certification has never been a priority for Cuba. Most organic certified products are exported (coffee, tobacco, sugar) and certification is done by international third-party private organizations. Despite growing interest among national and international consumers for chemical-free products, the centrally managed food distribution system makes it impossible to distinguish food coming from diversified chemical-free farms from that produced on large monocultures or farms with high chemical inputs. Recently, the Ministry of Agriculture through the National Program on Urban Sub-Urban and Family Farming Agriculture (AUSUF) has attempted to change this situation using a Cuban Participatory Guarantee System (PGS). The PSG supports smallholder farmers in their efforts to produce food following the Cuban Standard 500–2010 that regulates the production and preparation of food according to organic methods. PGS are quality assurance initiatives that are locally relevant, emphasize the participation of stakeholders including producers and consumers and operate outside the frame of third-party certification. The Alliance of Bioversity and CIAT, through the project 'Agrobiodiversity Conservation and Man and the Biosphere Reserves in Cuba: Bridging Natural and Managed Landscapes' and in collaboration with the Institute of Fundamental Research in Tropical Agriculture (INIFAT), leading the AUSUF program, and the project "Apoyo a una Agricultura Sostenible en Cuba" developed a PGS manual which allows producers to access a guarantee seal on a voluntary basis (Díaz Fernández and Echevarría León 2016). The PGS gives farmers from Man and the Biosphere Reserves the opportunity to add value to their marketed goods and be recognized for conserving traditional agricultural systems based on local agrobiodiversity, agroecological practices and traditional knowledge in harmony with the natural environment of the protected area (Fernández León 2016) (Fig. 2e–f)

Six farmers from Cuchillas del Toa MAB Reserve have volunteered to test the PGS guidelines. The produce from these farms includes a wide range of fruit and vegetables. To get "organic" status and the PGS label, farmers need to meet specified levels on indicators of crop and animal diversity, soil quality, crop health, economic viability, social responsibility (e.g. contribute to local food supply, equality between men and women in job type and responsibility), resilience to climate change, water and air quality and integrated water management. Each of these criteria is scored from one to ten by the organic producers themselves followed by a verification process conducted by external evaluators. Farmers, processors, marketers, consumers, authorities, institutions and others who commit to organic agriculture actively participate in this process. The PGS in Cuba is still in development, but the state is interested in advancing the scheme to involve all the actors engaged in food production, distribution and consumption. Development of National Guidelines and testing them in Cuban Biosphere Reserves represents positive first steps towards valuing the products of these areas and supporting local markets

**Case study 4: Reconnecting consumers and producers through agroecological, nutrient-rich foods in Brazil**

Despite harbouring around 18% of global plant diversity, including significant food biodiversity, Brazil's food and agriculture systems are largely reliant on exotic or introduced biodiversity (Beltrame et al. 2016). These largely uniform systems, closely aligned with global agri-food industry policies and market conditions, make it hard for family farmers to maintain agrobiodiversity and promote agroecological practices. One response to this has been for governments to develop new forms of public support for agroecological practices and products through targeted public food procurement (Valencia et al. 2019, 2021). For example, in 2009, the Brazilian National School Meals Programme (PNAE) decreed that at least 30% of the food purchased through its programme must be bought directly from family farmers. The national Food Acquisition Programme (PAA) also pays 30% more for organic and agroecologically produced food from family farmers compared to conventionally produced foods, encouraging local, diversified procurement (Beltrame et al. 2016, 2021; Kennedy et al. 2017). A study examining the relationship between farmer participation in Brazil's National School Feeding Program, farm diversification and household autonomy has produced interesting and encouraging results (Valencia et al. 2019). Two key features of the public food procurement program—structured demand for diversified food products, and a price premium for certified organic and agroecological production— were found to increase farm-level agrobiodiversity and the use of agroecological practices. In the first study of its kind, the authors conclude that the National School Feeding Program plays a key role in driving transitions on family farms from low agrobiodiversity, input-intensive farming systems to diversified farming systems and a significant increase in the cropped area under diversified farming systems (Fig. 2g—h)

Alongside this, over the last decade a project on 'Biodiversity for Food and Nutrition (BFN)' has addressed some of the barriers and obstacles to promoting agrobiodiversity and agroecological practices in Brazil, especially around consumption. Achievements of BFN include: establishment of national and regional databases on the nutritional value of local agrobiodiversity; aligning local agrobiodiversity with national food-based dietary guidelines; guidance on mainstreaming food diversity into relevant national development strategies and plans; identifying policy innovations and emerging markets; capacity-building of school canteen staff and nutritionists; and reconnecting consumers and producers to local agrobiodiversity through sustainable gastronomy, food fairs, culinary tourism and alternative food networks (Hunter et al. 2019, 2020). In particular, BFN has helped develop a new supporting policy, the *Official list of native Brazilian socio-biodiversity species of nutritional value* (Ordinance N° 163/2016 and 284/2018), which officially defines and recognizes over 100 native food species. This is the first policy of its kind in Brazil, drafted to meet demands of the Ministry of Social Development. Ministries now refer to the ordinance list to monitor PNAE and PAA institutional purchases of neglected agrobiodiversity, which support production and marketing (with a fair price) for family farmers. The inclusion of species in the ordinance has greatly increased their marketing potential and encourages smallholders to conserve, use, produce and commercialize local agrobiodiversity. The ordinance also facilitates the mainstreaming of agrobiodiversity though other important policies in Brazil including the National Policy for Agroecology and Organic Production, the Promotion of Socio-biodiversity Product Chains, and the Minimum Price Guarantee Policy for Biodiversity Products

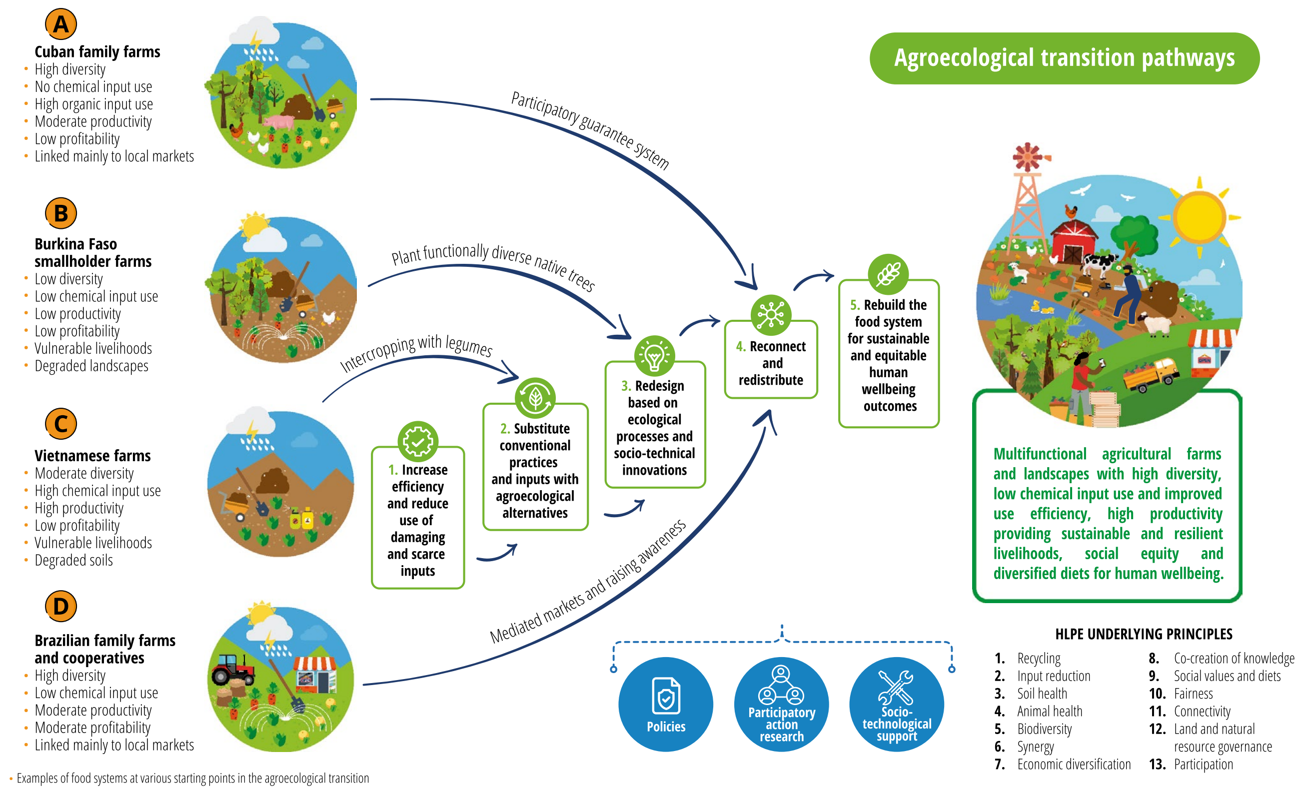


**Fig. 3** Farms at various starting points in unsustainable food systems (left) described in our case studies (**A**–**D**) can take different agroecological transition pathways through Gliessman's transition levels (central boxes) to arrive in a sustainable food system (right) that adheres to the High-Level Panel of Expert's (HLPE) agroecological principles. Policies, participatory action research, and socio-technological support are enabling factors that can accelerate transitions

The case studies illustrate how specific actors and measures stimulated progress towards Gliessman's level 2 in Vietnam, level 3 in Burkina Faso and level 4 in Cuba and Brazil following HLPE principles (Fig. 3). In Burkina Faso, technical support provided by a non-governmental organization has stimulated farmer interest and capacity to set aside farmland for forest regeneration, while researchers have helped improve farmer knowledge and use of functionally diverse tree varieties (HLPE Principle 5) with multiple ecosystem benefits (Principle 6) that have opened up new income sources for farmers (Principle 7). In Vietnam, district level policies promoting cereal-legume intercropping, supported by researcher-led monitoring and farmer training days, are associated with increased farmer adoption of this practice, providing farmers with an additional source of revenue (Principle 7) while helping to restore soil health (Principle 3). In the Cuban case, participatory action research to identify and monitor outcomes, together with policy incentives to farmers through development of a Participatory Guarantee System (PGS), is set to help scale out adoption of local varieties (Principle 5) and organic farming practices (Principles 2 and 3) while improving farmer livelihoods (Principle 10) and knowledge sharing opportunities (Principle 8). In Brazil, national policies to structure markets fostered systemic changes in food networks, enhancing connectivity between producers and consumers (Principle 11) and diversification of farms (Principle 5), while technical support to gather data on native species and nutritional values is enabling a shift towards healthier diets (Principle 9).

The four case studies illustrate plausible transition pathways towards more sustainable food systems from socially, economically and agroecologically distinct starting points in LMICs (Fig. 3). Across the case studies, local and national government, non-governmental organizations, farmers, consumers and researchers, are involved as key actors of change (Table 3). The case studies highlight three major catalysts for increasing adherence to agroecological principles: (i) enabling policies and markets, (ii) participatory action research, (iii) socio-technical support. While our case studies only capture a tiny portion of the diverse starting points and activities that can contribute to agroecological transitions across LMICs, the importance of these catalysts is echoed in other studies (Chan et al. 2020; Fan and Cho 2021; Gautam et al. 2022; Ingram and Njikeu 2011) and is discussed further in Sect. 4.

**Table 3** Comparison of agroecological transition starting points, constraints, key actors and measures enabling change, and main outcomes, across four case studies

| Case study | Starting point | Major constraints to transition | Actors facilitating transition | Measures facilitating transition | Outcomes |
|---|---|---|---|---|---|
| Tree functional traits for nutrition and land restoration in Burkina Faso | **Smallholder farms** producing mainly **subsistence** products on **marginal lands.** Increasing **pressure on land** from population growth has led to a spiral of **overexploitation and overgrazing** reducing plant diversity and associated biodiversity and ecosystem productivity | - **Political instability** has affected Burkina Faso since 2015<br>- **Lack of public funding** available to invest in restoration<br>- **Insecure land tenure** reducing farmer incentive to preserve and restore land for the benefit of future land users<br>- Firewood is the main cooking and heating source for most families and **alternative energy sources will be needed** to avoid conflicts over restored forest uses | - **Farmers** with customary rights to use their land and with sufficient land to spare (minimum 3 ha)<br>- **Non-governmental organization** (Association Tiipaalga)<br>- **Researchers** (e.g. The Alliance) | **Socio-technical support:**<br>- Provision of equipment (e.g. fences)<br>- Provision of technical advice on tree species selection, planting and maintenance<br>-Provision of training on land preparation techniques (e.g. zai pits, half-moons, stone bunds)<br>**Participatory action research:**<br>- Research to monitor plot diversity, costs and benefits of new forest for farmer livelihoods and wellbeing, and farmer training needs | Creation of **forest patches** on and adjacent to farmland (Vinceti et al. 2020). Association Tiipaalga has supported at least **300 farming households** and many more households are interested in joining the scheme (Valette et al. 2019). Farmers favour **natural regeneration** but also enrich their plots through planting **useful tree species**, increasing biodiversity and local ecosystem goods and services, including firewood and wild foods. Farmers joining the scheme earn **income from selling forage**, produced more abundantly inside the fenced plots which are protected from grazing animals. Many farmers also place beehives inside the fenced areas and produce honey |
| The effect of intercropping on soil biology and rhizobial inoculation of cowpea in Northern Vietnam | **Intensive production** of cassava in **mono-cropped** fields mainly for local markets | - Long-history of farmers applying heavy pesticides and chemical fertilisers **depleting soil health**, **creating lock-ins** and gradually **eroding farmer knowledge** of how to manage pests and maintain soil nutrients using ecological methods | - **Local government** (e.g. Yen Bai province)<br>- **Researchers** (e.g. Cirad) | **Enabling policies and markets:**<br>- Local government recommendations that farmers intercrop cassava and cowpea to restore soil health<br>**Participatory action research:**<br>- Research to monitor and compare soil microbial communities in intercropped and monocropped fields<br>**Socio-technical support:**<br>- Field day for farmers to showcase research findings and provide advice on intercropping | Rapid growth in the number of **farmers intercropping cassava and cowpea**. Cassava-cowpea intercropping provides **additional income** from cowpea sales at local markets, without reducing the income farmers receive from cassava, which may in part explain farmer willingness to convert |

**Table 3** (continued)

| Case study | Starting point | Major constraints to transition | Actors facilitating transition | Measures facilitating transition | Outcomes |
|---|---|---|---|---|---|
| Participatory guarantee system to stimulate agroecological transition in Cuba | **Lack of transparency** in food supply chains and **no added value** recognized to agroecologically produced food in national markets | - Centralised food distribution system means that it is **impossible to distinguish foods coming from diversified, chemical-free farms** from those produced in large, intensively managed monocultures | - **Farmer associations** (e.g. National Association of Small Farmers)<br>- **National government** (e.g. Ministry of Agriculture)<br>- **Researchers** (e.g. The Alliance, INIFAT) | **Enabling policies and markets:**<br>- Participatory guarantee system (PGS) initiated by national government to regulate the production and preparation of food according to organic methods, emphasizing the participation of producers and consumers<br>**Participatory action research:**<br>- Participatory research to create a PGS manual that allows producers to obtain a guarantee seal by monitoring and confirming they meet specified levels across a wide range of environmental, social and economic indicators (Díaz Fernández and Echevarría León 2016) | **Six farmers** from Cuchillas del Toa MAB Reserve have **volunteered to test the PGS guidelines**. The PGS in Cuba is still in development, but the **national government is interested in advancing the scheme** to involve all the actors engaged in food production, distribution and consumption. **Development of National Guidelines** for PGS and testing of these in Cuban Biosphere Reserves represents positive first steps towards valuing the products of these areas and supporting local markets |

**Table 3** (continued)

| Case study | Starting point | Major constraints to transition | Actors facilitating transition | Measures facilitating transition | Outcomes |
|---|---|---|---|---|---|
| Reconnecting consumers and producers through agroecological, nutrient-rich foods in Brazil | **Low share of products in national markets** that are produced locally following agroecological principles. **Knowledge and market barriers** to producing food in agroecological ways | - Heavy reliance on exotic and introduced biodiversity largely driven by **global agri-food industry policies and market conditions**, making it hard for family farmers to maintain agrobiodiversity or promote agroecological practices<br>- **Poor recognition** of the diversity and nutritional value of **local native food species** | - **National government** (e.g. Ministry of Social Development, Ministry of Environment, Ministry of Agrarian Development, Ministry of Agriculture)<br>- **Researchers** (Federal and other universities and research agencies, The Alliance) | **Enabling policies and markets:**<br>- National policies that favour practices compatible with agroecological principles (e.g. National Policy for Agroecology and Organic Production)<br>- Public procurement schemes initiated by nationalgovernment to support agroecological practices (e.g. Food Acquisition Programme pays 30% more for organic and agroecologically produced food (Beltrame et al. 2021))<br>**Socio-technical support:**<br>- Production of guidelines supported by databases identifying and demonstrating the nutritional value of over 100 native crop species (e.g. the Official list of native Brazilian socio-biodiversity species of nutritional value (Ordinance Nº 163/2016 and 284/2018))<br>- Public food fairs and knowledge sharing events including with school canteen staff to promote use of native and nutritional species in diets | Structured demand for diversified food products, and a price premium for certified organic and agroecological production were found to **increase farm-level agrobiodiversity and the use of agroecological practices**, driving transitions on family farms from low agrobiodiversity, input-intensive farming systems to diversified farming systems (Valencia et al. 2019). The Ordinance of native nutritionally rich species is now referred to by relevant ministries to **monitor institutional purchases** of neglected agrobiodiversity, which **supports production and marketing (with a fair price) for family farmers** (Hunter et al. 2020) |

## Research strategies to catalyze systemic change towards agroecology

Research has a key role to play by providing evidence on the characteristics, costs and benefits of different agroecological approaches and on appropriate policies and measures to support transition pathways in different political and economic contexts (González-Chang et al. 2020). The case studies presented above highlight that enabling policies and markets, participatory action research and socio-technical support can help catalyze systemic change towards agroecology in LMICs. We use evidence from literature to discuss what factors can make each avenue a catalyst for positive change highlighting the role of science.

## Strategy 1: Monitoring holistic outcomes at multiple scales to identify enabling policies, institutions and markets

Achieving a sustainable food system will require a transformation of our whole food system, from the farmer through to the consumer, to shift ways of thinking, producing, consuming, investing and making policies (IPES-Food 2016). Different components in the food system are interconnected and changes that positively impact one area, e.g. farm practices that boost biodiversity, can have positive or negative outcomes in another area, e.g. farmer income or nutritional value of consumer diets. This is particularly relevant in the context of the interconnected global challenges of climate change, biodiversity loss, malnutrition and environmental degradation. Important trade-offs may occur across scales from plot to farm to landscape, e.g. related to resource allocation or deforestation (Landholm et al. 2019) or even across continents. Understanding the types of incentives and how to implement them to create synergies and reduce trade-offs among agronomic, environmental, economic, social and human wellbeing outcomes requires systems approaches to research and implementation, conducting and aligning activities at nested scales and integrating diverse expertise, actors and methodologies. It also calls for assessments of farm performance that recognize and value the multifunctionality of agriculture, rather than measuring only agricultural production outcomes, to make comparisons between farming approaches meaningful (IPES-Food 2016).

Evidence is needed on supportive public policies, governance and institutions and markets in the transition to more sustainable food systems, while acknowledging that no one single policy is key and rather a harmonized portfolio of complementary policies is required (Nicholls and Altieri 2018). A wide range of public consumer, producer, market and food environment, trade and macroeconomic oriented policies can support farmers in transitioning to agroecology and finding markets for agroecological products. These include for example, public procurement strategies for agroecological produce (see case study 4), removing subsidies for synthetic inputs and introducing them for inputs compatible with agroecology, enabling local seed exchange in national legislation, facilitating the registration of agroecological farmers with food trade and safety authorities, recognizing participatory guarantee systems that certify agroecological producers (see case study 3) and providing public facilities to host farmers' markets of agroecological products (FAO and INRA 2018).

Research should critically evaluate policy outcomes, including unintended consequences, and use evidence from these assessments to help identify and inform policymakers on the most appropriate set of policies and institutional arrangements for each food system context. Stronger collaboration between crop scientists, breeders, agronomists, animal scientists, landscape ecologists, gender specialists and behavioural change scientists, together with experts in nutrition, economics, political science and food systems will be essential to ensure robust scientific support for an agroecology transition.

Alongside public incentives, there is a need to build more private sector and consumer support for inclusive business models for agroecology and overcome vested interests in the status quo. The private sector may be better able than the public sector or civil society to raise capital or target investments, and thus catalyse change towards sustainable agricultural development in the Global South (van Westen et al. 2019). Private sector investments and inclusive business models can benefit smallholder producers by providing higher or more stable incomes, but have also been linked to an increase in monocropping, decrease in diet diversity and increase in inequality at the community level, disadvantaging the poorest (van Westen et al. 2019). The highly detrimental social, economic and environmental outcomes created by some agribusinesses in our current food system, including through large scale land acquisitions (Dell'Angelo et al. 2021), need to be resolved. This will not happen through unregulated market forces because production externalities are not costed into the market, highlighting the critical role for public policy. Research on outcomes of different types of business models and policies at different levels of the food system can help prevent such externalities and other consequences that are incompatible with agroecological principles.

Certification schemes and food labelling have proven valuable marketing tools to shift demand towards ecologically or socially sustainably produced foods. For example, organic certification has enabled consumers to differentiate between organically and conventionally grown food and farmers to sell produce at preferential rates to help cover the additional costs of organic production. Consumer support for organic food has risen due to a growing perception that there are health, animal welfare and environmental benefits of eating organic. Yet the amount of land under certified organic production has not increased as fast as might be expected, with many farmers entering and leaving the organic sector each year for various reasons (Sahm et al. 2012). The cost of organic food remains high relative to heavily subsidized conventionally produced foods and failure to include the cost of externalities in the market price, making it prohibitive to many consumers (Eyhorn et al. 2019). Through a review of 12 case studies mainly from developing countries, FAO and INRA found that farmers are capturing the value of agroecology through increasing the diversity of market channels as well as through direct relations with consumers (FAO and INRA 2018). Further research, piloting and monitoring alternative approaches are needed to help farmers market agroecological products to consumers based on nutrition, health, environmental and/or social grounds, e.g. see Deaconu et al. (2019). These may include reviving cultural pride, biocultural traditions, demand for high quality food, food tourism and increased traceability and transparency along value chains, and jurisdictional approaches where value chains are associated with a specific desired environmental attribute of the territory (e.g. zero deforestation products and value chains).

A core barrier to widespread food system behavior change is a fundamental lack of training in educational institutions on agroecology as an approach to more sustainable food systems. For decades, research has focused on breeding for higher yields as the primary solution to meeting rising food demands (Francis 2020), while breeding for other traits, such as nitrogen-fixing capabilities, deep roots, high nutritional quality and frost and drought resistance, has been neglected yet could open up opportunities to grow a wide range of multifunctional crops (Tittonell et al. 2020). Farmers actively or potentially interested in transitioning towards agroecology may be starting with limited experience and faced with going against their peers and technical advisors who have ingrained support for conventional methods. Researchers need to make concerted efforts to identify and respond to the demand for scientific evidence that can support farmers, institutions and value chain actors that want to do things differently (Aerni et al. 2015). Yet beyond this, reforming agricultural programs in schools, colleges and universities is an urgent priority, to establish a new generation of farmers, extension services, breeders and agricultural researchers with support networks and with a solid understanding of agroecological principles, practices and how and why to monitor and seek to achieve multiple outcomes from agriculture (IPES-Food 2016).

Key research questions include the following:

1) What are the trade-offs and synergies among agronomic, ecological, social, economic and human wellbeing outcomes of agroecology at multiple scales (e.g. spatial, temporal, jurisdictional, institutional, knowledge) and levels (e.g. field, farm, landscape; today vs future; agribusinesses, consumers)?
2) What expertise, skills and project designs are needed to successfully implement trans-disciplinary research projects and answer systems-level research questions?
3) What types of public and private policies, investments and education systems (curricula) facilitate innovation, adoption and continued adherence to agroecology and how is this affected by the social-ecological context?
4) How can producer and consumer interests and wellbeing be protected in modern agriculture and food systems?
5) What drives private and consumer support for agroecology and how do changes in consumer demand drive land use decisions?
6) How can carbon and other ecosystem service markets support agroecology and what are the risks of these approaches?
7) What are key elements of inclusive business models that can support agroecological transitions?
8) What are the minimum social, technical, political and economic conditions that need to be present for transition to be possible as well as the context-related factors that influence success or failure?

## Strategy 2: Conduct participatory action research to co-create and exchange knowledge

Projects looking to catalyse agroecological transitions need to foster a shared vision and establish trust between key stakeholders across public, private, civil society, farmer and wider society using bottom up, gender transformative, participatory approaches. This means moving beyond the idea that scientists create knowledge and farmers apply the results, to empowering farmers as data producers, owners and consumers, and establishing strong farmer-scientist and farmer-to-farmer relations for co-creation and exchange of knowledge (Levidow et al. 2014). Decision making for the design, implementation and evaluation of programs and projects also needs to be made in a participatory way involving food producers and their organizations to ensure that actions are grounded in the communities' realities and meet the different priorities of a wide range of stakeholders equitably (Anderson et al. 2021).

Researchers have a key role to play in shifting the type of knowledge that is co-created in studies of field and farm-level performance. While there is strong evidence and wide recognition that agricultural production impacts on multiple sustainability and human wellbeing outcomes, the way in which farmers, researchers and policymakers traditionally measure performance of agroecosystems is problematic and outdated, concentrating almost exclusively on yield enhancement, and intensification of production (increased return per unit of land or labour) (Struik and Kuyper 2017). This has probably been the biggest obstacle to transforming agriculture in the last decades, underpinned by the prevailing political economy which prioritises economic growth over all other outcomes. The disproportionate focus on yield has meant that other important outcomes have been neglected, e.g. nutritional value or quality of food production, animal welfare, farmer and food system workers' wellbeing, fair wages, soil health (see case study 2), maintaining cultural traditions, biodiversity conservation and ecosystem services (see case study 1), including those services that support sustained agricultural production (Tscharntke et al. 2012). Increasing awareness among farmers and researchers of agriculture's role in contributing to environmental and social goals, and enabling measurement of multidimensional outcomes, may be part of the solution. This can be facilitated through innovation networks for peer-to-peer and cross-sector learning that help transfer knowledge between farms, regions and even countries as well as increasing connectivity among food value chain actors. Research projects can contribute by actively including and valuing farmers as data providers and setting up new, or contributing to existing, learning networks.

Several frameworks and tools have been developed specifically to help monitor progress towards achieving agroecology using holistic and consistent indicators and metrics (Table 4). These tools range from measuring performance across multiple outcomes at the agroecosystem level (e.g. MESMIS, the Handbook), or dimensions of sustainability at the household, farm or landscape level (e.g. Tool for Agroecology Performance and Evaluation), to the resilience of the farm to climate variability (e.g. Didactic Toolkit). There are also tools to identify what level of transition has been achieved generally (e.g. Food Systems Transformation Toolkit) or using Gliessman's agroecology transitions framework (e.g. Agroecology Criteria Tool). These tools can already be integrated more systematically into research projects but this should be done using participatory approaches to integrate farmer knowledge and facilitate learning at all levels and along the transition. Further work is needed to establish routine use in farm and food system management of integrated, multi-criteria indicators that measure a suite of agronomic, environmental, social, economic and human wellbeing outcomes, consider interaction effects and allow for trade-off analysis. There is also a need to develop standardised performance measures to assess efficacy of farms, projects and policies at improving sustainability outcomes to enable comparisons across studies and geographies (Wiget et al. 2020). Research in this area should include co-creation and identification of indicators that farmers and other citizens can measure, and digital tools for both sharing that data and receiving new knowledge. Measurements and metrics that capture short to medium-term outcomes of adoption of agroecological practices are a key gap for development practitioners (Caron et al. 2014).

Key research questions include the following:

1) What elements of a tool lead to uptake and what can we learn from experience to guide development of more effective tools?
2) What tools and measures facilitate holistic and participatory monitoring of adoption and outcomes of different approaches to farming, processing, packaging, marketing and consuming agricultural produce?
3) What are the tools and measures farmers can implement to foster participatory approaches to the long-term process of redesigning farming systems?
4) What type of support do learning networks (or innovation platforms) need to thrive?

## Strategy 3: Co-develop socio-technical solutions adapted to context

Social and technical support and interventions at the farm-level and across whole food networks will be needed to stimulate systemic change towards sustainable food systems and overcome challenges with transitioning to agroecology, such as higher production costs, knowledge intensity of agroecological practices and approaches and the need for capacity building, overcoming system inertia and vested interests, the need for regulation and institutional change, or difficulties in marketing.

Social solutions, focused on changing attitudes, norms, relationships and cooperation between individuals and groups in the food system, and usually driven by grassroots organizations or farmer communities, are critical to enabling transitions towards agroecological principles (IPES-Food et al. 2018; van der Ploeg et al. 2019). Bottom-up approaches can be very effective catalysts for change where there is an enabling policy, institutional and market environment. Evidence from integrated landscape approaches across Latin America and the Caribbean, shows that these long-term and participatory efforts dominantly promote agroecology as a means to achieve multiple outcomes (Carmenta et al. 2020). Change does not happen overnight and the integration and study of community dynamics, leadership skills, rural youth education, and community ownership and empowerment, are vital to success.

Research can shed light on the minimum conditions that need to be present for transition to be possible as well as the

**Table 4** Key tools developed to monitor progress towards achieving agroecology

| Tool | Aim | Further information |
|---|---|---|
| Tool for Agroecology Performance and Evaluation (TAPE) | TAPE was developed to evaluate the contribution of agroecology and other approaches to the transformation of sustainable agriculture and food systems. A global analytical framework provides metrics and methods to measure the multi-functional performance of agroecology, and a supporting database functions as a repository of data populated with specific case studies of application of the framework. The analytical framework is the result of the adaptation of existing assessment frameworks. TAPE assesses performance at the household/farm level as well as providing metrics at the community and territorial level | (FAO 2019) |
| Didactic Toolkit for the Design, Management and Assessment of Resilient Farming Systems | "The main objective of this toolkit is to aid farmers and technicians to better understand the principles and/or mechanisms that underlie the resiliency (or lack thereof) of farming systems and how agroecological management can enhance the capacity of farmers to adapt to unpredictable and severe climatic variability. The tool allows users to better clarify their perceptions of climate change, use indicators to assess the vulnerability of their farms and improve their ecological resiliency via agroecological interventions that enhance the adaptive response capacity of farmers." (Altieri et al. 2016) | (Altieri et al. 2016) |
| Agroecology Criteria Tool (ACT) | Biovision's ACT tool is based on the 5 levels of food system change proposed by Gliessman and is embedded within the 10 elements of agroecology by FAO. The methodology is intended to help visualize to what extent a project, a program or a policy is aligned with the various dimensions of agroecology | (Agroecology Info Pool 2021) |
| Food Systems Transformation Toolkit | Beacon's of Hope's toolkit "includes a Food Systems Transformation Framework and Discussion Guide. It can be used to analyze and explore the transformation process, learn about the experiences of diverse Beacons of Hope and facilitate discussion and action that accelerates food systems transformation." | (Beacons of Hope 2019) |
| Handbook for Evaluating Agroecology (Mémento pour l'Évaluation de l'Agroécologie) | This Handbook proposes methodological benchmarks to evaluate an agroecosystem performance across environmental, social and economic sustainability domains, either as a one-off evaluation or as part of a system of monitoring and evaluation for an intervention | (Levard et al. 2019) |
| The Framework for the Evaluation of Management Systems using Indicators (MESMIS) | MESMIS uses a "systemic, participatory, interdisciplinary and flexible framework to assess outcomes of conventional and alternative farming approaches" (López-Ridaura et al. 2002). MESMIS has been validated through applications in over 20 diverse case studies, mainly in Mexico, other Latin American countries and Spain | (Astier et al. 2012; López-Ridaura et al. 2002) |

context-related factors that influence success or failure. More attention is needed to monitor and understand the 'social' factors driving farmer communities and grassroots organization behaviour, as these may be more important catalysts for change at the farm-level than access to technologies (FAO and INRA 2016). For example, fewer people are choosing farming as a profession which is especially a problem in developing countries with high unemployment rates.

Re-establishing farming as a skilled, profitable, respectable and desirable occupation with attractive working conditions is key to engaging youth in LMICs. Research from Belgium shows that income, employment security and working hours are not necessarily better on farms that prioritise environmental outcomes, but occupational health, work-related stress and social status are improved (Dumont and Baret 2017). This was attributed in part to more varied daily activities, more opportunities for cooperative work and the higher knowledge base required on diversified farms. A study in Brazil reported similar findings with farm staff reporting more difficult working conditions on diversified compared to conventional farms but similar working hours and improved work quality and occupational health (Stratton et al. 2021). Job satisfaction among youth could be improved through improving the quality of, and modernizing, tools and services (a technical solution), e.g. knowledge sharing apps, digital services and digital outcome monitoring tools, and through the empowerment of farmers generating new knowledge as citizen scientists.

Technological support may be needed to facilitate a transfer to, or maintenance and enhancement of the benefits from, agroecology. In some cases, agroecological transitions may be stimulated by scaling out or transferring technological solutions, ranging from simply upgrading low-quality tools and inputs, to improving farm or landscape arrangements and management systems (see case study 1), to introducing new machinery or digital tools and services. In other cases, overcoming challenges may require developing completely new technologies, for example breeding crops for multifunctional traits, machinery suited to complex farming systems and tools based on robotics and automatic sensors (Herrero et al. 2020). For example, laboring on agroecological farms often requires a varied skill set and different way of working to conventional farms, e.g. there may be more manual weeding and regular mulching in cropping systems to avoid use of pesticides, and more outdoor working hours on livestock farms embracing free-range, natural ways of rearing animals.

Technological interventions, such as digital tools and services, could reduce labour requirements or help increase profitability on farms with higher labour inputs. Empirical data from nine European countries showed that while labour needs are higher on agroecological farms, income levels per person are equal or higher than on conventional and industrial farms (van der Ploeg et al. 2019). They note that this positive labour-income relationship is possible because of social-technical interventions (e.g. investing in local processing and marketing services) that result in higher resource use efficiency and/or higher market prices (due to higher quality and nutritional value of end-products, or certification), solutions that are likely to be applicable in many developing country contexts. However, higher labour requirements can improve agronomic outcomes without technical interventions in some farming systems. Hand pollination, and not pesticides or inorganic fertilizers, was found to increase cocoa yields by up to 161% and farmer income by 69% in Indonesia, indicating providing habitat for pollinators can be more effective at increasing yields than applying agrochemicals (Toledo-Hernández et al. 2020). In LMICs, new demand for labour under agroecology opens up rural employment opportunities. Therefore, technologies should be selected and adapted to specific farming challenges and contexts keeping in mind there is no silver bullet solution applicable everywhere. Research can help identify and implement these context specific solutions, including allocating a budget for upgrading farm tools and services and investing resources in developing and testing specialized technical solutions as part of proposals.

To help identify technical solutions at the farm level, research is needed to identify varieties, breeds, farm and landscape arrangements and management systems that are effective at achieving the improved biodiversity, soil health, animal health and other improvements in ecological functioning (Tittonell et al. 2020). While evidence is expanding, many knowledge gaps remain regarding linkages between specific farming practices, landscape configurations and the effect on ecological functioning as well as socio-economic outcomes. There is a shortage of primary studies on how to diversify vegetables, fruits and fibre crop production for improved soil health, biodiversity or reduced input use (Beillouin et al. 2019; El Mujtar et al. 2019). The CGIAR and other institutes with crop and animal breeding stations can help to fill these gaps by testing crop performance, soil health, pollinator and natural enemy diversity, carbon storage and other outcomes, under a range of management scenarios, e.g. different types of inputs, different crop diversity arrangements and varying levels of non-crop vegetation, as well as trialing different types of low-cost machinery to facilitate production in diversified farming systems. Providing improved, multifunctional varieties requires focusing efforts to breed varieties for multiple traits and not only yields (Brussaard et al. 2010; Tittonell et al. 2020) and engagement with multidisciplinary research teams (Kholova et al. 2021). This should include teams with modelling skills so that breeding crops for resilience to variable and extreme climates can be informed by, and in turn improve, crop modelling efforts (Ramirez-Villegas et al. 2020).

Key research questions include the following:

1) What technical and social options increase the value added, reduce production costs and overcome logistical challenges (e.g. lack of organic inputs) of agroecological farming approaches?
2) What existing and new crop varieties and species, arrangements and management practices can provide positive agronomic and ecological outcomes, including for biodiversity, soil health, carbon storage, yields and food nutritional content in specific pedoclimatic contexts?
3) Which farm practices, livelihood strategies and institutional contexts are most effective for improving farm resilience to extreme weather events and climate change, price shocks and other external stressors?
4) What generates positive perceptions of and adherence to agroecological farming as a livelihood particularly among youth?

## Conclusions

As the trajectory of our current food system threatens several planetary boundaries, a shift to sustainable and multifunctional food systems has become critical. Evidence is mounting that agroecology can provide farmers with profitable livelihoods, while contributing to restoring biodiversity and ecosystem functioning, and creating fairer societies and climate-resilient farms and landscapes, provided that context-relevant approaches are co-developed. As political leaders, businesses, civil society and research institutes take increasing interest in agroecology, we urge them to accelerate the transition by focusing on major catalysts of change. In practice, this requires updating research agendas and integrating science and policy for targeting and enabling investments, regulations, incentives, procurement strategies, taxation and curricula that encourage food production, trade, and market systems that empower producers and consumers, while embracing local, healthy, nutritious, culturally valued and sustainably produced food.

Catalysing agroecological transitions will require new ways of doing research that help farmers and consumers, governments and actors along the entire food value chain, to unite around a shared vision and pathway towards a sustainable food system. We highlighted the following three strategies central to this endeavor: (i) monitoring holistic outcomes that integrate research across multiple disciplines and scales to account for the interconnected multidimensional functions of our food system, to help design enabling policies, institutions and markets; (ii) participatory action research for co-creation and exchange of knowledge and; (iii) co-developing social and technical solutions to adapt agroecological approaches to different contexts. Our case studies and examples from literature showed how these strategies, together with other carefully targeted actions, can help break down barriers preventing transitions and strengthen adherence to agroecological principles from the farm to the food system level.

The OneCGIAR, which is the future of the CGIAR centres, has a unique opportunity to channel agricultural research towards approaches that aim to achieve sustainable food systems through scaling agroecology. This will require integration of agroecology and systems research more clearly into funded research programs and into farmer, policy and private sector engagement. While research on some isolated topics will continue to be vitally important particularly for developing technical and social solutions, transitioning to sustainable food systems requires transdisciplinary teamwork engaging stakeholders at multiple governance levels to bridge knowledge gaps and foster cooperation and innovations that enable systemic change.



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