European Chemical Pesticide-Free Agriculture in 2050. Foresight Report.

Olivier Mora, Jeanne-Alix Berne, Jean-Louis Drouet, Chantal Le Mouël, Claire Meunier, Agneta Forslund, Victor Kieffer, Lise Paresys

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European Chemical Pesticide-Free Agriculture in 2050
Foresight report

November 2023

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This document is the full report of the European Chemical Pesticide-Free Agriculture foresight study commissioned and financed by the French Priority Research Program "Growing and Protecting crops Differently". This foresight study was conducted by INRAE's Directorate for Collective Scientific Assessment, Foresight and Advanced Studies (DEPE).

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Directorate for Collective Scientific Assessment, Foresight and Advanced studies (DEPE)

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Table of contents of the report

Introduction

The impacts of chemical pesticides on human health (see for example Inserm, 2022[1]) and the environment (biodiversity, water, air and soil) (see for example Leenhart *et al.*, 2023[2]) have become a major concern for civil society and consumers (Finger, 2021[3]). Recently, the Farm to Fork strategy has set an ambitious target of reducing chemical pesticides use and risks by 50% by 2030 (EC, 2020[4]).

This foresight study addressed several issues. Is it possible, in the mid-term, to withdraw chemical pesticides from agriculture while ensuring a good crop protection? As chemical pesticides are crucial for conventional agricultural systems, reducing significantly their use to the point of withdrawing them from agriculture is a wicked issue, meaning that there is no simple solution to this problem. With this foresight study, we go further in terms of target and horizon by examining the feasibility of efficient crop protection in a pesticide-free agriculture in Europe in 2050, and how a transition to such agriculture would be achievable. What could be the specific forms of a European agriculture without chemical pesticides in 2050? Under which conditions such transition would be possible? What would be its impacts on production, land use, trade balance, greenhouse gas emissions?

To shed light on these issues, this foresight study was conducted as part of the French Priority Research Program (PRP) 'Growing and Protecting crops Differently'[5] and in connection with the European Research Alliance 'Towards a Chemical Pesticide-Free Agriculture'. It aims at building scenarios of chemical pesticide-free[6] agriculture in Europe in 2050, identifying transition pathways, and assessing their impacts.

Two main principles guided this foresight study. Firstly, the idea that the limited impacts of past European and national public policies to reduce pesticide use in agriculture (Hossard *et al.*, 2017[7]; Buckwell *et al.*, 2020[8]) raised the need for a paradigm shift from an incremental approach aiming at reducing pesticide use to a disruptive approach aiming at building cropping systems without chemical pesticides (Jacquet *et al.*, 2022[9]). Secondly, the idea that cropping systems are strictly embedded in food systems, which must be taken into account when building scenarios of chemical pesticide-free agriculture. This foresight study took a systemic approach, considering that the transition to chemical pesticide-free agriculture would require a simultaneous transformation of the various components of food systems.

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[1] Inserm (2022). Effects of pesticides on health: New data. Summary. Collection Expertise collective. Montrouge: EDP Sciences, 2022.

[2] Leenhardt S., Mamy L., Pesce S., Sanchez W. (2023). Impacts des produits phytopharmaceutiques sur la biodiversité et les services écosystémiques, Versailles, Éditions Quæ, 184 p.

[3] Finger, R. (2021). No pesticide-free Switzerland. Nature Plants, 7(10), 1324-1325.

[4] European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. COM(2020) 381 final.

[5] https://cultiver-proteger-autrement.hub.inrae.fr/

[6] The term chemical pesticide refers to synthetic pesticides (whether or not the substance exists naturally), substances extracted from living organisms and minerals such as copper and sulphur. It excludes the living organisms (microorganisms and natural enemies) used in biocontrol. Chemical Pesticide-Free Agriculture is in some way close to organic production, which by definition excludes the use of synthetic pesticides, and whose experience and practices such as crop spatial and temporal diversification have been a source of inspiration for building hypotheses and scenarios. It however differs mainly from organic production in one specific way: the absence of constraints on mineral fertilisation.

[7] Hossard, L., Guichard, L., Pelosi, C., & Makowski, D. (2017). Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France. Science of the Total Environment, 575, 152-161.

[8] Buckwell, A., De Wachter, E., Nadeu, E., Williams, A. (2020). Crop Protection & the EU Food System. Where are they going? RISE Foundation, Brussels.

[9] Jacquet, F., et al. (2022). Pesticide-free agriculture as a new paradigm for research. Agronomy for Sustainable Development, 42(1), 8.

The project team carried out this foresight study over a two-year period and involved 144 European experts, including scientists and stakeholders, divided into eight groups of experts. The main outcomes of the foresight study are three scenarios of chemical pesticide-free agriculture in Europe in 2050 and their transition pathways, the downscaling of the scenarios in four European regions, and the quantitative assessment of their impacts on production, land use, international trade, greenhouse gas (GHG) emissions in Europe and at the global level.

This document is the final report of the foresight. It describes in detail all the work that has been carried out and all the results that have been obtained. Chapter 1 reports the method of the foresight. Chapters 2 and 3 deal with the components of the foresight's system and provide for each component a retrospective analysis and alternative hypotheses of change in 2050. Chapter 2 focuses on crop protection strategies and cropping systems without chemical pesticides, while Chapter 3 deals with the other components of the system such as farm structures, value chains, public policies and others dimensions. Chapter 4 presents the three scenarios of European pesticide-free agriculture in 2050, their transition pathways and their dowscaling in four European regional case studies (in Finland France, Italy, Romania). Chapter 5 details the quantitative impacts of scenarios on European agricultural production and trade, land use and greenhouse gas emissions. Finally, Chapter 6 reports the main insights learned from the foresight.

The foresight team comprised: Olivier MORA (coordinator, INRAE DEPE), Jeanne-Alix BERNE (INRAE DEPE), Jean-Louis DROUET (INRAE ECOSYS/DEPE), Chantal LE MOUËL (INRAE SMART/DEPE), Claire MEUNIER (INRAE DEPE). Agneta FORSLUND (INRAE SMART), Victor KIEFFER (INRAE SMART) and Lise PARESYS (INRAE DEPE) contributed to some parts of this study.

The foresight team would like to sincerely thank:

- The members of the European Expert Committee: Sari AUTIO (TUKES - Finish Safety and Chemicals Agency, Finland), Paolo BARBERI (Sant'Anna School of Advanced Studies, Italy), Pascal BERGERET (CIHEAM - Mediterranean Agronomic Institute of Montpellier, France), Oana BUJOR-NENITA (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Stefano CARLESI (Sant'Anna School of Advanced Studies, Italy), Henriette CHRISTENSEN (PAN - Pesticide Action Network Europe, Belgium), Roxana CICEOI (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Jean-Philippe DEGUINE (CIRAD - French Agricultural Research Centre for International Development, France), Jérôme ENJALBERT (INRAE, France), Gina FINTINERU (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Laurent HUBER (INRAE, France), Philippe JEANNERET (Agroscope, Switzerland), Steffen KOLB (ZALF - Leibniz Centre for Agricultural Landscape Research, Germany), Claire LAMINE (INRAE, France), Guillaume MARTIN (INRAE, France), Antoine MESSÉAN (INRAE, France), Aline MOSNIER (FABLE consortium- Food, Agriculture, Biodiversity, Land-use and Energy, France), Savine OUSTRAIN (Agricultural Cooperative Vivescia, France), Emmanuelle PORCHER (MNHN - French National Natural History Museum, France), Yann RAINEAU (INRAE, France), Elin RÖÖS (Swedish University of Agricultural Sciences, Sweden);

- The coordinators of the regional case studies: Sari AUTIO (TUKES - Finish Safety and Chemicals Agency, Finland), Ana BUTCARU (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Stefano CARLESI (Sant'Anna School of Advanced Studies, Italy), Hubert DE ROCHAMBEAU (VitiREV program, Territorial Innovation Laboratory network, France), Gina FINTINERU (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Marja JALLI (Luke – Natural Resources Institute, Finland), Viorica LAGUNOVSCHI (University of Agricultural Sciences and Veterinary Medicine of Bucharest, Romania), Emilia LAITALA (TUKES, Finland), Cécile LELABOUSSE (IVBD – Interprofession of Bergerac and Duras wines, France), Giovanni PECCHIONI (Sant'Anna School of Advanced Studies, Italy), Yann RAINEAU (INRAE, France) ; and the participants to the regional workshops;

- The members of the Monitoring Committee;

- The scientists and stakeholders involved in the thematic experts groups;

- The experts interviewed for the retrospective analyses;

- The members of the PPR “Growing and Protecting crops Differently” who participated to the research gaps identification;

- Marc-Antoine CAILLAUD, Kim GIRARD and Sandrine GOBET (INRAE, DEPE) for the administrative management of the project, and for their support in the organisation of the workshops, the meetings and the final conference;

- And Andrew LEUWER for the translation and proofreading of large part of this report.

European Chemical Pesticide-Free Agriculture in 2050

Chapter 1

Method of the foresight study

Authors: Olivier Mora, Chantal Le Mouël, Claire Meunier

Table of contents

1.1. Context of this foresight study

As part of the French Priority Research Program (PRP) “Growing and Protecting crops Differently”, this foresight study has been commissioned in order to anticipate and support changes towards pesticide-free agriculture in Europe with adequate research. The aim of this foresight study is not only to anticipate the use of knowledge (produced by the research projects of the PPR) to implement transition trajectories towards chemical pesticide-free agriculture in Europe in 2050, but also to identify possible research gaps.

1.2. The foresight method: An articulation of scenario, simulation and backcasting approaches

Foresight is not about predicting the future but “*a systematic, participatory, future-intelligence-gathering and medium-to-long-term vision-building process aimed at enabling present-day decisions*” (Miles *et al.*, 2016). This foresight study is a “medium-to-long-term vision-building process” whose aim is to highlight diverse pathways of changes that could be taken in order to build a European agriculture without chemical pesticides in 2050.

This foresight study is a normative one: the target to reach in the future is set from the beginning (the target is a chemical pesticide-free agriculture in Europe in 2050). But it is also an explorative study: our aims are to explore the broad range of possible changes that could lead to an agriculture without chemical pesticides in 2050 in Europe, and to assess the various impacts of such changes. In this study, we assumed that the targeted future is multiple and that from the interactions of diverse public and private actors and from the interaction of agricultural systems with socio-ecosystem dynamics will derive one future rather than another (see also Durance and Godet, 2010).

Going out from chemical pesticides is not an easy task for agriculture, as chemical pesticides are crucial for conventional agriculture. Withdrawing chemical pesticides from agriculture is a wicked issue, meaning that there is not a simple solution to this problem, due to its complex and interconnected nature. To think about chemical pesticide-free agriculture requires to take into account multiple interactions in which agriculture and food systems are embedded: with natural entities and resources, ecosystem dynamics, upstream and downstream actors of the food system, local actors, public policies, trade and consumers.

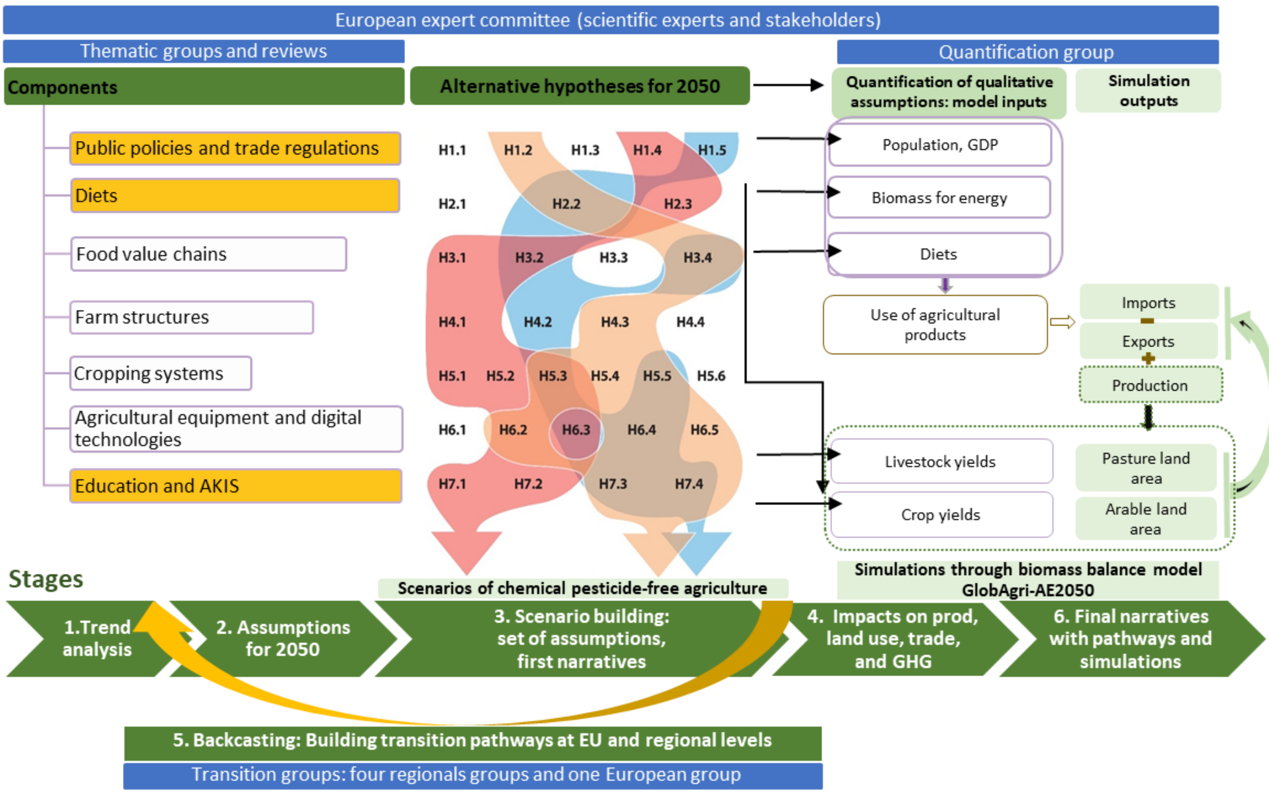
The foresight method is designed firstly, to integrate the complexity of the European agricultural system and to imagine the various future entanglements that will give rise to a pesticide-free agriculture in Europe; secondly, to assess the impacts of such scenarios in quantitative terms; and thirdly, to elaborate possible pathways of transition that could lead to such situation in 2050.

The first part of the method is a coupled approach combining scenario approach and quantitative simulations (Figure 1-1). The scenario building process aims at ensuring the consistency and plausibility of scenarios, while quantitative simulations measure the scale and scope of changes described in scenarios and provide elements for scenario comparison (Mora *et al.*, 2020).

The scenario approach is an exploratory approach using morphological analysis (Ritchey, 2011; Zwicky, 1969). The morphological analysis is “*a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable problem complexes*” (Ritchley, 2011). Applied in the field of foresight studies, the morphological analysis helps “*to consider the entire field of possibilities and construct scenarios*” (Durance and Godet, 2010; see also Amer *et al.*, 2013). This systemic approach allows exploring the range of possibilities for building pesticide-free agriculture in Europe. First, the system under study and its main components are defined. Then alternative hypotheses of change are elaborated for each component. The morphological table sets together these alternative hypotheses per component and thus helps visualize and explore combinations of components' hypotheses. Internal consistency of combinations is assessed leading "*to eliminate incompatible combinations (…) and create plausible combinations*" (Amer *et al.*, 2013; see also Jenkins, 1997). The whole process is conducted with the implementation, at the different stages of the study, of various forums (i.e. expert groups) to discuss hypotheses of change of components, combinations of hypotheses and their internal consistency, and scenarios as retained plausible combinations of hypotheses (Mermet, 2009).

Figure 1-1: General method of the foresight study

The method is based on a morphological table (central panel) articulating a scenario approach (left-hand and central panel, based on components in white, Stages 1-2-3), a simulation approach (right-hand panel, Stage 5) and a backcasting approach (bottom panel, based on components in yellow, Stage 4).
In the central panel, the coloured arrows represent the combinations of hypotheses that form the scenarios.



Quantitative simulations are conducted with a biomass balance model, GlobAgri-AE2050 (Tibi *et al.*, 2020; Le Mouël *et al.*, 2018), whose outputs are land use, production and trade for considered agri-food products in Europe and in other considered world regions. The qualitative hypotheses that are combined in the scenarios and their quantitative translation into input data for the simulation model are linked through the morphological table. For each component, each alternative hypothesis of change in 2050 must be translated into quantitative levels for the model's input variables or parameters that are concerned by the driver. This translation was based on literature reviews and expert interviews (see Chapter 5). During the whole quantitative work, the translation of qualitative hypotheses and the simulation results were analysed and discussed with a dedicated group of experts, the quantification group, and with the European expert committee.

The second part of the method combines exploratory scenario with backcasting. The backcasting approach consists, starting from a desirable future which is an end-point, in working backwards to determine the possible conditions for the realisation of this future and the action and public policies necessary to achieve it (after Robinson, 1982). Backcasting scenarios are useful "*to tackle complex, wicked problems that give rise to high uncertainties on future developments while radical changes might be needed*" (Kok *et al.*, 2011). The backcasting method is particularly appropriate to our foresight study since it allows addressing medium to long-term and complex issues, where the dominant trends are part of the problem, involving many aspects of society as well as technological, organisational and public policy changes. By breaking down the future into steps, it contributes to making scenarios plausible and feasible and to listing the various steps necessary to achieve them (Dreborg, 1996).

As put by Kok *et al.* (2011), those two approaches are complementary. The scenario approach works from the past and the present to imagine a plurality of long-term futures, while backcasting starts from an image of the future and works backward to the present (Hines *et al.*, 2019). "*Exploratory scenarios (…) strive for awareness raising, the stimulation of creative thinking, or gaining insight into the way social, economic, and environmental drivers influence each other [while] Backcasting (…) are often used to examine paths to futures*". Exploratory scenario explores the range of possible long-term futures while backcasting highlights the diverse paths to theses futures.

The scenario approach first defined contrasted scenarios of what could be a chemical pesticide-free agriculture in Europe in 2050. Then, the backcasting approach looked at the conditions for the realisation of each chemical pesticide-free agriculture scenario, by identifying the milestones to reach and the actions to implement along a pathway that connects to the present.

The foresight method relies on the morphological analysis of a system divided into the following components: public policies and trade regulations, diets, food value chains, farm structures, cropping systems, agricultural equipment and digital technologies, education and Agricultural Knowledge and Innovation Systems (AKIS) (left-hand side panel; Figure 1-1). A retrospective analysis of trends, weak signals and potential ruptures was carried out on these components through literature reviews and expert judgments (Stage 1, Figure 1-1). Based on these analyses, several expert groups developed alternative hypotheses describing the possible changes of these components by 2050 (assembled in the morphological table, corresponding to the centre panel in Figure 1-1) (Stage 2), and combined them to build the qualitative scenarios (Stage 3). Then, the scenarios were backcasted at EU level and in four European small regions (bottom panel) (Stage 4), and were quantified through simulations using the GlobAgri-AE2050 model (right-hand side panel) (Stage 5).

1.3. The various expert groups of the foresight study

The main groups involved in this foresight study were:

- An INRAE **project team** from the Directorate for Collective Scientific Assessment, Foresight and Advanced Studies (DEPE) in charge of coordinating the whole project, building retrospective analyses on the components of the system (Table 1-1). The project team was also in charge of driving the elaboration of hypotheses, microscenarios, scenarios, transition pathways and quantification of scenarios, with experts' inputs;
- A **European expert committee** (top part of the Figure 1-1; Table 1-2) in charge of building scenarios (transdisciplinary collective of 23 members, including INRAE, other European researchers and stakeholders; six meeting were held between September 2020 and October 2022);
- A **monitoring committee** including representatives of the French Ministries (Ministry of Agriculture and Food Sovereignty, Ministry of Higher Education and Research, Ministry of Ecological Transition), and of the PPR Growing and Protecting crops Differently (Table 1-3).

Several thematic groups of experts (in blue, in Figure 1-1) were also involved at different stages of the foresight study, and have fed the thinking of the expert committee:

- **Four thematic groups explored pesticide-free cropping systems** (left top part of the Figure 1-1), including one focused on 'Reducing pest pressure', one focused on 'Strengthening plant resistance', and one focused on 'Agricultural equipment and digital technologies';
- A **transition group** explored transition pathways at EU level (bottom part of the Figure 1-1);
- A **quantification group** was in charge of translating the scenarios into quantitative inputs for modelling, and analysed and discussed simulation results (right top part of the Figure 1-1);
- A **focus group** in charge of defining research orientations for achieving transition pathways towards scenarios;
- Four **regional groups** explored transition pathways for specific case studies (bottom part of the Figure 1-1).

In addition, individual interviews with experts were conducted for the retrospective analysis and for the quantification work. The names and affiliations of the experts who took part in the thematic groups and those who were interviewed are listed in the Appendix of the report. 144 experts were involved during the various stages of the study.

Table 1-1: Members of the Project Team

Name and first name	Organisation
Mora Olivier	INRAE DEPE, coordinator of the foresight
Berne Jeanne-Alix	INRAE DEPE
Drouet Jean-Louis	INRAE ECOSYS/DEPE
Le Mouël Chantal	INRAE SMART/DEPE
Meunier Claire	INRAE DEPE
Forslund Agneta	INRAE SMART
Kieffer Victor	INRAE SMART
Paresys Lise	INRAE DEPE

Table 1-2: Members of the European Expert Committee

Name and first name	Organisation
Autio Sari	TUKES (Finish Safety and Chemicals Agency, Finland)
Barberi Paolo	Sant'Anna School of Advanced Studies (Italy)
Bergeret Pascal	CIHEAM (Mediterranean Agronomic Institute of Montpellier, France
Bujor-Nenița Oana	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Carlesi Stefano	Sant'Anna School of Advanced Studies (Italy)
Christensen Henriette	PAN (Pesticide Action Network Europe, Belgium)
Deguine Jean-Philippe	CIRAD (French Agricultural Research Centre for International Development, France)
Enjalbert Jérôme	INRAE (National Research Institute for Agriculture, Food and the Environment, France)
Fintineru Gina	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Huber Laurent	INRAE, Ecosys (France)
Jeanneret Philippe	Agroscope (Swiss centre of excellence for agricultural research, Switzerland)
Kolb Steffen	ZALF (Leibniz Centre for Agricultural Landscape Research, Germany)
Lamine Claire	INRAE, Ecodéveloppement (France)
Martin Guillaume	INRAE, AGIR (France)
Messéan Antoine	INRAE, Eco-Innov (France)
Mosnier Aline	FABLE consortium (Food, Agriculture, Biodiversity, Land-use and Energy, France)
Oustrain Savine	Vivescia (Agricultural cooperative, France)
Porcher Emmanuelle	MNHN (French National Natural History Museum, France)
Raineau Yann	INRAE, ETTIS (France)
Röös Elin	SLU (Swedish University of Agricultural Sciences, Sweden)

Table 1-3: Members of the Monitoring Committee

Organisation	Name and first name
Ministry of Agriculture and Food Sovereignty	Dangy Louise, Hardelin Julien, Schwoob Marie-Hélène
Ministry of Higher Education and Research	Barriuso Enrique
Ministry of Ecological Transition	Couderc-Obert Céline, Le Loarer Marina, Prévost Thibault, Soulard Marie-Camille
Priority Research Program "Growing and Protecting crops Differently"	Jacquet Florence, Latruffe Laure
INRAE	Huyghe Christian, Richard Guy

1.4. The seven stages of foresight study

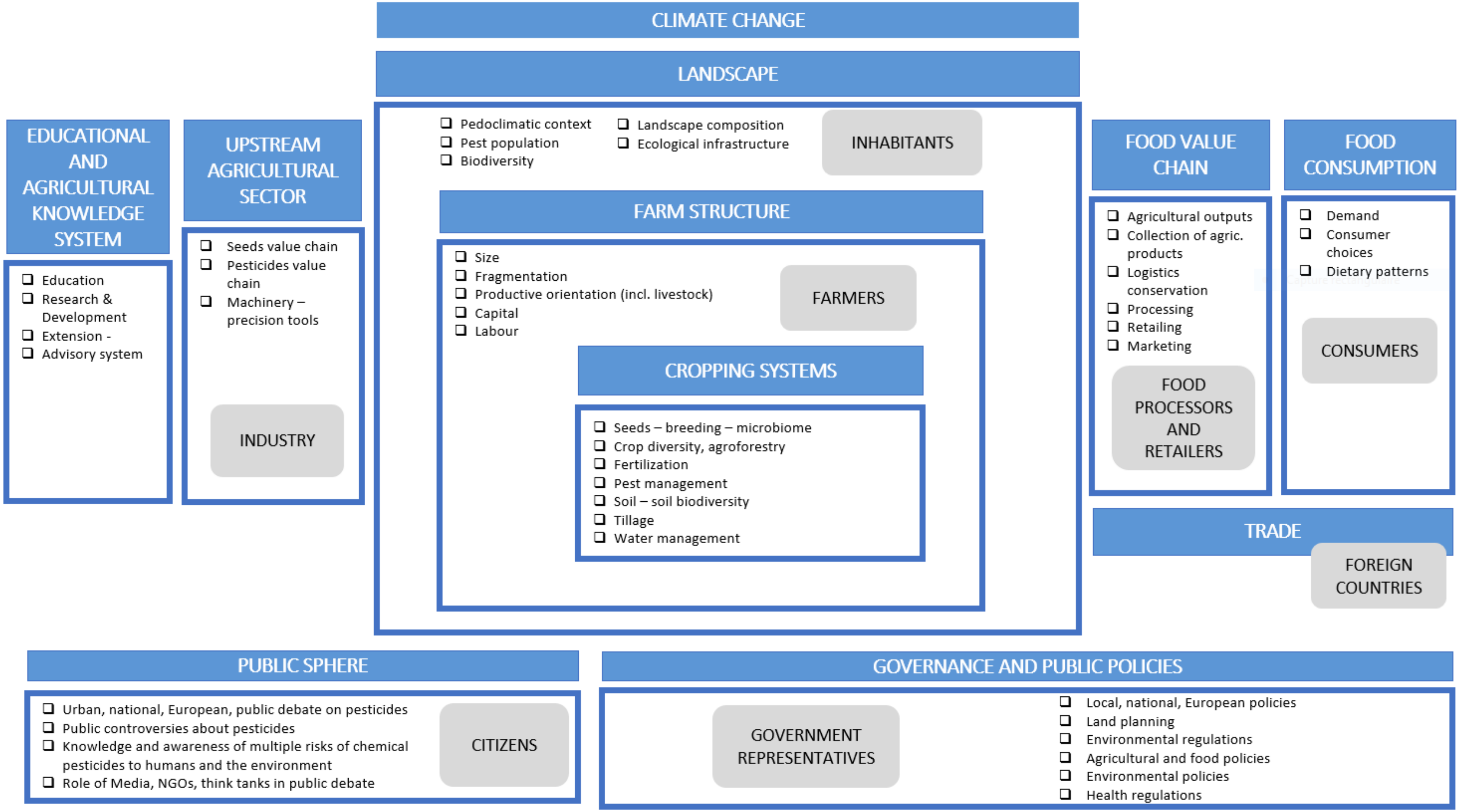
The project was settled into seven stages (Figure 1-1).

1. The first stage consisted of defining the so-called 'system' and its components according to the 'chemical pesticide-free agriculture in Europe in 2050' foresight study.
2. The second stage referred to conducting a retrospective analysis of the various components of the system, as well as to set up hypotheses of change for the components of the system in 2050.
3. The third stage consisted of developing scenarios in 2050 presenting different agricultural and food systems without chemical pesticides at the European scale in a global environment.
4. The fourth stage involved quantifying the impacts of the scenarios on production, land use, trade, greenhouses gas (GHG) emissions, using modelling.
5. The fifth stage consisted of elaborating transition pathways towards scenarios of agriculture without chemical pesticides in Europe, and in four case studies, using a backcasting approach.
6. The sixth stage was the finalisation of the narratives of the scenarios including transition pathways and outputs of the simulations. It included a discussion of the scenarios for identifying future research areas consistent with each scenario and research gaps.
7. The seventh stage was the public dissemination of the results of the foresight (deliverables and public presentations).

Stage 1: Defining the system and its components

The foresight system developed after the first expert committee meeting is shown in Figure 1-2. The system has several components: cropping systems, farm structures, educational and agricultural knowledge, upstream agricultural sector, food value chain and consumption, public policies, governance and public sphere, and trade. The climate change was taken into account through its future impact on pest and crop-pest interactions (see Section 2.4). The analysis of upstream agricultural sector was initially reduced to agricultural equipment and digital technologies (see Section 3.4), other elements concerning production of biocontrol products and new services of monitoring, and seed production were introduced later in the scenario and the transition pathways. Trade was analysed jointly with public policies through trade regulations and discussed during the quantification of the scenarios (See Section 3.3 and Chapter 5).

Figure 1-2: The system of the foresight study



Stage 2: Conducting a retrospective analysis and building hypotheses of change for the components of the system

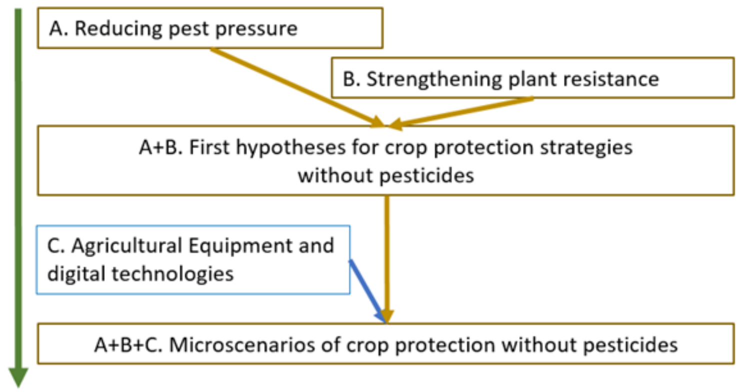
The objective of the retrospective analysis is to build a knowledge base on past trends of the system in order to understand its current dynamics on which we want to act. The aim of the retrospective analysis is to identify major trends, weak signals or the seeds of change, and possible long-term ruptures. Retrospective analysis is the basis of foresight reasoning, because it is by analysing the past that we can build the hypotheses of future change. Even if our aim is to build normative hypotheses, we need to know whether these normative hypotheses are in line or in rupture with current dynamics, and whether there are weak signals in the present that anticipate their emergence.

Based on literature reviews and expert groups, several retrospective and prospective analyses were conducted on cropping systems, food value chains, farm structures and public policies. Components were analysed through trend analyses with the objective of identifying past and current trends using when available, time series data’s from international agencies such as Eurostat.

Thematic workshops were organised to analyse the component “Cropping system”. Two workshops involved specific groups of academic researchers specialised in cropping systems to analyse past and current trends in (A) Pest management and (B) Plant resistance (Figure 1-3). Another thematic workshop was organised to analyse trends in agricultural equipment and digital technologies (Figure 1-3). The objectives of these workshops were to identify weak signals, new concepts and new knowledge based on cutting-edge science that could support, in the future, pesticide-free crop protection. The outcomes are presented in Section 2.5.

Based on this knowledge, we developed a disruptive approach in order to identify key elements and elaborate principles of chemical pesticide-free cropping systems in 2050. Using the sociological theory ‘Innovation through withdrawal’ in a heuristic mode (Goulet and Vinck, 2015), we imagined possible future changes in cropping systems and crop protection strategies if chemical pesticides are withdrawn (see Section 2.6). In order to develop such hypotheses, several groups were brought together in two successive meetings to combine their different approaches (Figure 1-3). A first ‘Cropping systems’ meeting, aiming to develop the first hypotheses for crop protection strategies without pesticides (pest management strategies without pesticides and rupture hypotheses), brought together experts from the previous A and B groups. A second ‘Cropping systems’ meeting brought together experts from the same A and B groups with those from the C group. At this meeting, the experts were asked to complete and validate the previously developed hypotheses and then to build hypotheses of crop protection without pesticides in 2050 (presented in Section 2.6).

Figure 1-3: Organisation of thematic groups for building crop protection strategy without chemical pesticides



For other components like food value chains, diets, farm structures, public policies, education and AKIS, retrospective and trend analyses were conducted by the project team through scientific literature reviews and/or expert interviews, and reviewed by the European expert committee. The project team and the expert groups, including the European expert committee and the transition groups developed future hypotheses jointly on public policy, education and agriculture knowledge system.

Chapter 2 of the current report presents past and future hypotheses of change for cropping systems without chemical pesticides in Europe. Section 3.1 presents past trends and hypotheses of change for farm structures in Europe. Section 3.2 presents past trends and hypotheses of change for food value chains based on pesticide-free agriculture in Europe. Section 3.3 presents past and hypotheses of change for public policies towards pesticide-free agriculture in Europe. Section 3.4 presents past and hypotheses of change for the other components: diets, education and AKIS, and agricultural equipment and digital technologies.

Stage 3: Building scenarios of pesticide-free agriculture in Europe in 2050

As a result of the stage 2, alternative assumptions about normative and possible changes in 2050 have been built for each component; they form the 'building blocks' of the morphological table (see the graph in the central panel of Figure 1-1: for each component in line, the alternative hypotheses in 2050 are reported in the cells of the table). The direct components involved in the scenario building are: Food value chains, Farm structures, Cropping systems, and Agricultural equipment and digital technologies.

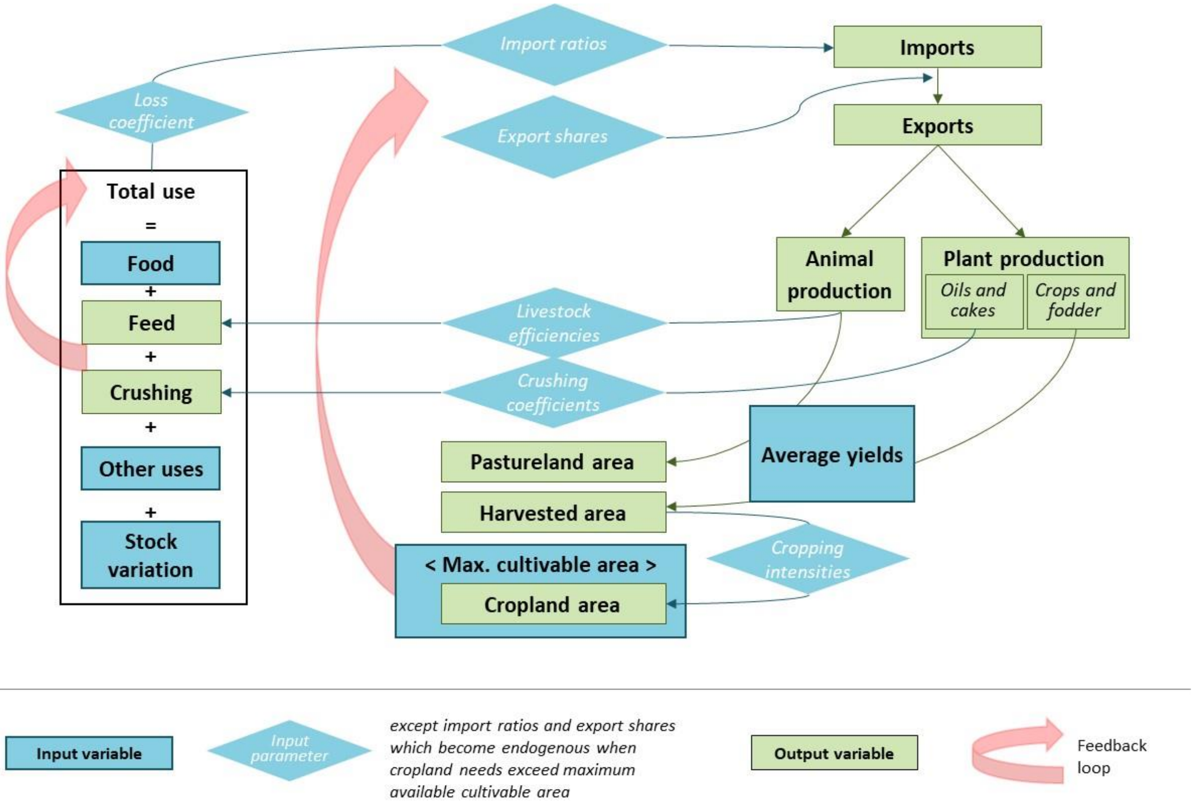
Three contrasted scenarios were built based on extensive discussions between academic researchers and stakeholders within the European expert committee, in January 2022. The European expert committee first assessed the alternative hypotheses in 2050 for all components resulting from the previous stage. Then, it built contrasted scenarios mobilising the morphological table. Each scenario combines one or several hypotheses of change per component, respects causal relationships and seeks consistency across hypotheses as well as plausibility. Each scenario describes a complete change towards chemical pesticide-free agriculture in Europe in 2050 and is developed into a narrative. The scenarios were crafted in order to describe the wide range of possible change towards chemical pesticide-free agriculture. The narratives of the scenarios were drafted by the project team and discussed among experts of the European expert committee. They are presented in Section 4.1.

Stage 4: Quantification of scenarios of pesticide-free agriculture in Europe in 2050

The quantitative impacts of the scenarios in terms of land use, agricultural production, trade and greenhouse gas emissions were analysed and discussed through an iterative process with the quantification group and the European expert committee.

Scenario simulations were carried out with GlobAgri-AE2050. The structure and functioning of the model are depicted in Figure 1-4. The model is described in more details in Chapter 5.

Figure 1-4: Overview of the model functioning – GlobAgri-AE2050 (21 geographic regions, 38 products) (adapted from Forslund *et al.*, 2020)



For each agri-food product (including grass and various forage plants) in each world region, there is a resource-use equation. In vegetal product equations, the production component is linked to required land area (arable and pasture) through yield parameters, while the feed component is linked to animal production through feed-to-output parameters. In each equation, imports are fixed shares of domestic use while exports are fixed shares of the world market. The food and other uses components are exogenous in the model. Their levels, which are an input for the simulation model, result from assumed changes in demography, food diets and non-food use in scenarios. Production and land use, feed and trade components are endogenous in the model. Their levels are calculated by the model given the changes in crop and livestock productivity assumed in the scenarios.

Each world region faces a maximum cultivable area. When domestic needs change in one region, domestic production adjusts freely until the maximum cultivable area is reached. Then, additional needs are covered through trade: first, the region decreases proportionally all its export market shares; second, if not sufficient, the region increases all its import coefficients.

GlobAgri-AE2050 considers 38 agri-food products and 21 world regions including 6 European sub-regions. The reference year is the 2009-20011 average and the simulation horizon is 2050. Data used are mainly the FAO's commodity balances, with some additional data from Herrero *et al.* (2013) for feed rations, Monfreda *et al.* (2008) for production and area of forage plants, and GAEZ version 4 for maximum cultivable areas.

For the simulation of scenarios, the starting point is the morphological table, which reports the alternative hypotheses of change for each driver. These qualitative hypotheses are first translated into quantitative model inputs. This involves establishing detailed translation matrices between global qualitative hypotheses (e.g., the evolution of cropping systems) and model input levels for each agri-food product in each geographical region (e.g., the level of crop yields and cropping intensity in 2050).

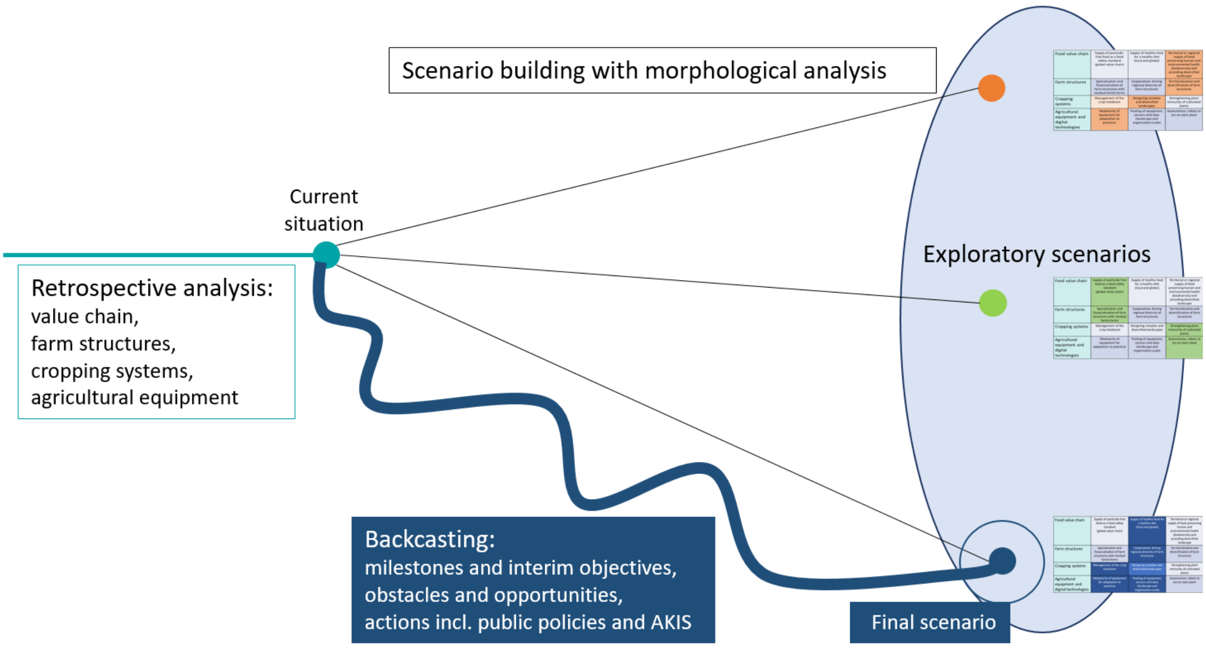
The black arrows between the central and the right-hand panel of Figure 1-1 show these translation matrices. They are described in detail in Chapter 5. Once all qualitative hypotheses for all drivers have been translated into quantitative inputs for the model, scenarios may be simulated.

The results of the simulation of the pesticide-free agriculture scenarios are presented in Chapter 5.

Stage 5: Elaborating transition pathways towards scenarios of chemical pesticide-free agriculture in Europe, using a backcasting approach

Based on the generic scenarios elaborated during stage 3, two backcasting approaches were conducted in parallel to explore the conditions required for reaching the scenarios (Figure 1-5).

Figure 1-5: Articulating exploratory scenarios with backcasting (adapted from Kok *et al.*, 2011)



NB: The blue curve is an illustrative example of the backcasting approach.

The first backcasting approach was conducted through regional case studies with the aim of downscaling the scenarios built during stage 3.

The regional case studies of the foresight aim at building in a specific sector and in a specific region scenarios and transition pathways towards chemical pesticide-free agriculture in 2050, by downscaling the generic scenarios. The regional case studies complete the work done by illustrating each scenario for specific cropping systems and food sector in a specific region. In order to conduct these studies, partnerships were developed with regional coordinators that were part of the European expert committee. We chose a participatory approach, involving experts in the region and sector studied, in complementary domains: scientists, farmers, non-governmental organisations, food processors, local authorities, representatives, etc. With a specific method combining the downscaling of scenarios and a backcasting approach, four regional case studies were conducted in South Finland on cereals and oilseeds production, in South, South-east Romania on vegetable growing, in Tuscany (Italy) on durum wheat production, in Bergerac-Duras (France) on wine production. These four regional studies and their outcomes are presented in Section 4.2.

The second backcasting work was conducted at the EU level with the aim of imagining different paths for a transition at EU level corresponding to the three pesticide-free agriculture scenarios.

A European transition group was assembled with experts from the European expert committee, experts in transitions (AKIS or public policies) and coordinators of regional workshops. The backcasting work was divided into two sequences. During a first workshop, based on a retrospective analysis carried out by the project team, the participants built alternative hypotheses of change for public policies and for education and AKIS in 2050 that could support the transition towards the various scenarios (Figure 1-5). During the second workshop, based on the scenarios and alternative hypotheses of change for public policies, education and AKIS, experts defined the milestones for each scenario, identified obstacles and opportunities for these milestones and imagined the actions to achieve the milestones of each scenario. Finally, they elaborated a timeline for each scenario (Figure 1-5). Following the two meetings of the European transition group, through a dedicated meeting of the European expert committee, the timelines were converted into narratives of transition pathway for each scenario, including hypotheses of change of diets. Such narratives are presented in Section 4.1.

Stage 6: Assessing the scenarios and transition pathways for identifying future research areas and knowledge gaps, and comparing the scenarios in terms of strengths and weaknesses

Scenarios were mobilised to identify research directions that should be developed or strengthened to anticipate future developments. In December 2021, during a dedicated meeting, a group of researchers involved in projects funded by the French Priority Research Program ‘Growing and Protecting crops Differently’ assessed the chemical pesticide-free crop protection hypotheses against current knowledge and research needs (see Chapter 6).

To facilitate discussion in the next stage, the scenarios were analysed in terms of strengths and weaknesses. In October 2022, the members of the European expert committee of the foresight discussed scenarios and their transition pathways at its lastest meeting. They conducted a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the three scenarios, to identify, given the current situation, their main advantages (internally – strengths, and externally – opportunities), and obstacles to overcome (internally – weaknesses, and externally – threats) (see Chapter 6).

Stage 7: Public dissemination of the results of the foresight – setting a strategic conversation

Debating the results is a crucial stage of the foresight. By the issues they raise, the scenarios of European agriculture without chemical pesticides seek to open up a strategic conversation on possible and desirable futures. Mobilising the deliverables described above, members of the project team presented and discussed the foresight scenarios in various arenas with interested stakeholders: national and European decision-makers, researchers, agricultural and agro-food professionals and civil society stakeholders.

Scenarios aim to develop stakeholders' ability to imagine possible futures in order to strengthen the capacity to imagine future (the “Future literacy”; Miller, 2018), eventually to translate them into their concrete situation and to implement concrete transition pathways; but also to open up a public debate on the possibilities of implementing such transition. Scenarios were also used in research planning to identify research directions that should be developed or strengthened to build a European pesticide-free agriculture.

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European Chemical Pesticide-Free Agriculture in 2050

Chapter 2

Building efficient chemical pesticide-free crop protection strategies and cropping systems in 2050

Table of contents

Introduction

In the process of building scenarios of European chemical pesticide-free agriculture in 2050, we first chose to study cropping systems and to define, with a disruptive approach, what could be pesticide-free cropping systems and crop protection in 2050.

Since the 1950s, chemical pesticides have become a major management tool in European cropping systems. They have greatly transformed crop protection and cropping systems and made possible an important increase in agricultural production, while maintaining high crop quality. Since the 1990s, the negative impacts of pesticides on human and environmental health have led to a rethinking of crop protection strategies, trying to limit their use and impacts, but with limited effects.

We start this chapter with a brief overview of the current state of knowledge on the impacts of pesticides on human and environmental health based on the latest scientific collective assessments (Section 2.1). We then present a retrospective analysis of changes in cropping systems and pest management strategies (Section 2.2), and the identification, based on current scientific knowledge, of weak signals for crop protection strategies without chemical pesticides (Section 2.3). We also studied through a literature review the possible impacts of climate change on pests' pressure and crops in Europe in 2050 (Section 2.4). Then, we focus on crop protection, and present six modes of action with associated levers and epidemiological monitoring that could be mobilised for a pesticide-free crop protection in 2050 (Section 2.5).

Based on these analyses, the project team and the expert groups drew hypotheses of change for crop protection and cropping systems in 2050 (Section 2.6). All these analyses were conducted though literature reviews, and experts' group discussions organised through a series of meetings on crop protection, plant resistance and cropping systems.

2.1. Environmental and Human health effects of pesticides

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This Section has been reviewed by Sophie Leenhardt (INRAE, DEPE).

Table of contents

Introduction

Pesticide is a generic term derived from the Latin “pestis” (plague) and “caedere” (to kill). By definition, pesticides are designed to control or kill living organisms that could negatively affect crops development. Since the middle of the 20th century, their use in agriculture has played a key role in protecting crops from pests, contributing to increasing and stabilising agricultural yields from possible harvest losses and decrease in product quality, and therefore to ensuring food security in Europe and around the world (see Section 2.2 for a retrospective analysis on the use of chemical pesticides in agriculture).

However, pesticides not only act on the targeted organisms, as they affect the overall environment, including the atmosphere, soil, groundwater surface and marine waters, and can contaminate the whole ecosystem (Leenhardt *et al.*, 2022; de Souza *et al.*, 2020). The negative impacts of pesticides will depend on the substances and their modes of action, the concentration level of the active substances in the formulations, their sprayed amount, and exposure time (Margni *et al.*, 2002; Rice *et al.*, 2007), and the level of exposure combined with the sensibility of exposed organisms. The toxicity of pesticides also comes from their high persistence and their accumulation in organisms and the environment (Porter *et al.*, 2018).

Since pesticides are intrinsically toxic and spread in the environment, they are potentially toxic to other organisms, including humans. They can affect human health from different sources of exposure: residues in food, drinking water, prenatal ingestion, contaminated air, dust and surfaces, and occupational exposure (ECA, 2019; HBM4EU, 2022; Inserm, 2021). Pesticides, their active substances and metabolites can cause health problems “*such as cancer, infertility, malformation, and chromosomal changes as a consequence DNA mutation and oxidative stress, both of which are related to ageing and diseases like Parkinson’s and Alzheimer’s*” (de Souza *et al.*, 2020).

These harmful impacts of chemical pesticides on human health and environment have raised the need to monitor and reduce pesticide use in agriculture through public policies, in order to remove these contaminants from the environment and protect public health.

Various disciplines, scientists and stakeholders have been studying the effects of pesticides on human health and on the environment. Scientists - mainly toxicologists and epidemiologists and ecotoxicologists - develop the body of scientific evidence on notably the effects of pesticides on human and environmental health, including new methods for analysing pesticides and their metabolites, and models for assessing their impacts. Health and environmental impacts of pesticides also rise societal concerns and movements, through protests, petitions, and sometimes production of knowledge, rising from associations of victims, farmers, local residents, and consumers, exposed to pesticides, as well as environmental NGOs. Such movements lead to actions from policy makers, to develop new or updated research and policies, in line with the mounting body of evidence on pesticides and health and societal concerns. The negative impacts of pesticides are also studied by lawyers and courts, to rule on the legal actions taken by stakeholders against pesticides uses.

This Section summarises the recent developments and current evidence about the effects of pesticides on the environment and on human health. It is mainly based on several scientific collective assessments conducted at the request of public authorities to get an understanding about the level of evidence on the effects of pesticides on the environment and on human health. In particular, in 2005, the French ministries of agriculture and environment commissioned to INRA and Cemagref a collective scientific assessment on pesticides, agriculture and the environment (Aubertot *et al.*, 2005). In 2013 and 2021, INSERM (Institut national de la santé et de la recherche médicale - National Institute of Health and Medical Research), at the request of the French ministry of health, published its collective expertise report on the effects of pesticides on human health (INSERM, 2013; updated in 2021). In 2022, INRAE and Ifremer published the outcomes of their scientific collective assessment on the impacts of plant protection products on biodiversity and ecosystem services (Leenhardt *et al.*, 2022).

Very recently, the European Environment Agency (EEA) published a briefing document 'How pesticides impact human health and ecosystems in Europe' (EEA, 2023), summarising the latest knowledge on the impact of pesticides on human health and the environment, and presenting good practices to reduce their use and risk across Europe.

2.1.1. Pesticides contaminate all types of environments

Pesticides can reach the environment at three steps in their lifecycle: during their production, their use and their elimination. At production site, leakages, industrial accidents may lead to environmental pollution of the neighbourhood, although risk is limited thanks to public policies in place ("Seveso" Directives), ensuring the application of preventive measures against these potential leakages. At the end of their life cycle, pesticides elimination is done mainly by incineration, potentially leading to air contamination.

The main cause of environmental contamination with pesticides is through their use, notably for crop protection. Pesticides can be sprayed, applied in the field as granules or powders, or directly applied to the seed. In the field, the applied amount of pesticides reaches the target organism (weeds, insects, fungi, bacteria), and it ends up in the soil or on the crops from where the pesticides can diffuse to other environmental sectors or enter the food chain (Storck *et al.*, 2017).

Pesticides are present in all environments, as shown in Figure 2-1: terrestrial, aquatic marine and continental, atmospheric, as well as biotic (Leenhardt *et al.*, 2022).

Figure 2-1: Overview of the environmental contamination from pesticides
(Source: Leenhardt *et al.*, 2022)

Credits: Lucile WARGNIEZ

There is a variety in contamination, in terms of substances and concentrations, according to the location (relative position from the spraying area), the type of environment, and the characteristics of the substances (active substances, adjuvants, co-formulants) contained in the pesticides formulations. Certain substances that have been banned in Europe for several years are still found in some environments. For example, lindane, DDT (dichlorodiphényltrichloroéthane), atrazine, and their transformation products are still found in soils, or herbicides in waters (Leenhardt *et al.*, 2022). Overall, herbicides, which are in majority hydrophilic, are found in waters, and insecticides, in majority hydrophobic, are found in organic soil matter, sediments and biota.

Contamination has been defined, in the INRAE 2005 scientific collective assessment on pesticides, as "*the unusual presence of substances, micro-organisms, etc. in an environmental compartment*" ("*la présence anormale de substances, de micro-organismes […] dans un compartiment de l'environnement*"). For pesticides, their presence in the environment automatically means contamination according to this definition, even in soils where pesticides application is voluntary and expected (Aubertot *et al.*, 2005). Pesticides contaminate all matrices - waters, air, soil, biota and food.

The knowledge about the environmental contamination from pesticides has progressively increased since the 2000's, thanks to monitoring/surveillance schemes that have been set up across Europe, especially on waters. More recently, the European Soil Data Centre (ESDAC) has been launched, with the objective of being the centre for soil related data in Europe[1]. In addition, new methods for monitoring pesticides in the environment have been developed, to better inform the level of contamination, the type of substances present and their dynamics. The scientific collective expertise conducted by INRAE and Ifremer describes several tools that have been developed and should be further researched and/or implemented. For example, new sampling methods such as integrative passive samplers allow to better identify situations of chronic exposure at low concentrations; they also allow to quantify molecules that cannot be detected by one-off sampling. Analytical methods have also improved to allow for a larger scope of molecules to be analysed, better sensitivity and non-targeted research. Finally, modelling tools are being developed, to predict the fate of pesticides in the environment (Leenhardt *et al.*, 2022).

In the following paragraphs we provide a short overview of the knowledge about pesticides contamination in different matrices. We do not cover in this Section marine environments that are out of scope of the foresight study, but information on this topic can be found in Leenhardt *et al.* (2022).

2.1.1.1. Soil contamination

Available data show that pesticides (active substances, metabolites, adjuvants, co-formulations) are found in the vast majority of studied soils, in particular in conventional cultivated areas. A wide diversity of substances, mostly in combinations, are found in soils (Leenhardt *et al.*, 2022). But, similar to air, the absence of a regulatory framework for monitoring soil concentrations of pesticides limits the availability of pan European data. The announced upcoming European soil health law could address this gap and set conditions for quality of soil monitoring[2].

A study recently analysed 76 pesticide residues in 317 agricultural topsoils, taken from 11 European countries and 6 cropping systems (Silva *et al.*, 2019). Only in 17% of the tested agricultural topsoils no pesticide residues were detected (meaning that 83% contained at least one residue). The number of residues found in the soil samples vary significantly according to the region, the country and the crop studied. Out of the 76 analytes measured, 43 different residues were present in the tested soils, in majority present in combinations, although in a high diversity of combinations across European soils.

[1] https://esdac.jrc.ec.europa.eu/, last consulted in May 2023

[2] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13350-Soil-health-protecting-sustainably-managing-and-restoring-EU-soils_en, last consulted on May 2nd, 2023

The most frequent substances found in soil samples were AMPA, boscalid, epoxiconazole, DDE pp. (persistent metabolite of DDT, p,p'-DDE (1,1-dichloro-2,2-bis(p-chlorophenyl)ethylene)), glyphosate and tebuconazole. They were also the ones present in the highest quantity (Silva *et al.*, 2019). In another study, conducted in three European countries and four different crops (Geissen *et al.*, 2021), soils from organic farms contained 70 to 90% less pesticide residues concentrations than conventional soils. They also contained fewer number of pesticides residues per sample: maximum 5 in organic farms soil samples, in comparison to 16 residues per sample for soils from conventional farms.

The European Soil Data Centre (ESDAC) is the thematic centre for soil related data in Europe. Its ambition is to become the single reference point for and to host all relevant soil data and information at European level. It will provide harmonised soil monitoring system for the EU by integrating the current LUCAS Soil programme with national or regional soil monitoring activities (Orgiazzi *et al.*, 2022).

2.1.1.2. Water contamination

Pesticides get into water by runoff from treated fields, leaching through the soil, and during pesticide spraying. High levels of pesticide applications can harm the water quality for groundwater, surface and marine water and drinking water, affecting both aquatic ecosystems and human health.

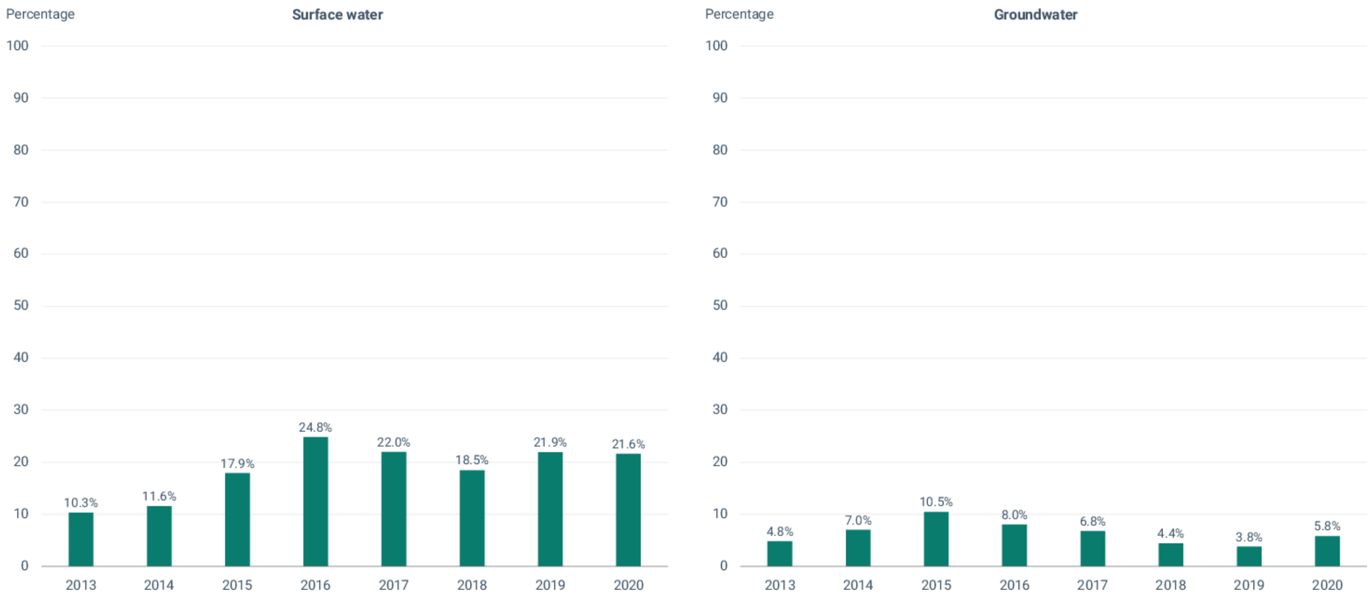
Adopted in the 2000's, the regulatory framework on water – mainly the water framework directive – sets objectives for good chemical and ecological status of waters across Europe. It requires monitoring of specific substances, including some pesticides. This allows to gather substantial data on the presence of pesticides in continental waters.

A report published by the European Environment Agency (EEA) in 2018 on the status of European water bodies covered by the water framework directive (EEA, 2018) showed that 74% of groundwater areas have good chemical status according to the definition of the Directive, and 89% achieve good ecological status. For surface waters, the figures are worse, with "*around 40% of surface waters (rivers, lakes and transitional and coastal waters) in good ecological status or potential, and only 38% in good chemical status*". According to EEA, hydromorphological pressures (40%), diffuse sources (38%), particularly from agriculture, and atmospheric deposition (38%) are the main significant pressures on surface water bodies (EEA, 2018).

Looking more specifically at pesticides, EEA published a new indicator to monitor pesticides in Europe's rivers, lakes and groundwater (Figure 2-2). With this new indicator, EEA analysis against available data shows that levels of pesticides exceeding thresholds were measured in 21.6% of all reported monitoring sites in European surface waters in 2020. The share for groundwater was considerably lower, between 3.8% and 10%. Some of the pesticides most often causing exceedance in surface waters are no longer approved for use in Europe, which, according to EEA, highlights the issue of the long-term impacts of pesticide use and potential emergency authorizations. In groundwater, the herbicide atrazine and its metabolites was found as most often causing exceedance, despite restrictions on its use since 2007, and because of its persistence (EEA, 2022).

Herbicides are in majority found in waters, as well as some fungicides such as copper and tebuconazole. They are among the most frequently detected and quantified molecules in surface waters (Leenhardt *et al.*, 2022). Apart from the substances identified through the regulatory framework on water, other active substances are detected in continental waters, as highlighted in the INRAE and Ifremer collective scientific assessment report (Leenhardt *et al.*, 2022). These include for example glyphosate and its transformation product aminomethylphosphonic acid (AMPA), found in respectively 43% to 63% of samples of surface waters in France (Carles *et al.*, 2019). AMPA is also a transformation product of other molecules than glyphosate, making it difficult to assess precisely AMPA contamination coming from glyphosate contamination. However, when AMPA is found in agricultural areas, it very likely comes from glyphosate use in agriculture.

Figure 2-2: Percentage of reported monitoring sites with pesticides exceeding thresholds in surface waters (left) and groundwater (right) in Europe, weighted by country area (Source: extracted from EEA, https://www.eea.europa.eu/data-and-maps/figures/percentage-of-reported-monitoring-sites-5)



2.1.1.3. Air contamination

In France, the presence of organic pesticides in the atmosphere is demonstrated, both in rural and urban areas, though in variable concentrations (Leenhardt *et al.*, 2022). All categories of pesticides – herbicides, fungicides, insecticides - are found in the atmosphere, although in very variable concentrations depending on the substance, the quantities sprayed, and the relative position with respect to the sprayed area (ibid.). Pesticides components can also reach the atmosphere through volatilization, *i.e.* the process leading to the transfer from the soil or plant compartment into the atmosphere. This process can last for several days to a few weeks (Bedos *et al.*, 2002).

However, in the absence of dedicated European regulation on the monitoring of ambient air contamination with pesticides, data are more limited and heterogeneous across Europe.

Studies are ongoing to better understand the pesticide exposure through air contamination. One example is the "PestiRiv study", aiming at comparing the pesticide exposures among residents of wine-growing and non-wine-growing areas[3].

2.1.1.4. Biotic contamination

In this paragraph, we cover the contamination through exposure to pesticides for non-targeted organisms, and the contamination through accumulation of pesticides in organisms' tissues.

The use of pesticides can reach non-targeted organisms, directly or indirectly by the consumption of contaminated items, as many pesticides are not selective. The level of contamination will depend on the composition of the pesticide, the physico-chemical properties of its active substances, its persistence, etc. Indeed, pesticides application can drift or volatilize, and indirectly reach non-targeted

[3] www.santepubliquefrance.fr/etudes-et-enquetes/pestiriv-une-etude-pour-mieux-connaitre-l-expposition-aux-personnes-vivant-en-zones-viticoles-et-non-viticoles, last consulted in March 2023

organisms through contamination of air, soil, and water (Aktar *et al.*, 2009). Volatilization from soil can account from up to 90% of the applied amount of pesticide in the field, depending on the substances physico-chemical characteristics, and environmental conditions (Bedos *et al.*, 2002).

Despite limited data available, and the absence of a pan European system in place to monitor species' exposure to pesticides, numerous studies document the fact that the whole biota is contaminated with pesticides, from microbial communities up to predators (Leenhardt *et al.*, 2022). Pesticide residues are found in non-target organisms, for example in bee colonies (Murcia-Morales *et al.*, 2021), birds, fishes, small mammals, etc. (EEA, 2022). Citizen-science projects can help to further understand the effects of pesticides on ecosystems pollution. For example, the Insignia project is a citizen-science-based project that aims at monitoring environmental pollution in bee colonies[4]. A pilot study completed in Denmark in 2020 detected 75 different pesticide residues, including the long banned DDT. The data collected by the project also indicate a seasonal variation, with increased detection when these pesticides are more frequently used in agricultural activities (EEA, 2022).

Pesticides residues in soils also interact with soil microbial communities in two ways: toxicity to the various microorganisms, and potential to degrade pesticide compounds (Karpouzas *et al.*, 2022). Beyond soil microbial communities, according to Karpouzas *et al.*, pesticides could also affect the composition of the microbial communities present in internal or external plant tissues, *i.e.* the plant microbiome. Recent studies also indicate that pesticide effects could even reach the microbiomes of insects and earthworms (Karpouzas *et al.*, 2022).

2.1.1.5. Food and drink contamination

The use of pesticides for crop protection can result in the presence of pesticides residues in the food produced from these crops. Pesticide residues refer to "*measurable amounts of an active substance and/or related metabolites and/or degradation products that can be found on harvested crops or in foods of animal origin*" (EFSA, 2022a). European Regulation (EC) 396/2005 sets Maximum Residue Limits (MRL) for active substances in food product groups, in order to ensure high level of consumers protection. Member states and EU regularly check compliance of products sold in the European market with these MRLs through their monitoring programs. EFSA publishes annually a report on the results of the controls conducted at EU and member states levels, together with an analysis of chronic and acute risks to the health of consumers from pesticide residues.

According to EFSA 2022 report (analysing data from 2020 controls): "*94.9% of the overall 88,141 samples analysed fell below the maximum residue level (MRL), 5.1% exceeded this level, of which 3.6% were non-compliant (samples exceeding the MRL after taking the measurement uncertainty into account)*". EFSA assessed the risks to consumers of these MRL exceedances and considered that "*Dietary exposure to pesticides for which health-based guidance values were available is unlikely to pose a risk to EU consumer health. In the rare cases where dietary exposure for a specific pesticide/product combination was calculated to exceed the health-based guidance value, and for those pesticides for which no health-based guidance value could be established, the competent authorities took appropriate and proportionate corrective measures to address potential risks to consumers*". However, some organisations argue that food still contain multiple pesticides residues, and that the potential adverse effects of these mixes of pesticides residues are not sufficiently taken into account[5].

Pesticides can also reach drinking water. In a Dutch study conducted on surface and ground waters used for drinking water supply, pesticides and/or metabolites were found in 2/3 of the abstraction

[4] www.insignia-bee.eu, last consulted in May 2023

[5] https://www.pan-europe.info/blog/pesticide-residues-eu-food-nothing-applaud#, last consulted on 2023, May 5th

areas, and in 1/3 of these areas pesticide and/or metabolite concentration exceeded water quality standards (Sjerps *et al.*, 2019).

There is also evidence from American data of a transfer of pesticides (chlorpyrifos and pyrethroids) from mother to child trough breastmilk, which might be a route of dietary exposure to pesticides for infants (HBM4EU, 2022).

2.1.2. Effects of pesticides on biodiversity

Pesticides contaminate natural ecosystem in two different ways. On one hand, some pesticides, dissolved in water and other parts of the environment, enter into the groundwater, rivers, and streams and may cause damage to organisms. On the other hand, some pesticides go into the tissues of organisms and have a long existence in the food web. Organisms can be exposed to pesticides through three ways: exposure by contact, inhalation, direct ingestion and ingestion of product contaminated with pesticides (water, pollen, seeds, etc.).

The collective scientific assessment conducted by INRAE and Ifremer, published in May 2022, provides updated information on the impact of pesticides on biodiversity (Leenhardt *et al.*, 2022). It concludes: "*There is strong evidence that plant protection products are one of the main causes of the decline of terrestrial and aquatic invertebrates in agricultural areas, including pollinating insects and pest predators (ladybirds, carabids, etc.) as well as birds*". It goes in the same direction as Rani *et al.* (2021) conclusion: "*Contemporary there is an urgent need to think about the effect of pesticides on the number of terrestrial and aquatic animals, birds and plants*", etc. "*Herbicides that volatilize the treated plant and vapours are enough to produce acute harm to non-target plants, etc. The consequence […] is a decrease in various aquatic and terrestrial plants as well as animal families*."

The effects can be direct, by impairing the physiological state and behaviour of individuals, and by reducing the number and dynamic of the population. They can also be indirect, mainly by reducing the food availability and habitat, and by modifying the biotic interactions.

More specifically, pesticides have major effects on some specific taxonomic groups: terrestrial and aquatic invertebrates, birds and, with a lower level of scientific evidence, chiropters, amphibians and microbial communities (although for the latter data are more controversial).

2.1.2.1. Terrestrial and aquatic invertebrates

The effects of pesticides on terrestrial invertebrates, such as insects, are well known. For these populations, exposure to chemicals, including pesticides, is considered as the second cause of their decline (Sánchez-Bayo and Wyckhuys, 2019). This is particularly true in agricultural areas, where decline in abundance and in specific richness are observed (Leenhardt *et al.*, 2022).

The study from Sánchez-Bayo and Wyckhuys (2019), conducted on 76 species of butterflies in Europe, found that fertilisers and pesticides negatively affected 80% of the species.

Hallmann *et al.* (2017) studied the evolution of the total aerial insect biomass between 1989 and 2016 in several locations in Germany. They calculate a dramatic decline in average airborne insect biomass of 76% (up to 82% in midsummer) in the 27 years of monitoring in protected areas. The authors identify agricultural intensification (use of pesticides, tillage, use of fertilizers and other agronomic measures) as a plausible cause for the observed decline, together with other factors such as climate change (Hallmann *et al.*, 2017).

Among terrestrial ecosystems, Lepidoptera, Hymenoptera and dung beetles (Coleoptera) appear to be the taxa most affected. According to Sánchez-Bayo and Wyckhuys (2019): "*about half of Coleoptera and Lepidoptera species (both moths and butterflies) are declining at a faster rate than the annual average (2.1% and 1.8% respectively). A similar trend is observed among bees, where one in six species have gone regionally extinct*".

According to IPBES report (2016) on pollinators, pollination and food production: "*Pesticides, particularly insecticides, have been demonstrated to have a broad range of lethal and sublethal effects on pollinators under controlled experimental conditions (well established). The few available field studies assessing effects of field realistic exposure provide conflicting evidence of effects based on the species studied and pesticide usage (established but incomplete)*".

The New Deal for Pollinators presented by the European Commission in January 2023 sets out actions to be taken by the EU and the member states to reverse the decline of pollinators by 2030 as today, one in three bee, butterfly and hoverfly species are disappearing in the EU. It includes actions to mitigate the impact of pesticide use on pollinators: "*for example, through legal requirements to implement integrated pest management or through additional test methods for determining the toxicity of pesticides for pollinators, including sub-lethal and chronic effects. As the excessive use of pesticides is a key driver of pollinator loss, reducing the risk and use of pesticides as per the Commission's Sustainable Use of Pesticides proposal will be critical*"[6].

Effects on aquatic macroinvertebrates are also described. In terms of types of pesticides, insecticides have a direct effect, and herbicides contribute indirectly to macroinvertebrate decline by impacting habitats and food resources (Leenhardt *et al.*, 2022).

Beketov *et al.* (2013) have demonstrated that pesticides have negative effects on the regional biodiversity of stream invertebrates in Europe (and in Australia), their use causing declines of up to 42% of the stream invertebrates' species pools. Schäfer *et al.* (2012), in reviewing data from eight field studies on the thresholds for the effects of pesticides on macroinvertebrate communities in freshwater ecosystems found out that the abundances of sensitive macroinvertebrates in the communities were reduced by 27% to 61% at concentrations corresponding to the current threshold used for the registration of pesticides in Europe.

2.1.2.2. Birds and chiropters

Pesticides are identified as one of the main cause of the decline in abundance and diversity of birds in agricultural areas, together with landscape homogenization and intensification of practices (Leenhardt *et al.*, 2022, and many references cited in this review). Effects can be direct poisoning, through the ingestion of treated seeds within insecticides (like neonicotinoids) or fungicides.

For insectivorous birds and chiropters, effects are more indirect, through the decline of the food resources due to the application of insecticides. For example, insect-eating birds such as the Common Swift (*Apus apus*), which used to be a common long-distance migrating specie, is going through major population declines in most member states (EEA, 2020).

In a study looking at agronomic variables that could predict grassland species evolution in the United States, Mineau and Whiteside (2013) concluded that the best predictor of grassland population declines was the use of lethally toxic insecticides, together with the loss of cropped pasture. Raptors can also be affected by pesticides, by either direct poisoning or through consumption of contaminated prey (ibid.).

[6] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_281 , last consulted on May 5th, 2023

Very recently, Rigal *et al.* (2023) investigated the direct relationships between population time-series of 170 common bird species, monitored in 28 European countries over 37 years, and four widespread anthropogenic pressures: agricultural intensification, change in forest cover, urbanisation and temperature change. They quantified the influence of each pressure and found out that agricultural intensification, in particular the use of pesticides and fertilizers, was the main pressure for most of the bird population decline (Rigal *et al.*, 2023).

2.1.2.3. Other groups

The use of pesticides, together with the use of fertilisers, are reported to have a considerable impact on many habitats and species. According to the 2020 report from the European Environment Agency (EEA): "*this holds especially true for plant protection chemicals and their effects on amphibians, insects, birds, mammals (bats for example, and also the European Ground Squirrel (Spermophilus citellus) or the European Hamster (Cricetus cricetus))*" (EEA, 2020).

The effects of pesticides on the decline of amphibians, who are one of the most affected taxa by diversity loss worldwide, are difficult to establish, mainly of many confusion factors (Leenhardt *et al.*, 2022.).

For other taxa, knowledge is scarcer on the impact of pesticides. This is particularly true for higher plants, lichens, microalgae, although some effects of herbicides have been demonstrated.

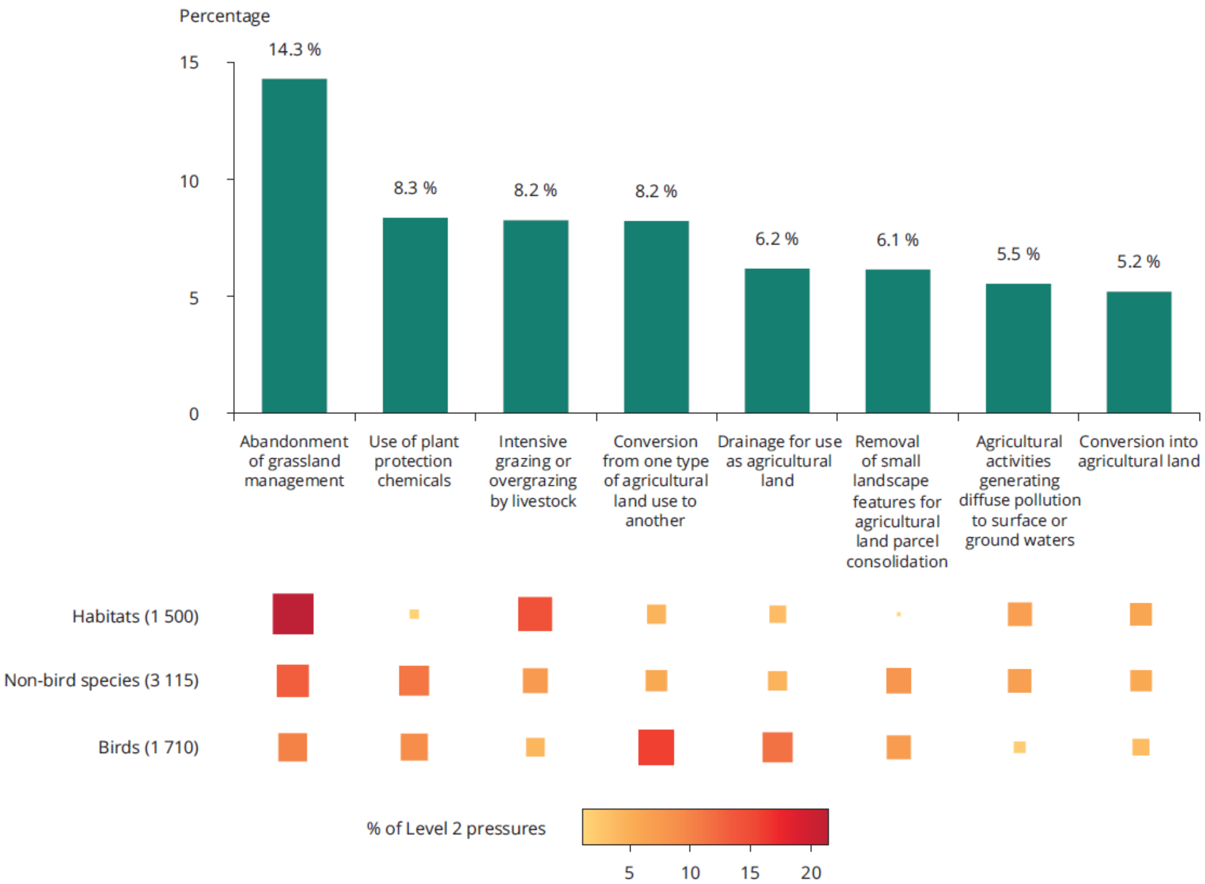
This is also true for microbial communities, which can be affected by herbicides, copper and more generally fungicides (ibid.). For example, pesticides and herbicides affect specific bacteria engaged in nitrification and denitrification microbial processes (Gigliotti and Allievi, 2001; Kinney *et al.*, 2005; Lang and Cai, 2009). The usage of herbicides slaughter or block the action of specific fungi species (Chen *et al.*, 2001; Harding and Raizada, 2015).

Contamination of soils is causing damage to its microflora and microfauna. Indeed, Geissen *et al.* (2021) quote scientific studies highlighting effects of pesticides and cocktails of pesticides on soil organisms, such as DNA damage and changes in the enzymatic activities of earthworms, and modification of the soil microorganisms balance, towards increased presence of pathogenic microorganisms and decrease of beneficial communities (Geissen *et al.*, 2021). Interestingly, in certain cases the effects of pesticides soil contamination on soil microorganisms can be positive, some microorganisms being able to degrade pesticides substances and use them as a source of energy (Karpouzas *et al.,* 2022).

The impact of pesticide soil contamination on soil microbiota can affect soil fertility for example by impairing the symbiotic nitrogen fixation (Sharma *et al.*, 2019).

Agricultural practices are by far the most dominant driver affecting habitats and species according to the EEA report on the State of Nature in the EU (EEA, 2020). Within agricultural practices, the use of chemical pesticides is the second most important pressure for habitats and species among the agricultural practices, as shown in the Figure 2-3, sourced from the EEA 2020 report.

Figure 2-3: Distribution of the eight most relevant agricultural pressures for habitats and species, shown as the percentage of agricultural practices pressure (Source: EEA, 2020)



Notes: The size of the squares and their shade reflect the percentage of pressures for each group: bigger darker squares indicate higher percentages. Total number of reports is given in parentheses.

Source: Article 12 and Article 17 Member States' reports and assessments.

2.1.2.4. Effects of mixtures of pesticide substances on biodiversity

As shown in 2.1.1, pesticides are present in the environment, most of the time in concomitance with other pesticides substances. This raises the question of the impact of mixtures of pesticides on biodiversity. Although each combination is unique and can elicit unique effects on ecosystems, scientific evidence accumulates on the effects of pesticides in vitro and in vivo (Rizzati *et al.*, 2016).

These effects can be cumulative – as demonstrated by Dupraz *et al.* (2019) on microalgae and the mixture of Diuron and Isoproturon. Pesticides mixtures can also have synergistic effects – as demonstrated on earthworms by Yang *et al.* (2017) with the mixture of four pesticide substances (chlorpyrifos, clothianidin, fenobucarb, and acetolachlor).

Studies also demonstrated cumulative or synergistic effects of various pesticide mixtures (such as insecticides and fungicides, herbicides and fungicides), on the hormonal system of red avadavat birds (Pandey *et al.*, 2017), on honeybees survival and behaviour (Tosi *et al.*, 2019), on fish species impairing their metabolism and neuronal function (Gandar *et al.*, 2017; Laetz *et al.*, 2009), and on molluscs blood cells (Moore *et al.*, 2018).

2.1.3. Effects of pesticides on human health

2.1.3.1. Human exposure to pesticides

Humans are exposed to pesticides through skin (dermal absorption), respiratory (inhalation) and oral (ingestion of drinks and food) routes. Pesticides can also reach the foetus leading to in utero exposure during pregnancy.

Human exposure to pesticides affects primarily the agricultural users of pesticides, mainly farmers and agricultural workers, but also industry workers in the pesticides manufacture or storage facilities (occupational exposure). It can occur during handling, dilution, mixing, application and disposal of pesticides, and also during cleaning operations. In the case of occupational exposure pesticides reach workers firstly through dermal and inhalation routes (ILO, 2021).

The French Agency for Food, Environmental and Occupational Health & Safety ANSES estimated that in 2010 in France, more than one million professionals in the agricultural sector were potentially exposed to pesticides (ANSES, 2016). In France, several occupational diseases are officially recognised as directly linked to pesticides exposure[7].

Pesticide exposure also reaches the general population, through the contamination of the environment near the treated zones, through food and drink consumption and their pesticide residues, and through domestic uses such as private gardens (although the use of pesticides by private individuals has been banned in some European countries).

Measurements of pesticides in biological matrices such as hair, urine, blood, provide evidence of exposure to pesticides and their degradation products, although they cannot be interpreted in terms of toxicity nor health impact. The European Human Biomonitoring Initiative (HBM4EU) is a joint effort of 30 countries, the European Environment Agency and the European Commission, co-funded under Horizon 2020 between 2017 and 2021, to generate evidence of the actual exposure of citizens to chemicals and their possible effects on human health[8]. HBM4EU worked on several contaminants including pesticides, for the latter focusing primarily on the following substances: selected members of the pyrethroid family, three organophosphates (chlorpyrifos, dimethoate and glyphosate) as well as the phenylpyrazole fipronil. Biomarkers for chlorpyrifos (TCPy), and pyrethroids (3-PBA, 4-F-3-PBA, cis-DBCA, cis-DCCA, trans-DCCA, CIF3CA) were analysed through urine samples in children and in adults from various European countries. The results showed a widespread exposure to pyrethroids and chlorpyrifos, with detection rates > 90% for TCPy and 3-PBA in most data collections, but with marked differences in exposure levels between the countries, and concentrations higher in children than in adults. Glyphosate/AMPA analysis showed a widespread low exposure with median values of urinary concentrations below the limit of quantification in most cases (HBM4EU, 2022).

To gather data on concomitant exposure to several pesticide substances, a dedicated study was conducted in five European countries among parent-child pairs of people living in agricultural and peri-urban areas. It showed that 84% of the urine samples contained at least two different pesticides ; also, the median number of pesticides found in urine samples was three, with a maximum of 13 pesticides detected (Ottenbros *et al.*, 2023). This confirmed other studies, which have found presence of complex cocktails of pesticides in meconium, hair and urine samples (INSERM, 2022).

Pesticides that have been banned several years ago – for safety reasons - are still found in biological matrices, due to their persistence in the environment and therefore long term exposure to these substances. For example, chlordecone is still detected and quantified in blood samples of people from

[7] https://www.inrs.fr/publications/bdd/mp.html, last consulted on 2023, May 5th

[8] https://www.hbm4eu.eu/about-us/about-hbm4eu/, last consulted on May 3rd, 2023

the French Carribean, although the substance has been banned since 1993 in the area. According to a very recent study from ANSES, Chlordecone is detected in 90% of blood samples analysed in Guadeloupe and Martinique; 14% of the adult population in Guadeloupe and 25% in Martinique exceed the TRV (chronic internal toxicity reference value) for chlordecone, and are considered at risk of overexposure to the substance (ANSES, 2022).

2.1.3.2. What do we know about the effects of exposure to pesticides on human health?

Effects of pesticides on human health can result from acute or chronic exposure.

Cases of human health issues related to the use of chemical pesticides can be tracked back in the end of the 19th century, as described by Jas (2007). Indeed, at that time, hygienists described acute poisoning with arsenical compounds, used as insecticides, after consumption of products produced with the use of these pesticides (vine, beer, etc.).

The knowledge about the health effects of pesticides have developed over the 20th century, thanks to progresses in toxicological research. Since the 90's, the European harmonized process for the registration of active substances and for the member states approvals of pesticide formulations is designed to reject pesticides posing a risk to human health, based on safety assessments conducted by food safety bodies (EFSA, 2021). Required protocols for toxicological studies have also been harmonised within OECD countries[9] (OECD, 2019). Numerous data must be produced regarding the toxicological effects – acute or chronic –of active substances marketed in Europe. These include data on genotoxicity, reproduction, skin irritation, neurotoxicity, fate and behaviour, ecotoxicology, etc. These standardised processes also show their limits, as highlighted by several authors (Robinson *et al.*, 2020; Rani *et al.*, 2021; Leenhardt *et al.*, 2022). These authors call for more regular updates of the guidelines and protocols, aligned with new scientific developments, new analytical methods and tools for characterising dangers and risks (*i.e.*, endocrine disruptive properties).

In addition to toxicological studies, since the 80's, epidemiological data have emerged on the association between exposure to pesticides and several health outcomes (INSERM, 2022). Contrary to toxicological data that are produced in laboratories, *in vitro* or *in vivo* on animals, epidemiological data are based on observations in human populations, using statistical tools to identify risks associated with exposure to pesticides. INSERM, the French National Institute for Health and Medical Research, conducted in 2013 – and updated in 2021 – a collective expert review on the effect of pesticides on human health, at the request of five Directorates General of the French government. For the 2021 report, the expert group compiled over 5 300 documents and updated its 2013 assessment on the level of evidence of the links between exposure to pesticides and several health issues. They analysed the outcomes of epidemiological studies – cohort, cross-sectional, original research, meta-analysis – to identify risk factors. They completed these by looking at data from toxicological studies to identify modes of action of pesticides active substances, supporting the biological plausibility of the observed links (INSERM, 2022).

In adults, the report confirms the 2013 conclusion of a strong presumed link between occupational exposure to pesticides and four diseases:

- Non-Hodgkin lymphomas (NHLs);
- Multiple myeloma;
- Prostate cancer;
- Parkinson's disease.

[9] https://www.efsa.europa.eu/en/topics/topic/pesticides#related-topics, last consulted in April 2023

It adds two new strong presumed links: cognitive disorders and chronic obstructive pulmonary disease / chronic bronchitis.

The report concludes on a moderate presumed link between exposure to pesticides, mainly in an occupational context, and Alzheimer's disease, anxiety, depression, certain cancers (central nervous system, bladder, kidney, leukemia, soft tissue sarcomas), asthma and thyroid diseases (INSERM, 2022).

In children, the report specifies the links between leukemia and mother's exposure to pesticides during pregnancy: strong presumed link between acute leukemia and domestic uses, and acute myeloid leukemia and occupational exposure. A new link, with moderate presumption, has been found between the risk of acute lymphoblastic leukemia in case of paternal occupational exposure in the preconception period. There is also a confirmed strong presumed link between central nervous system tumors and parents' occupational exposure to pesticides, as well as with domestic exposure to pesticides during pregnancy or childhood (INSERM, 2022).

The Table 2-1 summarizes the main conclusions from the INSERM report.

Table 2-1: List of diseases associated with pesticides exposure, with population exposed to increased risk and level of presumption of a link, according to INSERM collective scientific assessment (Source: INSERM, 2022)

Diseases	Populations exposed to an increased risk	Presumption of a link
Cognitive impairment	Farmers, with or without a history of acute poisoning	++
	General population or local residents of agricultural areas	+
Anxiety and depression	Farmers or applicators	+
Alzheimer's diseases	Occupational users	+
Parkinson's disease	Occupational users	++
	General population or local residents of treated areas	±
Amyotrophic lateral sclerosis	Farmers	±
Children leukemia (acute myeloid leukemia AML)	Children, through maternal occupational exposure during pregnancy	++
Children leukemia (acute lymphoblastic leukemia ALL)	Children, through paternal occupational exposure in the preconception period	+
Children leukemia (both AML and ALL)	Children, through domestic exposure	++
Leukemia	Farmers, applicators, production industry workers	+
Central nervous system tumors in children	Children, through parental occupational exposure during the prenatal period	++
	Children, through domestic exposure	++
Central nervous system tumors (glioma and meningioma)	Agricultural populations	+
Non-Hodgkin lymphoma	Farmers, applicators, production industry workers	++
Multiple myeloma	Farmers, applicators	++
	Livestock farmers	+
Hodgkin lymphoma	Agricultural sector professionals	±
Impaired motor and cognitive abilities in children	Non occupational exposure during pregnancy	+
	Occupational exposure to pesticides	±
Behavioral traits related to autism spectrum disorders	Non occupational exposure during pregnancy	±
Prostate cancer	Farmers, applicators, production industry workers	++

Table 2-1 (continued): List of diseases associated with pesticides exposure, with population exposed to increased risk and level of presumption of a link, according to INSERM collective scientific assessment (Source: INSERM, 2022)

Diseases	Populations exposed to an increased risk	Presumption of a link
Breast cancer	General population exposed to DDT during the prenatal period or before 18 years old	+
Bladder cancer	Occupational users	+
	General population	±
Kidney cancer	Occupational users	+
Soft tissue and visceral sarcomas	Agricultural workers, wood industry workers, gardeners, livestock farmers	+
Respiratory function	Occupational exposure to pesticides	+
	Environmental exposure to pesticides at home	±
Asthma, wheezing	Occupational exposure to pesticides	+
	Environmental exposure to pesticides at home	+
COPD, chronic bronchitis	Occupational exposure to pesticides	++
Thyroid disorders	Occupational exposure to pesticides	+
Endometriosis	General population exposed to organochlorine pesticides	±

(++): strong presumption of the link
(+): moderate presumption of the link
(±): weak presumption of the link

2.1.3.3. Effects of mixtures of pesticides on human health

The scientific literature is accumulating on the effects of mixtures of pesticides on human health. In a review, Rizzati *et al.* (2016) provided an update of the current knowledge on pesticide cocktail effects. They showed that 47% of the compiled studies in the review reported an additive effect of pesticides, pesticides interacting in various ways but mainly through to synergic effects. They also highlighted that mixture effects vary according to the dose and/or physiological target.

Beyond mixtures of pesticides, humans are exposed to mixtures of chemical compounds in their daily lives, whose safety is still assessed in isolation. Since 2019, the European Food Safety Authority (EFSA) has developed a harmonised framework to use across its scientific panels when evaluating the potential "combined effects" of chemical mixtures in food and feed[10]. The approach gives EFSA's scientists the tools to follow a mixtures approach when needed, which complements the current EU regulatory requirements for assessing single substances, although it only applies to exposure through food and feed.

2.1.4. Societal costs of pesticides

The management of the consequences of the effects of pesticides on human health and on the environment comes with costs. Several studies have tried to estimate these, based on available data, especially Bourguet and Guillemaud (2016) who did a review of studies on that topic, and more recently Alliot *et al.* (2022) estimating the social costs of pesticides use in France.

[10] https://www.efsa.europa.eu/en/press/news/190325, last consulted on May 5th, 2023

Societal costs can generally be divided into several categories. There are regulatory costs, for example the costs linked to the assessment of active substances by authorities, the costs linked to the reduction of the risks linked to the use of pesticides through member states National Action Plans. There are also environmental costs, such as those linked to the "*de-pollution*" of water contamination for drinking water, the costs linked to the biodiversity losses linked to pesticides use, etc. Public health costs are public expenditures linked to the treatment of diseases due to acute and/or chronic exposure to pesticides among farmers and the general population. Authors also include "*defensive expenditures*", that are costs associated with protection against the effects of pesticides such as buying protective equipment or pesticide-free products, and "*public financing support to pesticide manufacturing and use*" that are public subsidies provided to facilitate the use of pesticides (reduced VAT, public subsidies, etc.).

Authors acknowledge the difficulties in assessing the real costs associated with pesticides use, and point out the under-estimation of these in the majority of studies. For some costs, data are missing to estimate the costs (for example on the budget dedicated to public research on the health and environmental effects of pesticides). Also, for some effects, it is not possible to estimate the attribution factor of pesticides in comparison with other sources of contamination (for example on the attribution factor of pesticides in the public expenditures related to biodiversity protection, or to chronic diseases, that are multifactorial).

Overall, the costs estimates range from 5.4 million USD (Niger, in 2013) to 13.6 billion USD (USA, in 2012), and may have even reached up to 39.5 billion USD at the beginning of the 90's in the USA. For European countries, the estimated costs range from 195.56 million USD in Germany (1996) to 383.55 million USD in 1996 in the UK (Bourguet and Guillemaud, 2016). The latest study from Alliot *et al.* estimated social costs of pesticides use at 372 million euros in 2017 in France, accounting for more than 10% of the ministry of agriculture budget (Alliot *et al.*, 2022).

Bourguet and Guillemaud also looked at the benefit-cost ratio of pesticide use (calculated as the difference between the agriculture production gains with pesticides and the costs linked to their use). They concluded that the *"costs of pesticide use might have outreached its benefits in the past"* pointing out the lack of estimation of the cost impact of diseases linked to chronic exposure.

2.1.5. The impacts of pesticides on the environment and on human health trigger mobilisation of the civil society

The increased knowledge about the effects of pesticides on the environment and human health raised concerns within the population, and the other way around: people awareness about the effects of pesticides triggered the development of scientific knowledge, especially on famous topics such as bees health (Fortier *et al.*, 2020).

One of the first contribution to this rising awareness on the impacts of pesticides was the publication of Rachel Carson's book Silent Spring in 1962 (Jacquet and Jouan, 2022). In this book, Rachel Carson highlighted the carcinogenic properties of DDT and its impact on bird reproduction. This book received a huge coverage and contributed to the banning of DDT in the 1970s, together with other organochlorine pesticides, whose carcinogenic, mutagenic and reprotoxic effects were gradually demonstrated. Today, most organochlorines are on the list of persistent organic pollutants, defined by the Stockholm Convention of 22 May 2001, which came into force on 17 May 2004, and are therefore banned (Bonnefoy, 2012). To replace organochlorines, new classes of molecules appeared in the 70s, such as organophosphates (like parathion) or carbamates, whose acute toxicity was progressively discovered and cases of poisonings publicised (ibid.).

In the 90's, French beekeepers warned public authorities about alarming signs related to bees health, concomitant with the market introduction and increasing use of neonicotinoids substances –

imidacloprid in particular - for crop protection (sunflower, maize, sugar beet notably). This led to several studies, controversies related to quantification methods, effects at low doses, etc., assessments from food safety authorities, social debates, citizens mobilisations, a first application of the precautionary principle with a ban of imidacloprid in sunflower seed-dressing in 1999, and, 20 years later, a full ban of the three neonicotinoids active substances in Europe in 2018 (Maxim and Van der Sluijs, 2013).

More recently, from 2020 to 2022, cases of food contamination with unauthorised in Europe ethylene oxide led to thousands of products recalls across Europe, and reached the media[11].

Frewer (2017) describes two topics of concern in the societal response to pesticide use. The first relates to the presence of pesticide residues in foods, and consumers perceptions of food safety. The second concerns pesticide contamination of the environment, which may have negative environmental and agronomic impacts (*e.g.*, on biodiversity and on the emergence of pest resistance).

The mobilisation of the civil society to voice its concerns on the impacts of pesticides can take various forms and lead to different actions: campaigns, protests, petitions, production of knowledge, up to legal actions. Several authors have identified an increase in litigation cases, in majority based on the human health effects of pesticides, requesting compensation for the damages caused by pesticides exposure among users (Leenhardt *et al.*, 2022).

These concerns and mobilisations started in the USA from the 60's, and later in European countrie. They were raised within the users of pesticides, agricultural workers and farmers, affected by the consequences of their occupational exposure to pesticides. In France for example, Jouzel (2019) describes mobilisations from the civil society against the effects of pesticides, which started at the end of the 2000's, with non-governmental organisations (NGOs) gathering users of pesticides (farmers, agricultural workers), consumers, and environmentalists. The association "phyto-victimes" was created in 2011, supported by environmental NGO, to gather and help farmers in their request for acknowledgment of their diseases as "occupational diseases" (Jouzel and Prete, 2021).

At territorial or regional level, local residents groups gathered to protest against the use of pesticides near their homes, and public places (*e.g.*, schools). This contributed to political measures from some mayors in several European countries, to restrict or ban the use of pesticides in their towns[12]. In France, this led to the progressive ban of the use of chemical pesticides in urban areas, and in private gardens (so-called "Labbé law"[13]).

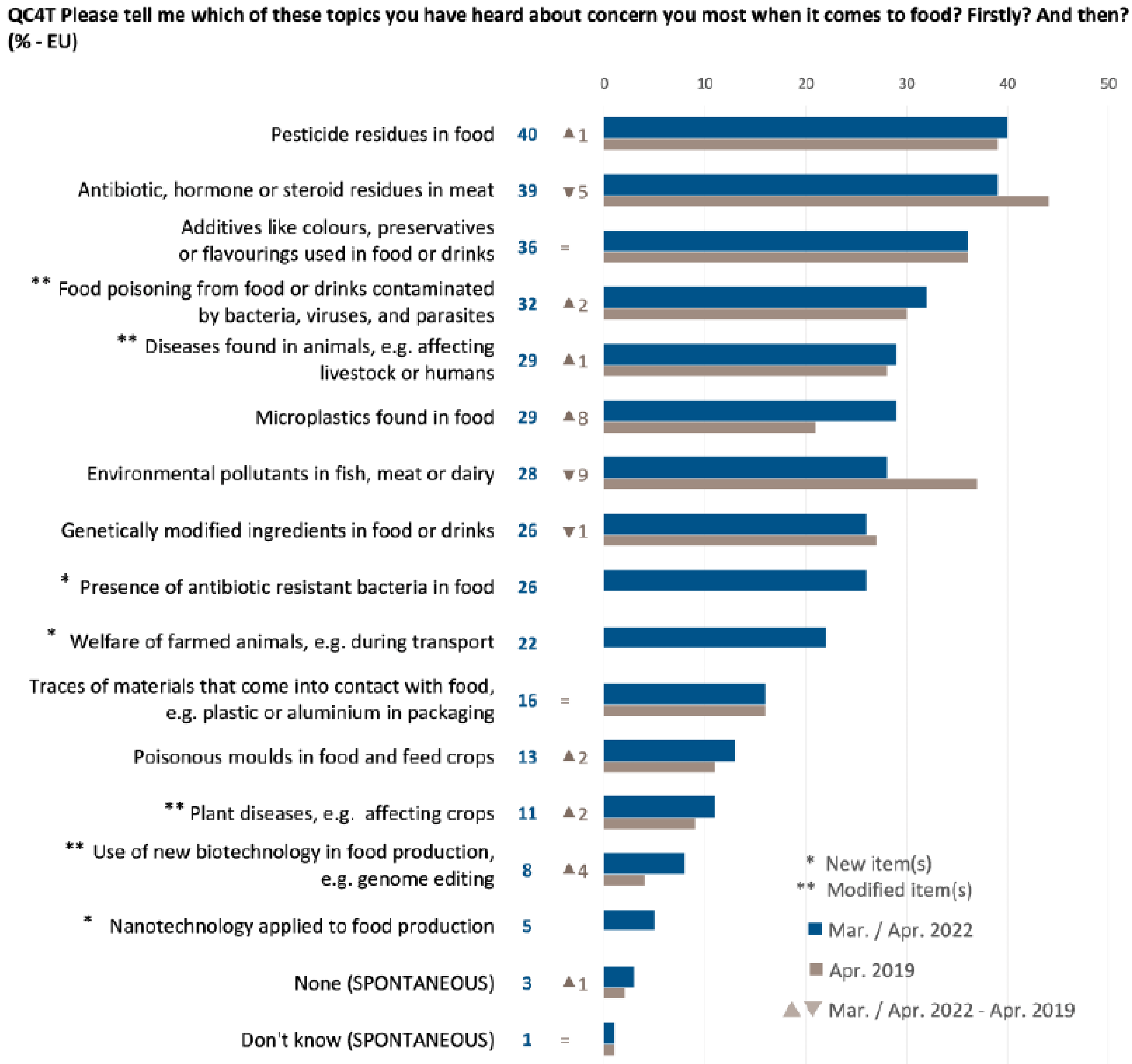
These social movements, together with the development of scientific work on the health and environmental impacts of pesticides, reached various media (newspapers, documentaries, internet webpages, social media), contributing to increased awareness of the population. In 2022, EFSA commissioned a survey - Eurobarometer - to gauge Europeans' perceptions of and attitudes towards food safety. From this survey, overall in Europe, the most important concern in food safety among European is pesticide residues in food (40%) before antibiotic, hormone or steroid residues in meat (39%) and additives used in food or drinks (36%) (Figure 2-4) (EFSA, 2022b).

[11] See for example: https://www.rfi.fr/en/france/20210616-over-7-000-food-products-recalled-in-france-due-to-carcinogens-sesame-health

[12] See for example the networks "pesticide free towns": https://www.pesticide-free-towns.info/policy-strategies

[13] LOI n° 2014-110 du 6 février 2014 visant à mieux encadrer l'utilisation des produits phytosanitaires sur le territoire national.

Figure 2-4: EFSA Eurobarometer "food safety in the EU": most concerning food safety topics among Europeans (Source: EFSA, 2022b)



At European level, two citizens initiatives (ECI – European Citizens Initiative[14])) dealing with pesticides have reached 1 million signatures, in 2017 ("Stop Glyphosate ECI") and in 2022 ("Save Bees and Farmers ECI[15]"). Once this signature threshold is reached, the European Commission must officially consider the petition, and spell out within 6 months what action it will propose in response to the initiative (if any), and its reasons for taking (or not taking) action. The 'Save Bees and Farmers' initiative is supported by a network of over 140 environmental NGOs, farmer and beekeeper organisations, charitable foundations and scientific institutions. It calls for "*a gradual elimination of 80% of the use of synthetic pesticides by 2030 and 100% by 2035*," as well as a restoration of biodiversity on agricultural land and financial support for farmers in the transition to agroecological practices. The European Commission should respond to it by mid-2023. This is the seventh initiative having successfully reached 1 million signatures across Europe since the launch of the ECI system 10 years ago.

[14] https://europa.eu/citizens-initiative/_en, last consulted in May 2023

[15] https://www.savebeesandfarmers.eu/eng/, last consulted in May 2023

Back in 2017, the European Commission answered to the "stop glyphosate ECI" by committing to presenting a legislative proposal in 2018, to further increase the transparency and quality of studies used in the scientific assessment of substances. This legislative proposal related to transparency entered into force on March 2021[16]. It also decided to renew the approval of glyphosate, but to reduce its renewal length, from the standard 15 years to 5 years. Finally, it committed to ensure that Member States comply with their obligations to reduce dependency on pesticides, to establish harmonized risk indicators, and to re-evaluate the need for EU-wide mandatory targets for pesticides use reduction[17].

Conclusion

The knowledge about the contamination of pesticides in various environments, and their impacts on environment, ecosystems and human health have substantially increased since the 2000's. Scientific studies have multiplied, and the level of evidence about the effects of pesticides and their active substances has increased. Several collective scientific assessments have recently reviewed the level of evidence of these topics, based on new scientific data. For example, between the two INSERM collective scientific assessments (2013 and 2021), with eight years of additional scientific data, the review of literature pointed out two additional diseases linked – with a strong presumption - with the exposure to pesticides among farmers (cognitive disorders and chronic bronchitis). Also new in the 2021 conclusion, the number of diseases linked to adult exposure to pesticides (with a moderate presumption) moves from four to nine.

This increased knowledge contributes to nurturing policy makers in the set up and update of policies to reduce the use and impacts of pesticides on environment and health. As a consequence, more and more active substances are withdrawn from the market (see Section 3.2 on public policies for more details). The scientific areas of research continue to develop, with for example investigations on the cocktail effects of these substances, or the conduction of cohort studies on inhabitants, to investigate the link between exposure to pesticides and diseases development.

In the future, we can anticipate that this increasing knowledge will lead to further bans of chemical active substances, limiting the possibilities for farmers to apply crop protection methods relying on chemical pesticides.

This trend goes together with increasing consumers' concerns about pesticides impact on health, lively societal debates around pesticides impacts on the environment and health, inhabitant's mobilisations and citizens' petitions against the impacts of pesticides on the environment and health, and significant societal costs of these impacts. Going one step further than current public policies focusing on reducing the use and risks of chemical pesticides, it calls for a disruptive approach, imagining a potential future where chemical pesticides would not be available anymore for crop protection, and studying what could be, in the future, a chemical pesticide-free agriculture in Europe.

[16] Regulation (EU) 2019/1381 of the European Parliament and of the Council of 20 June 2019 on the transparency and sustainability of the EU risk assessment in the food chain

[17] https://citizens-initiative.europa.eu/initiatives/details/2017/000002/ban-glyphosate-and-protect-people-and-environment-toxic-pesticides_en#:~:text=Answer%20of%20the%20European%20Commission,-Official%20documents%3A&text=Main%20conclusions%20of%20the%20Communication,legislative%20proposal%20to%20that%20effect, last consulted in May 2023

2.2. Analysis of past changes in crop protection strategies in Europe

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Table of contents

Introduction

This section describes the evolution of crop protection in Europe over past decades. First, we will define what crop protection is, based on the concept of pests and describing their impact on crops. Then we will study the evolution in crop protection since 1945, based mainly on the major use of chemical pesticides despite initiatives to limit their usage from the 1990s. Finally, we will examine the crop protection strategies that have been developed with the goal of limiting the use and impact of chemical pesticides.

2.2.1. Definition of crop protection

In order to develop hypotheses of change of crop protection strategies that do not use chemical pesticides in 2050, we studied the main trends and weak signals of the changes in crop protection in Europe since the end of the Second World War.

Crop protection refers to the strategies used to prevent or reduce crop losses caused by pests (Tibi *et al.*, 2022). In order to understand better the challenges of crop protection, we will first define what pests are and describe their impacts. Then we will examine the pest management strategy which is currently the most widely used, a crop protection based on the use of chemical pesticides.

Crop protection strategies are divided into two groups: curative (or control) strategies and preventive (or prophylactic) strategies. The strategy most frequently used today is the management of pest populations through chemical control (*i.e.* using chemical pesticides) (ibid.).

2.2.1.1. What is a pest?

Traditionally, pests are defined in relation to the damage caused to cultivated plants. According to the FAO, a pest is a "*living organism that causes damage to cultivated plants or harvests*" (FranceTerme, 2018). Assessing the damage caused to cultivated plants or harvests is therefore essential to evaluate whether or not a living entity should be considered as a pest.

The term 'pest' is equivalent to the concept of a '**crop enemy**' (FranceTerme, 2018) or '**harmful organism**' (IPPC, 1997). Some international legislation uses the term 'pest', such as European directives and the International Plant Protection Convention (IPPC). These texts define a pest as "*any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products*" (IPPC, 1997).

The damage caused by pests to cultivated plants can be characterised by an alteration in the plant's growth and/or vigour, its morphology or that of its organs (lesions, changes in colour, deformations, necrosis, galls etc.), or its chemical composition (nutrient content, presence of toxins etc.) (Tibi *et al.*, 2022).

The term pests covers different categories of organisms likely to cause damage to cultivated plants: (i) **pathogenic microorganisms** (fungi, bacteria, viruses etc.) causing diseases in cultivated plants, (ii) **animal pests** which include **phytophagous arthropods** (insects and mites) and **other pests** such as nematodes, gastropods, birds, mammals (rodents, moles etc.), and (iii) **weeds** (volunteer plants and crop regrowth) (Tibi *et al.*, 2022). Some pathogens are transmitted to plants via vector organisms (most often insects, but also mites, nematodes, mammals etc.) which are assimilated to pests (ibid.).

So, **the term 'pest' actually reflects a very heterogeneous reality**, which encompasses a wide variety of living organisms with very different characteristics. Life cycles vary from one pest to another (Aubertot *et al.*, 2005a).

The definition of pests comes down to considering an organism as a pest according to the damage it causes to crops. This means the same organism can be considered a pest in certain cases where it would cause damage to a crop, and as a beneficial in other cases where it would be useful to a crop. For example, weeds are considered pests because they compete with cultivated plants, while an abundance of weeds promotes pollination (Bretagnolle and Gaba, 2015). Some weeds can therefore be considered as crop beneficials.

From a conceptual perspective, the term pest implies a particular way of considering the relationship of a cultivated plant with its environment. The term pest draws a distinction in the environment of the cultivated plant between the living entities which are harmful to it and those which are not, or even those which are useful to it. So, a species that is considered a pest from the point of view of the crop and its cropping system can be considered, from another perspective, as an element of plant biodiversity. This is particularly the case for the weed community (Boinot *et al.*, 2023). **The term pest designates a role assigned to certain biological entities in their relationship to a cultivated plant**. This notion of a pest can be questioned. For example, a new framework considers disease as a process related to plant health and no longer as a strict host-pathogen interaction (Méthot and Alizon, 2014).

2.2.1.2. How do we assess the impact of pests?

The impact of pests on cultivated plants is evaluated through a chain of causality which links the presence (abundance) of pests to the occurrence of damage, to the level of damage and ultimately to the level of the associated economic losses (Tibi *et al.*, 2022; Aubertot *et al.*, 2005a).

Estimating impacts involves monitoring the risks associated with pests in general. Some specific pests are monitored internationally.

Concepts of damage, harm and loss related to pest presence

Pests cause damage to cultivated plants in different ways, affecting different organs and different growth stages. Pathogens and animal pests can cause metabolic or mechanical changes while weeds compete for resources (Tibi *et al.*, 2022). However, the presence of a pest in a plot is not systematically linked to an economic loss for the farmer. A pest can induce an injury or cause damage without causing economic losses (Figure 2-5).

An **injury** is defined as "*a **visible or measurable alteration** compared to a healthy plant (symptom) caused by the presence of a pest on a crop (deformations, necroses, bites, visual defects on fruit etc.)*" (Laget *et al.*, 2015). The relationship between pest abundance and injuries is not proportional and, notably, there are threshold effects for some pests (Tibi *et al.*, 2022).

Injuries can lead to **damage** at harvest time, *i.e.* the "*reduction of yield in quantity and/or quality. This term [damage] is synonymous with **loss of marketable yield** and/or loss of yield in processed products*" (Laget *et al.*, 2015). The relationship between injury and damage is generally not proportional, and depends on the development of the crop's yield and the relationship between injury and damage, which is specific to each plant/pest coupling. So, not all injuries necessarily result in damage (for example, when the injury does not concern a harvested organ). In addition, crop yield and quality are composite variables that result from a set of interacting factors including meeting the crop's nutrient and water needs, making it difficult to identify and quantify yield losses due purely to pests (Tibi *et al.*, 2022).

Damage can lead to an **economic loss**, *i.e.* "*the **reduction in the market value of the harvest** (and therefore in turnover per hectare) caused by the damage (lower yield and/or reduced production quality) due to the attack of pests*" (Laget *et al.*, 2015). The link between damage and economic loss depends on the socio-economic context. For example, in organic farming, certain quality defects, linked to the presence of a pest, do not necessarily lead to economic losses because they are tolerated on the market. This is not the case in conventional farming or under similar conditions when the value of products is seriously reduced (ibid.). Therefore it is possible to limit economic losses while tolerating injury and damage.

Figure 2-5 below presents the relationship between injury, damage and economic loss.

Figure 2-5: Relationship between pest presence, injury, damage and loss. Source: Aubertot *et al.* (2005a)

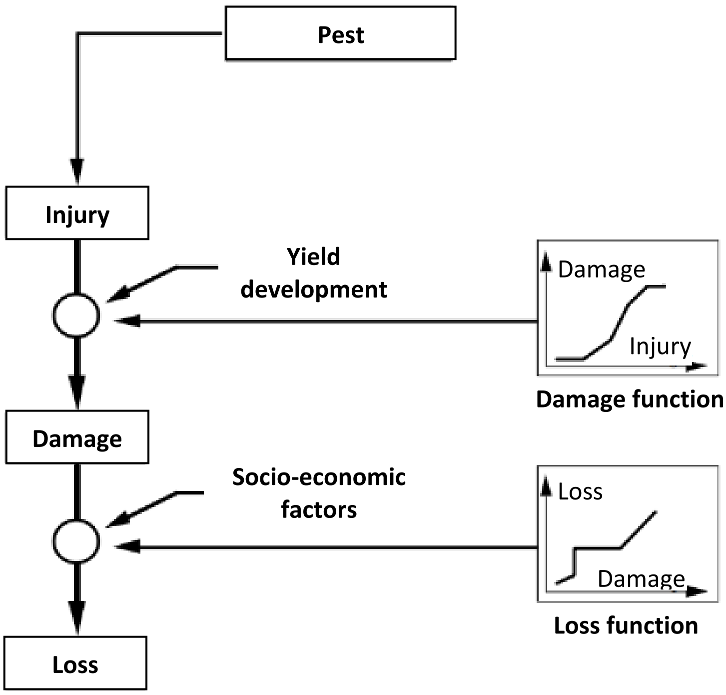


Table 2-2, adapted from Tibi *et al.* (2022), presents the different types of injury and damage caused by different types of pests.

Economic losses caused by pests can be significant. Massive pest attacks have marked the history of European agriculture and caused significant crop losses. For example, between 1845 and 1848, the introduction of the fungus *Phytophthora infestans* (potato blight) in Ireland destroyed European potato crops and led to a major famine (Jacquet and Jouan, 2022a; Russel, 2005). Similarly, at the end of the 19th century, an aphid called phylloxera was imported from the United States and led to the destruction of a large proportion of France's vineyards in just a few years (Jacquet and Jouan, 2022a).

More recently, Oerke (2006) has established that the potential economic losses due to pests (without crop protection) can average 50% to 80% depending on the crop worldwide. However, potential losses are produced by comparing plots with and without pesticides, all other things being equal, *i.e.* without any other adaptations of the cropping system when pesticides are not applied. Estimated losses are therefore most certainly overestimates and should instead be regarded as maximum theoretical values (Tibi *et al.*, 2022).

Table 2-2: Injury and damage related to different types of pests
(Source: adapted from Tibi *et al.,* 2022)

Type of pest	**Injury** (observable symptoms)	**Potential damage** (crop losses)
Pathogens and animal pests	Metabolic or mechanical alterations inducing: - Root development, germination and first growth stage hindered - Partial or total interruption of the absorption and/or translocation of water and nutrients - Damage to plant's vital parts: storage organs, photosynthetic surfaces, reproductive organs and support structures → Alterations to growth/vigour of cultivated plants, changes in morphology (lesions, colour modifications, deformations, necroses, galls etc.), changes in chemical composition (protein and sugar content, presence of toxins etc.) and of organs	Lack of growth in cultivated plants and/or deterioration of organs making crops more difficult to harvest → Yield losses Downgrading of harvested products due to organoleptic or health criteria not being met → Quality loss
Weeds (regrowth and volunteers)	Competition with cultivated plants for resources (light, water and nutrients) → Alterations to growth of cultivated plants	Reduced growth of cultivated plants → Yield loss Contamination of the harvest linked to the presence of weed seeds harvested at the same time as cultivated plants → Quality loss
Parasitic plants (which live at the expense of host plants)	Partial or total diversion of water and/or nutrients absorbed by cultivated plants → Altered growth/vigour in cultivated plants	Reduced growth of cultivated plants → Yield loss

The concept of phytosanitary risk at the European scale

The impact of pests on crops is linked to the concept of risk. Risk depends on the presence of the pest and the context of the crop (thematic workshop, November 2020). At the national and international scales, the concept of risk is linked to socio-economic issues, which lead to actions to avoid economic losses.

The International Plant Protection Convention (IPPC) and European Directive 2000/29/EC require each Member State to set up an official national plant protection organisation (NPPO). Among other things, they must conduct **pest risk analyses**, which are defined by the IPPC as a "*process of evaluating biological or other scientific and economic evidence to determine whether a pest should be regulated and the strength of any phytosanitary measures to be taken against it*". The main criteria for determining whether an organism should be regulated are the likelihood of entry, establishment and spread, and the possible or actual economic consequences. Directive 2000/29/EC also requires the listing of harmful organisms within the EU.

Some pests are subject to special monitoring internationally

Faced with significant economic risks, some pests receive special monitoring and regulation within the IPPC and are subject to official control. These are '**regulated pests**' divided into 'quarantine pests' (which are not yet present or disseminated in the threatened area and present an important economic issue and are the subject of official control) and 'non-quarantine regulated pests' (which are already present with unacceptable economic impacts) (IPPC, 1997).

At the European Union level, the same distinction between quarantine pests and regulated non-quarantine pests can be found in Regulation 2016/2031 of the European Parliament and the Council on protective measures for pests. Here we find the concepts of 'unacceptable economic impact', but also 'environmental or social impact'.

Official national plant protection organisations control imports of plants into their national territories in order to prevent the introduction and spread of these harmful pests (MAAF, 2015). They also issue European plant passports, authorising the movement of plants within the European Union (EU Regulation 2016/2031).

2.2.1.3. Managing the impact of pests: crop protection

What is crop protection?

In order to reduce the impacts of pests on crops and subsequent economic losses, farmers have developed different strategies that are grouped together under the term crop protection. Crop protection refers to the strategies introduced to prevent or reduce crop losses caused by pests (Tibi *et al.*, 2022). These strategies are divided into curative (or control) and preventive strategies.

Before the development of chemical pesticides, preventive strategies were the main type of measure used by farmers. Before 1940, cultural and mechanical practices made it possible to manage pests through the diversification of crops (Tibi *et al.*, 2022), manual weeding and ploughing (Buckwell *et al.*, 2020a; Jacquet and Jouan, 2022a), and the use of resistant varieties (Jacquet and Jouan, 2022a). After the Second World War, research on chemical weapons and advances in the chemical industry led to the discovery of new organic compounds that could be used directly in agriculture to control pets (Bonnefoy, 2012; Russel, 2005). Chemical pesticides became key elements in cropping systems, protecting crops from the risks related to pests (Bonnefoy, 2012).

There are three main types of pesticides corresponding to the different categories of pests: fungicides which target pathogenic fungi, insecticides which target insect pests, and herbicides which target weeds (Jacquet and Jouan, 2022a). There are also other types of pesticide: bactericides, acaricides, molluscicides, rodenticides and nematicides (ibid.).

Currently, the crop protection strategy most frequently used is the control of pest populations through chemical measures (*i.e.* using chemical pesticides). For this, crop protection is based on monitoring pests and the risks associated with their presence, triggering the implementation by farmers of curative actions to protect crops (Narenjo, 2001). Pest presence is monitored nationally and regionally to help farmers determine when it is necessary to intervene to limit risk and protect crops (Barzman *et al.*, 2015).

Pest epidemiological surveillance at the national and regional scales

At the European scale, each country's National Plant Protection Organisation (NPPO) must establish a **national monitoring system**, in the form of a programme that includes monitoring protocols (IPPC Secretariat, 2020). Several epidemiological surveillance networks exist in Europe (the international EuroBlight network and various national and regional epidemiological surveillance networks linked to platforms, decision support tools and weekly bulletins) (Barzman *et al.*, 2015).

For example, France monitors 1,500 agricultural plots as part of an observation network (MAAF, 2015). Observers measure the level of presence of a set of pests that has been predefined in advance, recording their presence, phenological stage and the damage they cause (ibid.). These observations can be supplemented w biological modelling, meteorological observations and laboratory analyses. The field data is then analysed and publicly disseminated by various actors in the form of a **plant health bulletin** (known in French as BSV) (ibid.). These plant health bulletins provide information to farmers, such as crop health status and pest risk assessment, including risk thresholds (MASA, 2016; Xicluna 2016).

In the field, various **decision support systems** (DSS) make it possible to assess the risk associated with pest presence and to make recommendations on the measures to be used (Jørgensen *et al.*, 2014).

Risk indicators for farmers: Damage thresholds and economic intervention thresholds

Once pest presence of has been observed, the potential impact on crops is assessed through **damage and treatment thresholds**. Laget *et al.* (2015) define the **damage threshold** as "*the population/ inoculum density or level of infestation/infection from which a reduction in yield or quality is statistically detectable*", and the **economic intervention threshold** as the "*population/inoculum density or level of infestation/infection from which the effect on the reduction in yield or quality is greater than the cost of the means used to combat the pest*".

Farmers' use of risk indicators for crop protection based on chemical pesticides

Damage and economic intervention thresholds give indications to farmers to trigger a curative intervention, mainly by means of chemical control (Laget *et al.*, 2015; Ramsden *et al.*, 2017).

In Europe, Directive 2009/128/EC encourages the use of these thresholds for managing chemical treatments: "*Based on the results of the monitoring the professional user has to decide whether and when to apply plant protection measures. Robust and scientifically sound threshold values are essential components for decision making*." However, in practice, an alert that a threshold has been exceeded almost automatically triggers the treatment of cultivated plants with chemical pesticides (thematic workshop, November 2020).

In addition, we observe that many treatments are applied as a kind of insurance, before thresholds are exceeded (Ramsden *et al.*, 2017; Reisig *et al.*, 2012). This is linked to not only the low cost of pesticides but also to thresholds that are not adapted to the specificities of the cropping system in question and local cropping practices (Ramsden *et al.*, 2017).

Crop protection based solely on the use of chemical pesticides?

Currently, crop protection is based mainly on the use of chemical pesticides which effectively reduce the presence of pests (Jacquet and Jouan, 2022b).

Nevertheless, crop protection does not only comprise of eliminating or reducing pest populations because the primary objective of crop protection is to reduce crop losses due to pests (Aubertot *et al.*, 2005a). Other approaches can be implemented such as avoidance or mitigation strategies (Laget *et al.*, 2015). Crop protection can also include many preventive or prophylactic actions (ibid.). These actions make it possible to manage pests by controlling their population in a preventive manner or by increasing the resilience of cultivated plants to pest attacks (ibid.).

2.2.2. The past evolution of crop protection in Europe

2.2.2.1. The development of crop protection centred on pesticides

The central role of pesticides for the development of productive agricultural production systems in the post-war period

While the use of insecticides or fungicides derived from minerals or plant extracts has existed for a long time, the development of synthetic pesticides and their mass use began after the Second World War (Oerke, 2006; Schiffes, 2012). After the Second World War, European States sought to increase their domestic agricultural production to ensure food security for their populations (Jacquet and Jouan, 2022a; Zobbe, 2001). In Europe, the implementation of the Common Agricultural Policy (CAP) in 1962 made a major contribution to the increase in agricultural productivity and production (Zobbe, 2001). Pesticides, though, have been a key element in agricultural intensification, in particular because they make it possible to control production risks (Bonnefoy, 2012).

In general, several factors jointly contributed to agricultural intensification: genetic selection geared towards high-yielding varieties, the use of nitrogen inputs and pesticides, and mechanisation (Jacquet and Jouan, 2022a; Buckwell *et al.*, 2020a).

After the Second World War, public and private research also conducted a lot of work on the biological functioning of pests in order to produce new effective molecules to combat pests and develop crop defence strategies (Buckwell *et al.*, 2020a).

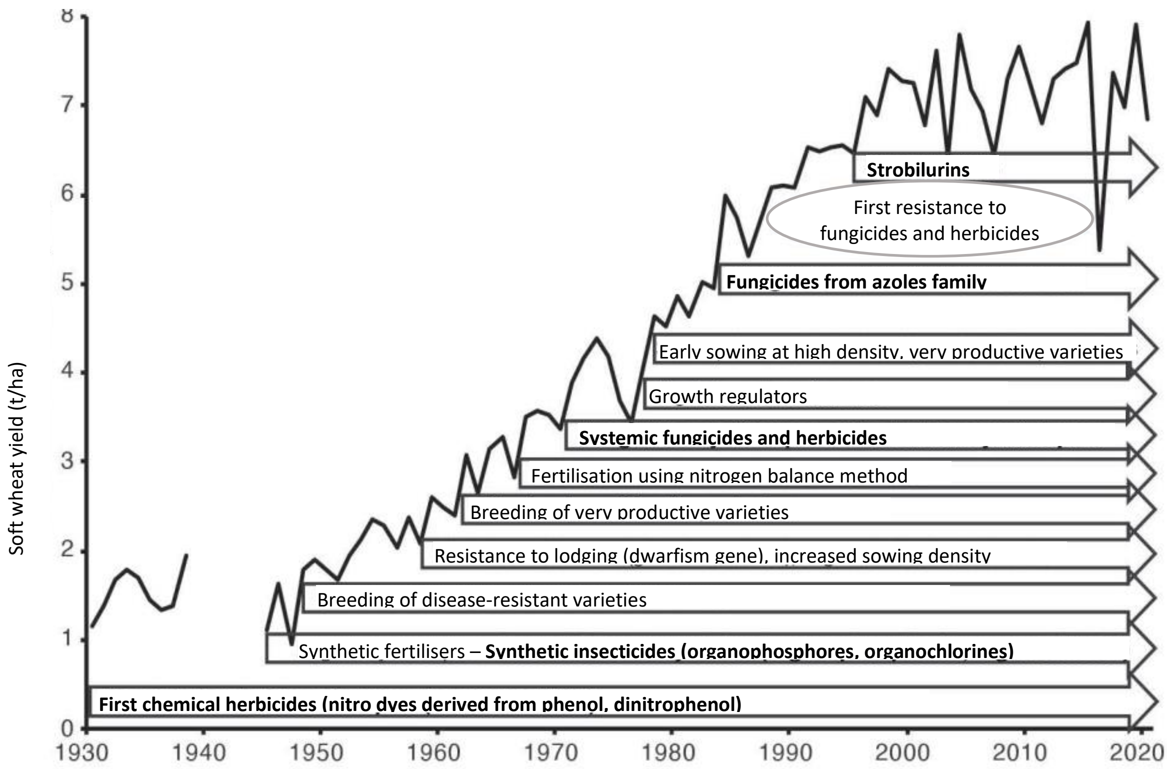
A search for productivity leading to technical itineraries dependent on synthetic pesticides

After the Second World War, plant breeding programmes focused on modern varieties with high yield potentials (Lamine *et al.*, 2010a; Bonnin *et al.*, 2014). These pure lines were highly homogeneous and sensitive to pest attacks. However, they made it possible to achieve high yields under optimal conditions achieved using inputs (fertilisers, water and pesticides) (ibid.). Many intensification practices were adopted, providing an increase in yields but weakening the crops. For example, in cereal crops, early sowing made it possible to lengthen the crop cycle but increased the risk of weed emergence. High seeding density made it possible to increase leaf area but increased the disease risk. Furthermore, the intensive use of mineral fertilisation ensured high yields but increased disease risk (Meynard and Girardin, 1991). These intensification practices would not have been possible without the extensive use of chemical pesticides, which became the cornerstone of these cropping systems (ibid.). The implementation of these practices was made easier by mechanisation, which facilitated input use (pesticides and fertilisers) and increased agricultural productivity (Jacquet and Jouan 2022a; Jeanneaux, 2018). Public policies, particularly the CAP and its price support and guaranteed outlets, supported the intensification of agricultural production (Jacquet and Jouan, 2022a).

The same problem is found in perennial crops. In arboriculture, the search for productivity led to the adoption of practices that made crops more sensitive to pests, such as the specialisation of production areas, high planting densities, high fertilisation and irrigation levels, and the use of high-potential varieties which are productive but offer little resistance (Plénet *et al.*, 2010). Perennial crops are particularly vulnerable because they are grown for many years and are concentrated in monoculture production areas that offer very stable conditions for pests, including diseases (Aubertot *et al.*, 2005b). In addition, a number of mechanical control options are not possible in perennial crops. For example, the crop cannot be destroyed every year through rotation and pests can settle in plots permanently (Alonson Uglaglia, 2011). This induces high pesticide consumption in perennial cropping systems (Aubertot *et al.*, 2005b).

The link between pesticide use, various technical developments and yield increases can be illustrated through the example of the evolution of soft wheat yields in France (Figure 2-6). We can observe that an eightfold increase in wheat yield in France between 1950 and 2020 is positively correlated with the use of new families of pesticides, synthetic fertilisers and productive varieties.

Figure 2-6: The link between the evolution of soft wheat yield in France and various technical innovations including the development of pesticides (in bold) (Source: Jacquet and Jouan, 2022a)



Simplification of agricultural landscapes

The intensification of agriculture in Europe was also accompanied by a specialisation and simplification of cropping systems (Hansen, 2020, Schott *et al.*, 2010) and a simplification of landscapes (Jongman, 2002; Tscharntke *et al.*, 2005), two factors making cropping systems fragile and dependent on pesticides. Indeed, pests develop all the more when they encounter continuous favourable conditions over time and space, which is what simplified agricultural systems offer them (Aubertot *et al.*, 2005b).

Cropping systems have become more specialised, leading to a reduction in mixed crop-livestock systems, in favour of intensive livestock systems concentrated in certain regions, and the ‘cerealisation’ of those regions most favourable to arable crops (Roguet *et al.*, 2015; Schott *et al.*, 2010; Schott *et al.*, 2018, Eurostat, 2022). This has contributed to a reduction in the area of permanent grassland (Schott *et al.*, 2018), considered as semi-natural habitats favouring the presence of natural enemies of pests (Bianchi *et al.*, 2006). Intra- and inter-specific crop diversity has decreased and crop successions have been shortened, making cropping systems sensitive to pests (Bonnin *et al.*, 2014; Schott *et al.*, 2010).

This specialisation and simplification of cropping systems led to a homogenisation and fragmentation of landscapes, including the expansion of agricultural plots and a sharp reduction in semi-natural habitats (Jongman, 2002; Tscharntke *et al.*, 2005). This creates conditions favourable to the presence of pests and unfavourable to their natural enemies (Bianchi *et al.*, 2006; Chaplin-Kramer *et al.*, 2011; Rusch *et al.*, 2016; Grilli, 2010).

All these elements made it possible to increase agricultural productivity and production but also contributed to making cropping systems sensitive to pests and dependent on chemical pesticides.

Massive use of pesticides leading to resistance problems

The intensive and large-scale use of pesticides gradually led to increasingly serious pest resistance problems. From the 1970s, pest resistance was seen as a threat to agricultural production (Russel, 2005), especially since resistance can appear and spread rapidly in just a few years (Aubertot *et al.*, 2005b). Farmers therefore found themselves in a kind of 'arms race', using new families of pesticides available on the market to counter resistance problems (Jacquet and Jouan, 2022a).

The transformation of cropping systems in Eastern Europe

The evolution of European agricultural production systems described above is mainly based on a bibliography centred on North-Western Europe. According to Jepsen *et al.* (2015) the process of agricultural intensification, the expansion of farms and fields and the use of many inputs and mechanisation is also found in Southern Europe and Eastern Europe between the 1950s and 1990s. Nevertheless, within Eastern Europe these transformations were spurred by the collectivisation of land within large state farms and by economic planning, unlike Western Europe, where market forces and public policies drove these transformations (Jepsen *et al.*, 2015).

Taking into account the impacts of pesticides on the environment and human health since the 1990s

Agricultural production systems based on pesticides quickly received many criticisms regarding the negative impacts of pesticides on the environment and human health. First, in the United States, Rachel Carson's 1962 book Silent Spring highlighted the link between the mass use of pesticides, the deterioration in the state of the health of the American population and the deterioration of wildlife due to synthetic chemistry (Jouzel, 2019). Scandals broke out in the 1960s in the United States, following health problems among agricultural workers who had handled pesticides (ibid.).

From the 1990s, faced with the many negative impacts of pesticides on human health and the environment, several European public policies were introduced to limit their use and impact (Jepsen *et al.*, 2015). The section 3.3 provides more details on the various policies related to pesticides.

Through regulations for placing pesticides on the market

In 1991, Directive 91/414/EEC established an initial framework for harmonising marketing authorisation procedures for active substances. This was reformed in 2009 through Regulation No. 1107/2009 (Jacquet and Jouan, 2022a). This regulation takes into account the risks associated with pesticides. It only approves substances whose evaluation demonstrates that there is no harmful effect on human health or unacceptable effect on the environment (Barthélémy *et al.*, 2022). Following these regulations, many active substances were withdrawn from the market from the 1990s (Buckwell *et al.*, 2020b). Nevertheless, there may be a gap between the ambitions displayed by European regulations and the ability to assess the risks associated with pesticides. The latter remains limited due to the difficulty of actually observing the impacts of pesticide use on the one hand and evaluation methods on the other (Barthélémy *et al.*, 2022).

Through the Common Agricultural Policy

Environmental issues were taken into account in the various CAP reforms from the 1990s, integrating measures designed to limit pesticide use. The 1992 CAP reform sought for the first time to limit agricultural production in order to reduce surpluses, replacing price support with aid per hectare decoupled from production and making set-aside compulsory (Jacquet and Jouan, 2022a; Kirsch, 2017). The 1992 reform also included the first agri-environmental measures (AEM), incentive bonuses for changes in practices favourable to the environment, such as the conversion to organic farming for example (Kirsch, 2017). Various measures favouring practices that are more respectful of the environment continued to be developed and were integrated into the creation of the second pillar in 1999, bringing together numerous agri-environmental measures. The conditionality of aid to several environmental standards and to good agricultural and environmental conditions was introduced from 2003. The establishment of green payments conditional on a minimum surface area devoted to agri-ecological infrastructure and crop diversification was introduced from 2015 (Jacquet and Jouan, 2022a; Kirsch, 2017; Lataste *et al.*, 2012). The new 2023-2027 CAP also provides for several agri-environmental measures, such as the strengthening of conditionality and the establishment of eco-schemes within the first pillar, and an increase in the share of the budget allocated to agri-environmental measures within the second pillar (Pe'er *et al.*, 2022). Nevertheless, these measures are often not very restrictive with regard to agricultural practices and have so far had little effect on pesticide use (Jacquet and Jouan, 2022a). The new CAP reform does not seem to be up to the environmental challenges either (Pe'er *et al.*, 2022).

Through various directives (water framework directive, SUD directive, Green Deal)

At the level of the European Union, other directives have intervened in the regulation of pesticide use. For example, the framework directive on water (2000/60/EC) requires Member States to achieve good status for water bodies, in particular by combatting pollution linked to pesticides (Jacquet and Jouan, 2022a). From another angle, the pesticides directive (2009/128/EC or Sustainable Use of pesticides Directive (SUD)), sought to reduce the impact and risks associated with pesticide use, in particular by encouraging the adoption of Integrated Pest Management (Buckwell *et al.*, 2020a). More recently, the Green Deal strategy set an ambitious goal of reducing pesticide use and associated risks by 50% by 2030.

We will see later that these numerous measures have made it possible to reduce the number of pesticides available on the European market, but they have not resulted in a real reduction in the quantities of pesticides used.

2.2.2.2. Changes in the number of pesticides available in Europe: From the rise of a diversity of pesticides to their reduction from the 1990s

As we have seen previously, current cropping systems were introduced thanks to the development of numerous chemical pesticides from various chemical families. The emergence of these chemical pesticides is rooted in the 19th century with the appearance of the first mineral pesticides and scientific advances. Their development really took off after the Second World War thanks to progress in organic chemistry and accompanied the intensification of cropping systems. The number of pesticides available in Europe continued to grow until the 1990s when awareness of their negative impacts led to the banning of many pesticides and their withdrawal from the market.

The first pesticides used in agriculture

The use of insecticides and fungicides derived from minerals or plant extracts has been around for a long time. The first traces of the use of insecticides and fungicides, based on sulphur and plant compounds, date from 2,500-1,500 BCE in Sumer (an ancient region located in modern Iraq) and in China (Oerke, 2006). Pyrethrin, derived from the *Pyrethrum* flower, was used as an insecticide in ancient China in the 1st century CE and in Persia in the Middle Ages (Davies *et al.*, 2007). Other plants have been known for their insecticidal properties since the Middle Ages, such as tobacco, neem, *Derris* and *Lonchocarpus* roots (containing rotenone) (Schiffes, 2012).

In the 19th century, fungicides derived from mineral chemistry were developed. In 1807, Prevost was the first scientist to make the link between a plant disease (common bunt in wheat) and a fungus (*Tilletia caries*), which could be controlled using copper sulphate (Russel, 2005). Sulphur, copper sulphate and lime became the main active molecules used in fungicide preparations (ibid.). In 1885, it was discovered that the mixture of copper sulphate and lime, forming Bordeaux mixture, was effective against downy mildew in vines and potatoes (ibid.).

At the start of the 20th century, the rise of organic chemistry led to the development of the first synthetic pesticides (Bonnefoy, 2012). Plant pathology and mycology became scientific disciplines (Russel, 2005). The first organochlorine pesticide, DDT (dichlorodiphenyltrichloroethane), was marketed in 1939 as an insecticide (Jacquet and Jouan, 2022a). The first herbicides were used at the beginning of the 20th century: inorganic copper salt and sulphuric acid (Hamill *et al.*, 2004).

Nevertheless, before the 1940s, pest management was mainly achieved through the adaptation of cultural practices and the use of resistant varieties, and the pesticides which were available were mainly prepared by farmers themselves (Russel, 2005).

The development of synthetic pesticides

The first synthetic pesticides marketed

After the Second World War, research into chemical weapons and advances in the chemical industry led to the discovery of new organic compounds that could be used directly in agriculture as pesticides (Bonnefoy, 2012; Russel, 2005). In the 194Os, there was a shift from 'home-made' chemical pesticides used on high value-added crops to synthetic pesticides that were marketed (Russel, 2005). It was during this period that DDT, an organochlorine insecticide, was marketed and would dominate the insecticide market until the 1970s (Bonnefoy, 2012). For herbicides, 2,4-D (2,4-dichlorophenoxyacetic acid) and MCPA (2-methyl-4-chlorophenoxyacetic acid) were the first synthetic herbicides marketed in the 1940s and continued to be used in Europe for the next 60 years (Chauvel *et al.*, 2012). Chemical protection against pathogenic fungi also became widespread from the 1940s, with the development and marketing of new families of fungicides, in particular dithiocarbamates (Morton and Staub, 2008).

The rise of chemical pesticides supported by research: 1945 to 1990

From the 1960s, research on chemical crop protection developed and the market for chemical pesticides grew rapidly (Russel, 2005). Many active substances were discovered, including new chemical families and new modes of action in order to control new pests (for example, organophosphate, carbamate and pyrethroid for insecticides; urea, paraquat and triazine for herbicides; mancozeb, chlorothalonil and thiabendazole for fungicides) (Oerke, 2006; Russel, 2005; Chauvel *et al.*, 2012; Schiffes, 2012; Morton and Staub, 2008). It was during this decade that the first systemic fungicides and the first broad-spectrum herbicides were marketed (Russel, 2005; Morton and Staub, 2008; Chauvel *et al.*, 2012). This movement continued in the 1970s, with major advances in chemical crop protection (Russel, 2005). Large agri-chemical companies, such as BASF and Bayer in Germany, invested heavily in research into new products for an expanding market (ibid.). The number of active substances increased until the 1990s, reaching around a thousand active substances on the European market (Schiffes, 2012; Chartier *et al.*, 2018).

The beginning of bans and the reduction in the number of active substances authorised on the European market: From the 1990s to today

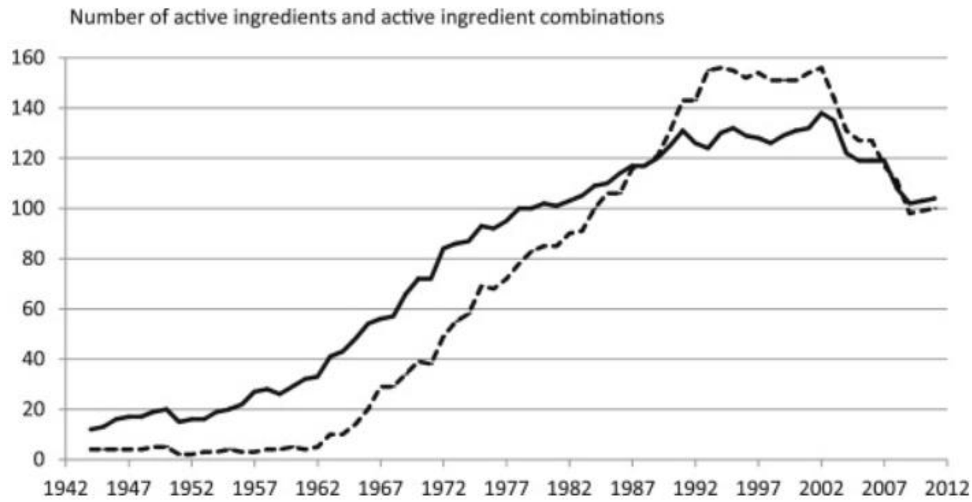
However, from the 1990s, the number of active substances authorised on the European market stopped growing. Awareness of the negative impacts of pesticides on the environment and human health from the 1960s led to the first bans on pesticides and the assessment of their effects in the 1970s (Martin, 2016). In 1978, Directive 78/631/EEC imposed the first legal framework at the European

Economic Community level in order to harmonise the regulations on pesticides in Member States. In 1991, Directive 91/414/EEC regulated the evaluation, authorisation, marketing and control of pesticides in Europe, leading to a long approval process for active substances (Chartier *et al.*, 2018). Faced with high marketing costs and an increasingly competitive market, companies then reduced their pesticide research efforts (Russel, 2005). Following this, from the 1990s the number of new active substances decreased while the number of active substances banned and withdrawn from the market increased (Chauvel *et al.*, 2012).

If we take the example of the French herbicide market (Figure 2-7), we can see that the number of active substances increased sharply between 1960 and 1990, before stabilising between 1990 and 2000. After 2000, the number of withdrawals of active substances is greater than the number of new active substances placed on the market, leading to a reduction in the number of herbicides available on the market (Chauvel *et al.*, 2012).

Figure 2-7: Evolution of the number of active herbicide substances approved in France, taking into account annual authorisations and withdrawals between 1942 and 2012
(Source: Chauvel *et al.*, 2012)

----- : active substances; - - - - : combination of active substances



Since the implementation of Directive 91/414/EEC, more than half of the active substances used for pesticides have been withdrawn from the European market (Hillocks, 2012; Buckwell *et al.*, 2020b). Figure 2-8 below shows the trend in the number of active substances authorised on the market from 1993 to 2010 within the European Union. It can be seen that the majority of active substances available in the 1990s that needed to be assessed, drastically decreased from 2001. Some of these active substances were authorised, but a large proportion disappeared because the authorisation files were incomplete, not submitted or withdrawn by manufacturers (Buckwell *et al.*, 2020b). At the same time, new active substances (NAS) were authorised.

In 2009, Regulation 1107/2009 replaced and strengthened Directive 91/141/EEC. Since 2011, there has been approximately between 400 and 500 active substances authorised within the European Union (Figure 2-9). We see an increase in the number of active substances available on the European market between 2012 and 2017 and then a slight decrease since 2017. In January 2023, there were 455 active substances authorised on the European market.[18]

[18] EU pesticide database https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/start/screen/active-substances consulted 03/01/2023

Figure 2-8: Development of the number of available active substances in the European Union between 1993 and 2010 (Source: Chartier *et al.*, 2018)

Substances are divided between active substances to be evaluated, active substances authorised and new active substances (NAS) approved.

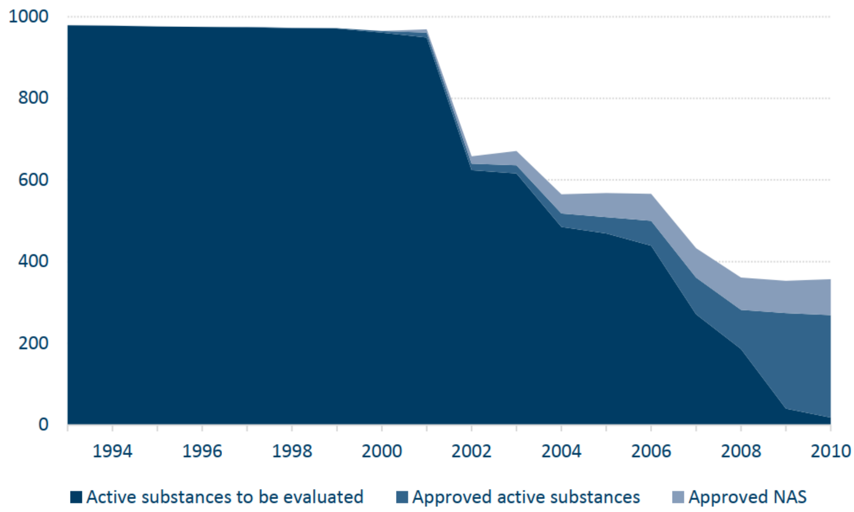
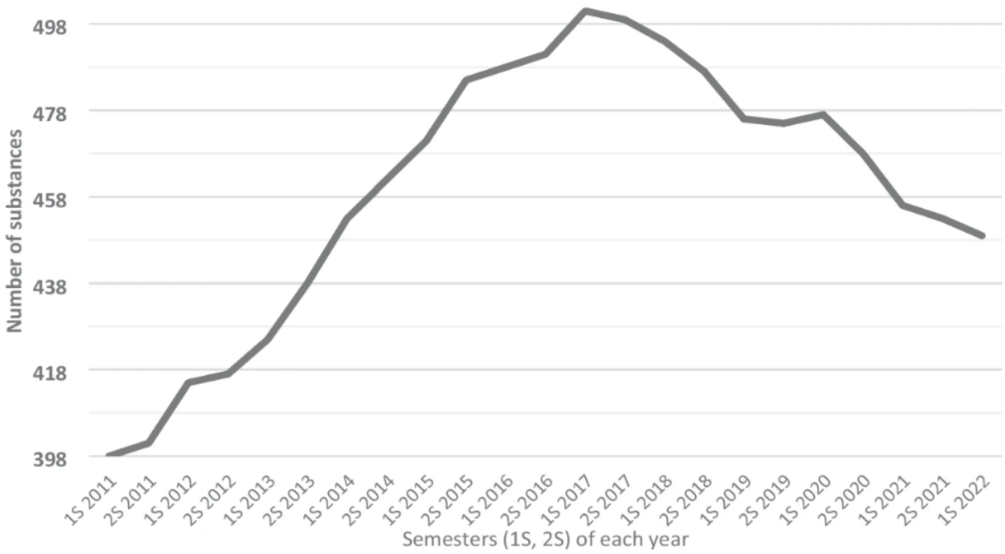


Figure 2-9: Evolution of the number of active substances available on the European market since 2011 (Source: Marchand, 2022)



The steady decrease in the number of pesticides available on the European market raises questions for an agriculture that relies heavily on pesticide use to protect crops. Farmers have access to increasingly fewer pesticides to manage pests. In addition, they use a limited number of pesticide families, which increases the risk of pest resistance (Chauvel *et al.*, 2012).

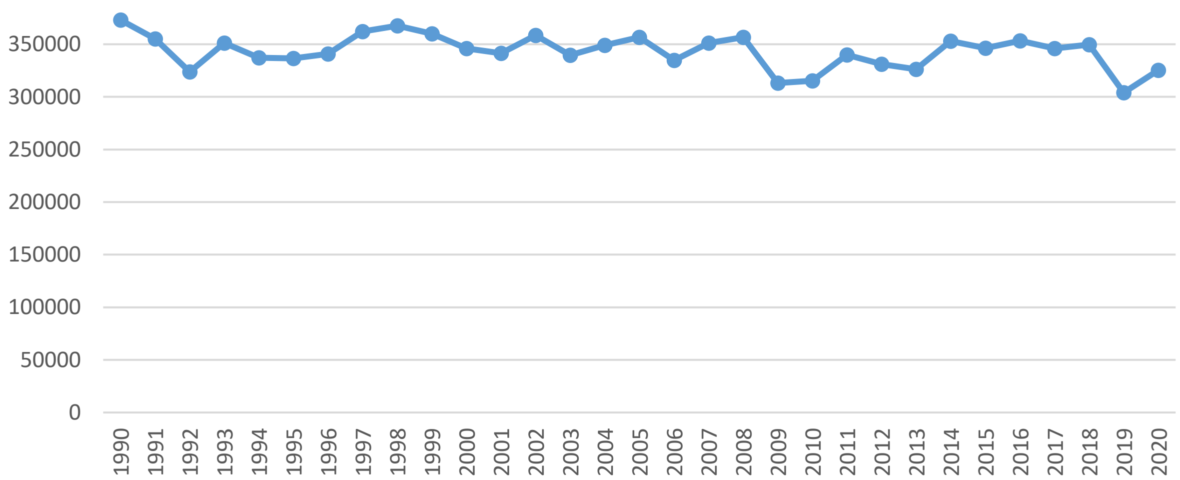
2.2.2.3. The development of agricultural pesticide use since the 1990s in Europe

We have seen that European regulations led to a decrease in the number of active substances available on the European market. Nevertheless, we can see that despite the restrictions on the active substances available and despite the numerous measures taken within the European Union, chemical pesticide use has not decreased in Europe.

Trends in the pesticide use in the European Union: Fluctuations and relative stability

Despite numerous public policies introduced since 1990 to limit the negative impacts of agriculture on the environment, in particular pollution linked to pesticides, chemical pesticide use has not decreased in EU over the long term. Based on FAOSTAT data, Figure 2-10 shows the evolution of pesticide use in tonnes of active substance within the European Union from 1990 to 2020. It is difficult to detect a downward or upward trend in pesticide use over this period. Rather, we observe a relative stability of use with fluctuations. In particular, we can identify two periods of increase in pesticide use: 1992 to 1998 and then, 2010 to 2017.

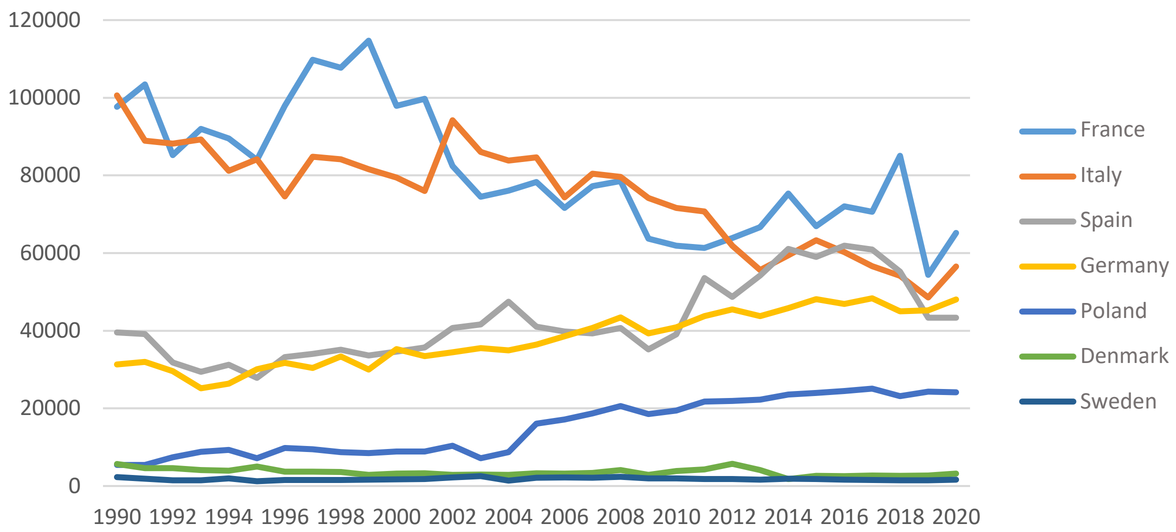
Figure 2-10: Total pesticide use in tonnes of active substance within the European Union between 1990 and 2020 (Source: Authors' own processing of FAOSTAT data)



Comparison of trends in the pesticide use between the various Member States: A disparity of national trends

The evolution of pesticide use at the European Union level does not reflect the disparities that may exist between Member States. The evolution of pesticide use may depend on several factors, such as a country's agricultural area and type of production, but also weather variations or changes in pest populations (Buckwell *et al.*, 2020b). Figure 2-11 compares the evolution of pesticide use in several Member States (France, Italy, Spain, Germany, Poland, Denmark and Sweden). Since the 1990s, there has been a downward trend in pesticide use in France (with an increase between 2011 and 2018), Italy and Denmark. In contrast, we can see a clear trend towards increased pesticide use in Germany, Spain (with strong fluctuations) and Poland. However, these figures should be treated with caution because the criteria for monitoring pesticide use transmitted to FAOSTAT differs between Member States (Buckwell *et al.*, 2020b).

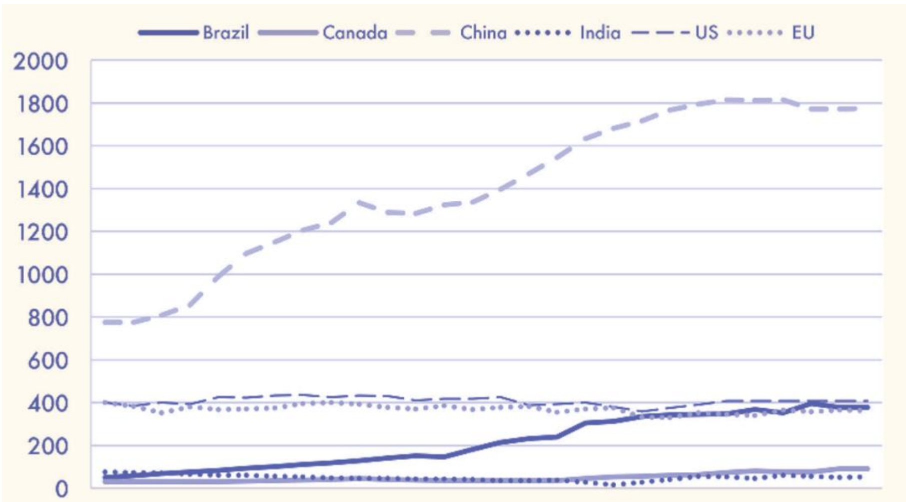
Figure 2-11: Trends in the pesticide use in tonnes of active substance in various European Union Member States between 1990 and 2020 (Source: Authors' own processing of FAOSTAT data)



Comparison with the rest of the world

We can also compare the trends in the pesticide use in the European Union with other countries since 1990 (Figure 2-12). There are huge disparities in pesticide use around the world. China and Brazil have experienced very rapid growth in their pesticide use, while the United States and Europe use comparable quantities of pesticides which have remained more or less stable over the period.

Figure 2-12: Total pesticide use in thousands of tonnes of active substance for Brazil, Canada, China, India, United States and the European Union, between 1990 and 2017
(Source: Buckwell *et al.*, 2020b based on FAOSTAT)



2.2.2.4. A locked-in socio-technical system

As we have seen previously, cropping systems have evolved towards a dependence on chemical pesticides through practices that, while providing increased production, make crops more sensitive to pests. Despite the many policies introduced to limit the dependence of cropping systems on pesticides, their use remains important within European agricultural systems.

Indeed, dependence on pesticides is not limited to farms alone, but concerns the entire agri-food system. The agricultural production system's dependence on pesticides is consistent in both the upstream and downstream links in the production chain, where the strategy of each actor reinforces that of the others, creating what is called a socio-technical 'lock- in' (Schott *et al.*, 2010; Lamine *et al.*, 2010b).

At the farm scale

The advantages of pesticides for farmers

Pesticides have many advantages: they are practical to use, effective, their effects are rapid and clearly visible, their cost is low, they provide immediate economic benefits and they ensure that farmers can market their harvest while guaranteeing quality products (Aubertot *et al.*, 2005b; Buckwell *et al.*, 2020a). Indeed, the existing assessments of crop losses due to pests in the absence of pesticide applications indicate that they can be very significant if no changes are made to cropping systems (Oerke, 2006). Pesticides alongside mechanisation facilitate the work of farmers by reducing working time and the difficulty of certain tasks, such as weeding (Jacquet and Jouan, 2022b).

A strategy reinforced by agricultural advice

Agricultural advice plays an important role in farmers' choices regarding pesticide use (Aubertot *et al.*, 2005b). There are a number of types of agricultural advisory systems across Europe: both public and private bodies, farmer-based organisations (such as chambers of agriculture) and non-governmental organisations (Knierim *et al.*, 2017). Many organisations that provide advice to farmers also sell agricultural inputs and products, or have links with input suppliers (for example, cooperatives and advisers working for commercial companies). Therefore they have an interest in advising solutions based on pesticides and promoting high yield levels (Lamine *et al.*, 2010a; Pedersen *et al.*, 2019; Dhiab *et al.*, 2021; Sutherland and Labarthe, 2022).

Several measures have been recently introduced to guarantee greater independence among agricultural advisers. For example, in France, a ruling on the separation of advice and pesticide sales was introduced on January 1, 2021 (Xicluna, 2021). At the European Union level, CAP 2023-2027 asks Member States to ensure that advisers are "independent" and "impartial" (Sutherland and Labarthe, 2022). Nevertheless, this measure seems difficult to implement because the presence of independent advisers is not guaranteed in all European regions and the independence of advice does not necessarily mean the advice provided is impartial (ibid.). Sutherland and Labarthe (2022) suggest supporting more transparent, evidence-based advice and ensuring that all European farmers have access to an advisory service.

At the level of upstream and downstream sectors

Upstream of production systems (breeding and research): Breeding of a small number of varieties with low resistance

Plant selection criteria strongly contribute to the development of intensive, low-diversity and pest-sensitive agricultural systems. As we have seen, in order to increase agricultural production, plant breeding has turned towards the search for high-yielding varieties rather than pest-resistant ones (Lamine *et al.*, 2010a; Bonnin *et al.*, 2014). In addition, the registration of seeds in a national or European catalogue imposes constraints on the varieties available on the market. For example, in France, the criteria for registration in the national catalogue, such as the stability and homogeneity of varieties, have contributed not only to the decrease in the number of varieties available, but also to favouring productive varieties at the expense of resistant ones (Bonnin *et al.*, 2014; Bonneuil and Hochereau, 2008). The demands of downstream actors (homogeneous and standard products, product transformability) lead to the breeding of only varieties that meet these criteria, to the detriment of diversification and pest resistance (Bonneuil and Hochereau, 2008; Lamine *et al.*, 2010b). Therefore, Magrini *et al.* (2016) observe that secondary crops (such as legumes) benefit from weaker breeding efforts than dominant crops (such as wheat).

In addition, in many European countries, the reduction in public subsidies and certain forms of privatised research have long contributed to directing research efforts towards short-term issues and the improvement of existing techniques, such as precision agriculture, rather than to a redesign of agricultural systems in order to limit pesticide use (Lamine *et al.*, 2010a; Vanloqueren and Baret, 2009).

Downstream sectors in the chain (collection and agri-food industry)

Downstream sectors in agricultural chains have also contributed to strengthening intensive production systems dependent on pesticides, whether through the criteria of processors, distributors and consumers on product quality (Carpentier, 2010) or the lack of outlets for secondary products, which is a real obstacle to the diversification of cropping systems (Tibi *et al.*, 2022).

Among collection and storage organisations, the tendency is to collect large volumes of a small number of crops in order to achieve economies of scale (Meynard *et al.*, 2018), and to meet the requirements of processing companies, which require homogeneous products in terms of both quality and quantity (Lamine *et al.*, 2010b). Therefore, storage and collection organisations (cooperatives and brokers) favour a limited number of varieties and cultivated species to the detriment of mixtures of varieties and combinations of species (Meynard *et al.*, 2018; Lamine *et al.*, 2010b).

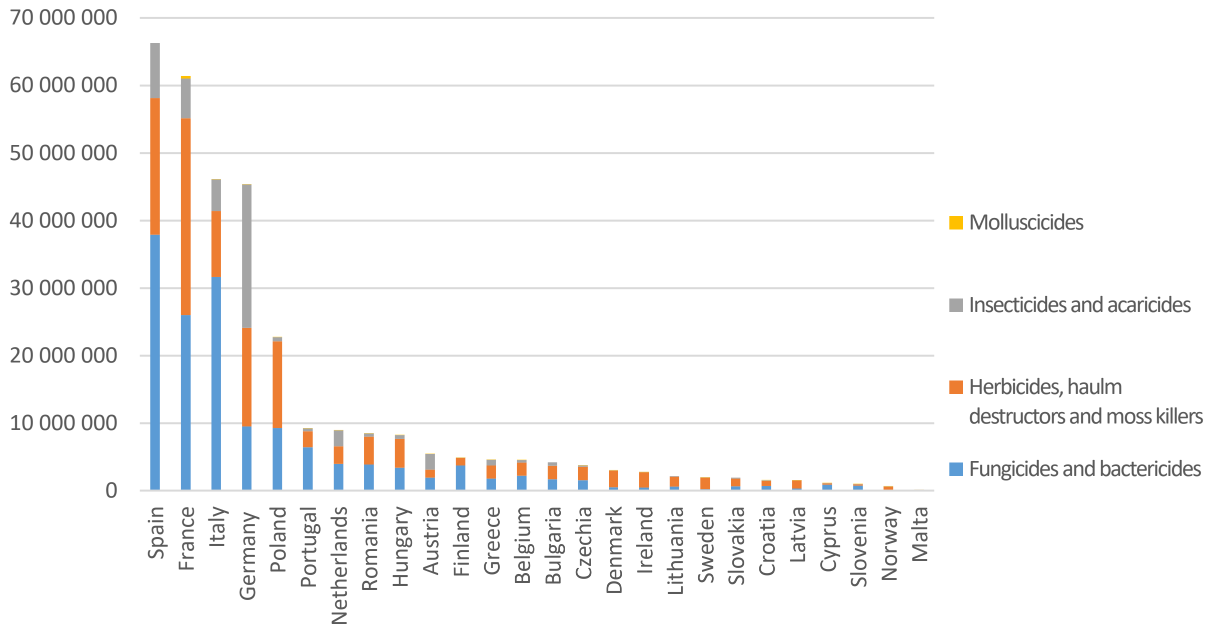
The requirements of processors, distributors and consumers also contribute to the intensification of agriculture. Production chains have become standardised, industrialised and globalised in order to produce food that meets sanitary standards, is inexpensive and convenient, and is available in large quantities (Murdoch *et al.*, 2000; Therond *et al.*, 2017). For O'Kane (2012), this type of agri-food system is based on agriculture that consumes a lot of pesticides. In this standardised system, agricultural products must meet certain health and technological quality standards that go hand in hand with pesticide use (Lamine *et al.*, 2010b). For example, in the fruit sector, quality criteria, such as size (minimum size, regularity) and flawless visual appearance, can only be met with the use of pesticides (Lamine *et al.*, 2010a; Carpentier, 2010). In milling, wheat is classified according to its protein content. High protein levels are more valuable but require the use of significant fertilisation (Lamine *et al.*, 2010b), often correlated with pesticide use. For cereals, standards requiring an absence of mycotoxins are also linked to pesticide use (ibid.).

2.2.2.5. An inventory of current pesticide use in Europe

At the European Union scale, Member States have recorded the volume of pesticide sales and type of pesticide since 2011. These data are accessible on the Eurostat database. Nevertheless, the sales of pesticides do not represent the actual uses of pesticides, since pesticides can be stored for later use (Buckwell *et al.*, 2020a). In addition, there are illegal practices of using pesticides banned by the European Union. Buckwell *et al.* (2020a) estimate that these practices could represent nearly 10% of pesticide use in Europe.

Figure 2-13 shows pesticide sales (in kg) by Member State and type of pesticide in 2020. In Europe, the largest consumers of pesticides are Spain, France, Italy, Germany and Poland. In contrast, the Member States consuming the least pesticides are Malta, Norway, Slovenia, Cyprus and Lithuania. Nevertheless, some States have a very small agricultural area, so it is logical that their pesticide consumption is lower. This does not necessarily mean that their use per hectare is not high (see Figure 2-14).

Figure 2-13: Sale of pesticides (in kg) by EU Member State and type of pesticide in 2020, except Estonia and Luxembourg (missing data) (Source: Authors' own processing of Eurostat data)

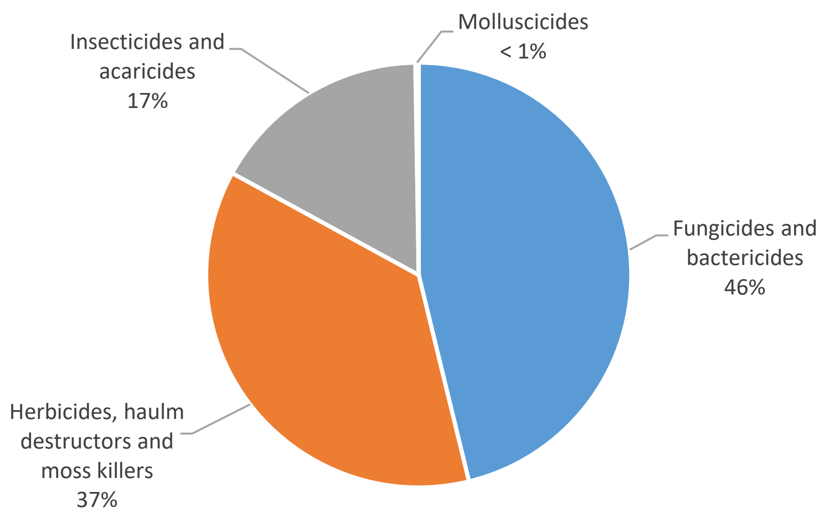


NB: The sales of molluscicides in Lithuania and Slovakia do not appear on this graph.

Figure 2-13 also shows the type of pesticides consumed by each Member State. We can see that the type of pesticide most consumed is not the same in each Member State. This reflects issues around different pests in connection with a diversity of cropping systems and weather conditions in Member States.

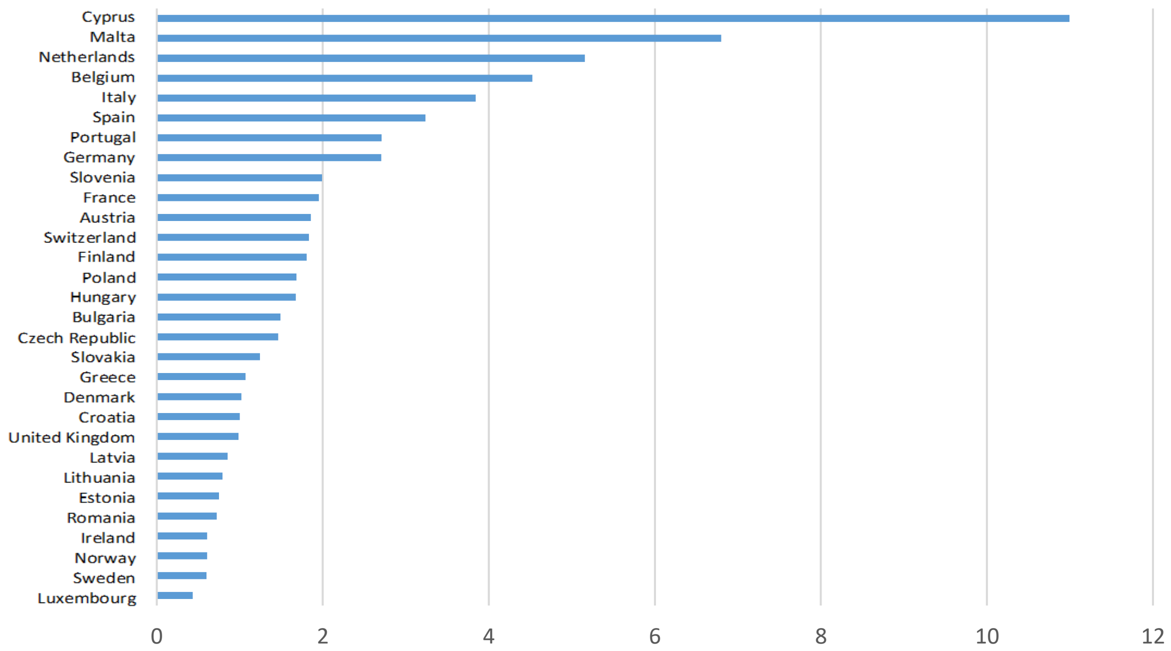
Figure 2-14 presents the percentage of each type of pesticide in the total pesticides sold in the European Union. We see that fungicides are the most consumed pesticide (46%), followed by herbicides (37%). Insecticides are used less, representing only 17% of sales. Finally, molluscicides are not widely used, representing less than 1% of sales.

Figure 2-14: Percentage of pesticide type in total sales in Europe in 2020 (Source: Authors' own processing of Eurostat data)



If we compare the sale of pesticides per hectare of agricultural area between Member States (Figure 2-15), we note that Members States with a small agricultural area can have very intensive consumption per hectare. This is the case for Cyprus, Malta, the Netherlands and Belgium, for example. However, States consuming large quantities of pesticides often also have a high consumption per hectare, such as Italy, Spain and Germany and, to a lesser extent, France and Poland.

Figure 2-15: Pesticide sales (in kg) per hectare of agricultural land for European Union Member States (2019) (Source: Authors' own processing of Eurostat data)



2.2.3. The development of cropping systems designed to limit pesticide use

While crop protection in Europe is mainly based on the use of chemical pesticides which effectively reduce pest presence, various crop protection strategies designed to limit chemical pesticide use already exist.

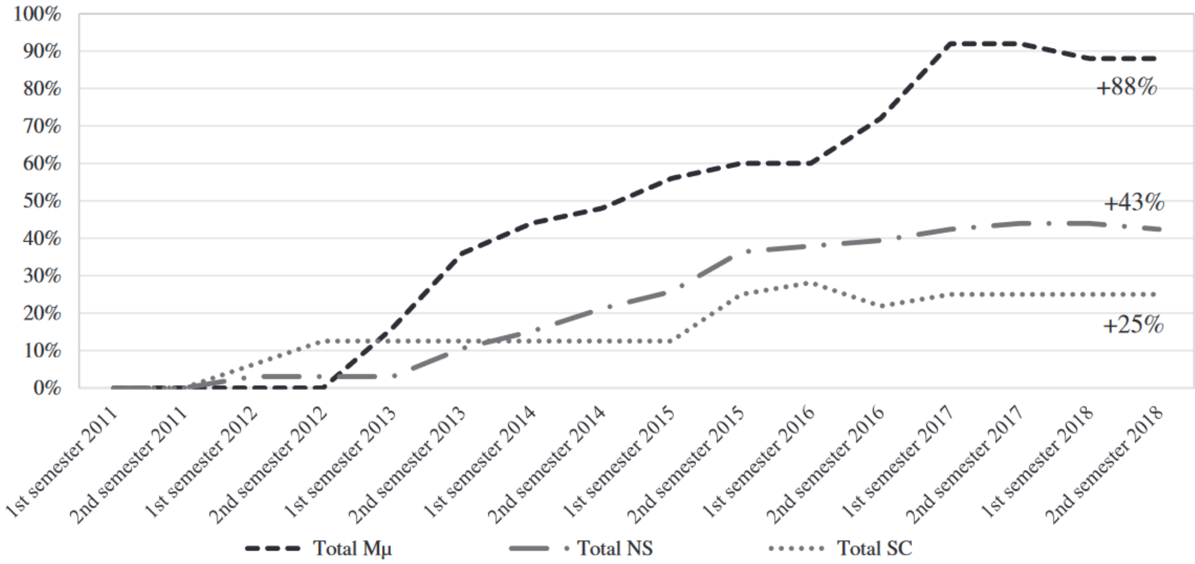
2.2.3.1. Substituting chemical pesticides with biocontrol products

In order to limit the risks associated with chemical pesticides, the first solution is to replace them with less dangerous products. Biocontrol products appear to be an interesting alternative because they are considered less dangerous than synthetic pesticides (Villaverde *et al.*, 2014). Biocontrol products are living organisms or natural substances. They are divided into four categories: macroorganisms, microorganisms, semiochemicals and substances of natural origin (Busson *et al.*, 2022).

The biocontrol market has experienced huge growth in recent years. According to Ravensberg (2015), it represented €549 million in Europe in 2014 and recorded annual growth of 15 to 20%. However, it remains a small sector within crop protection products, representing less than 5% of total control product sales worldwide (Buckwell *et al.*, 2020a), and around 10% of the crop protection product market in Europe in 2019 (IBMA, 2021). According to the International Biocontrol Manufacturers Association (IBMA), the most developed sector in Europe is that of macroorganisms (which accounted for 40% of the biocontrol market in Europe in 2015), followed by microorganisms (24%), natural products (20%) and semiochemicals (16%) (Carry, 2018).

Microorganisms, natural substances and semiochemicals are subject to the same marketing regulations as other plant protection products, 1107/2009 EC (Robin and Marchand, 2019). Macroorganisms are covered by national regulations. The evolution of approvals of biocontrol products since 2011 within the European Union gives an idea of the importance of biocontrol in Europe (Figure 2-16). The biocontrol substances available on the European market are growing rapidly. Microorganisms represent the fastest growing category of biocontrol product (+88% of substances authorised between 2011 and 2018), followed by natural substances (+43%) and then semiochemicals (+25%) (Figure 2-16). Macroorganisms are not shown in Figure 2-16, as their authorisations do not depend on European regulations.

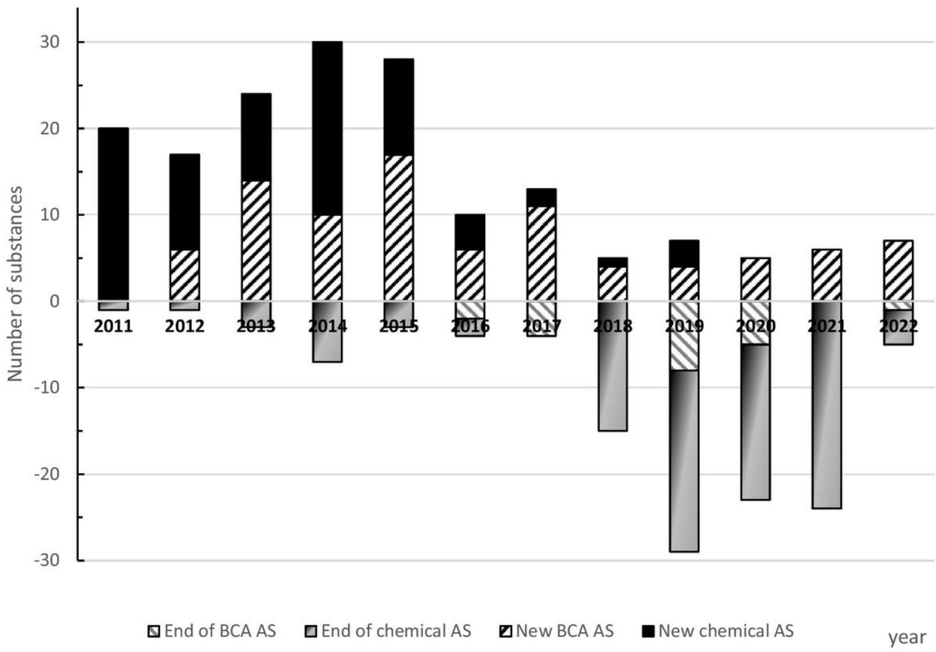
Figure 2-16: Development of authorisations for various categories of biocontrol between 2011 and 2018 in Europe (Source: Robin and Marchand, 2019)



Mμ: microorganisms, NS: natural substances, SC: semiochemicals (chemical mediators)

Figure 2-17 shows the evolution of marketing authorisations and withdrawals between biocontrol products and chemical active substances. Since 2011, the number of biocontrol substances authorised in the EU has been steadily increasing, unlike the number of authorised chemical substances, which is decreasing. This is all the more evident since 2017 when the number of biocontrol substances authorised each year has exceeded that of chemical substances authorised (ibid.). At the same time, many chemical substances have been withdrawn from the European market, and have been partially replaced by biocontrol substances (ibid.). However, biocontrol products are often specific, and alternatives to chemical pesticides are not available for all types of pests and crops (Robin and Marchand, 2019; Marchand, 2022).

Figure 2-17: Number of substances authorised (positive part of the y-axis) and withdrawn (negative part of the y-axis) per year, broken down into biocontrol substances (hatched area) and chemical substances (solid area) between 2011 and 2022 in Europe (Source: Marchand, 2022)



BCA: Biocontrol Agent; AS: Active Substance

Biocontrol products are still a minority among the active substances authorised in Europe: in 2018, they represented 36.8% of the substances authorised (Robin and Marchand, 2019). Since the European regulations that authorise biocontrol products are the same as those for synthetic pesticides, this can be seen as an obstacle to the approval of biocontrol products (Bourguignon, 2017). For example, it takes twice as long to register a biocontrol product in Europe than it does in the United States (Buckwell *et al.*, 2020a). However, biocontrol products can have impacts on the environment, for example macroorganisms that are introduced can become invasive species (Amichot *et al.*, 2022).

2.2.3.2. The development of organic agriculture and value chains using no synthetic pesticides

Organic farming is one of the forms of agriculture conducted without synthetic pesticides and also eschews mineral fertilisers. It has developed via a certification system which sets specific specifications. Organic farming is "*a mode of production based on agricultural practices that **exclude the use of synthetic biocides** and genetically modified organisms (GMOs) or products obtained from GMOs*" (Sanner *et al.*, 2022). Organic agriculture also seeks to limit its environmental impact and uses prophylactic methods to manage pests (ibid.). A limited number of pesticides of natural origin, such as biocontrol products, are authorised in organic farming (Buckwell *et al.*, 2020a). Nevertheless, some pesticides of mineral origin used in organic farming can have environmental impacts, such as copper (Karimi *et al.*, 2021).

Organic farming has been practiced in Europe since the 1920s. It really began to expand in the 1970s when it was recognised by certain States that introduced the first organic certification schemes (Reganold and Watcher, 2016). The first European certification, harmonising various national certification schemes, was established in 1991 (Barrett *et al.*, 2002).

In 2020, the area being organically farmed in Europe was around 14.5 million hectares, *i.e.* 9.1% of Europe's total utilised agricultural area (including certified and conversion areas) (Eurostat, 2023). This corresponds to a 56% increase in the area under organic farming compared to 2012 (*i.e.* an increase from 5.9% to 9.1% of the utilised agricultural area between 2012 and 2020) (ibid.). Between 2012 and 2020, the area under organic farming increased in all Member States apart from Poland (ibid.). Non-permanent crop production (cereals, fresh vegetables etc.) represented 46% of the total organically farmed area in 2020, permanent grasslands 42% and permanent crops 12% (ibid.).

In 2020, the Member States with the highest share of utilised agricultural area devoted to organic farming were Austria (25%), Estonia (22%) and Sweden (20%) (Figure 2-18). Other Member States had an area under organic farming of more than 10%, such as Italy, the Czech Republic, Lithuania, Finland, Slovakia, Denmark, Slovenia and Greece. In contrast, some countries had less than 5% of their utilised agricultural area dedicated to organic farming: Malta, Ireland, Bulgaria, Romania, Poland, the Netherlands, Cyprus and Luxembourg.

Figure 2-18: Share of utilised agricultural area being organically farmed in various Member States in 2020. (Source: Eurostat, 2023)

2.2.3.3. Principles in crop protection to reduce the use of chemical pesticides: Integrated Pest Management and Agroecological Crop Protection

Various crop protection strategies designed to limit the use of chemical pesticides already exist. Two strategies can be distinguished in particular: Integrated Pest Management (IPM), which is the oldest and most widely used approach, and Agroecological Crop Protection (ACP), which is more recent and still emerging in its applications. The principles of these two crop protection strategies have already been well developed in the scientific literature, with examples of implementation in the field (Barzman *et al.*, 2015; Deguine *et al.*, 2021).

Integrated Pest Management (IPM)

Origins and definitions of Integrated Pest Management

Integrated Pest Management (IPM) is a model of crop protection which emerged in the late 1950s in order to respond to the problems of pesticide resistance in pests (Deguine *et al.*, 2021). It is defined by the FAO as "*the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimise risks to human health and the environment. IPM promotes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms*" (FAO, 2018).

Many definitions of IPM, sometimes divergent (Coll and Wajnberg, 2017), have been developed since the 1950s. Deguine *et al.* (2021) identify several points common to these definitions: the integration and combination of pest management techniques, the search for socio-economic viability while reducing pesticide use and the use of chemical pesticides as a final recourse, based on thresholds.

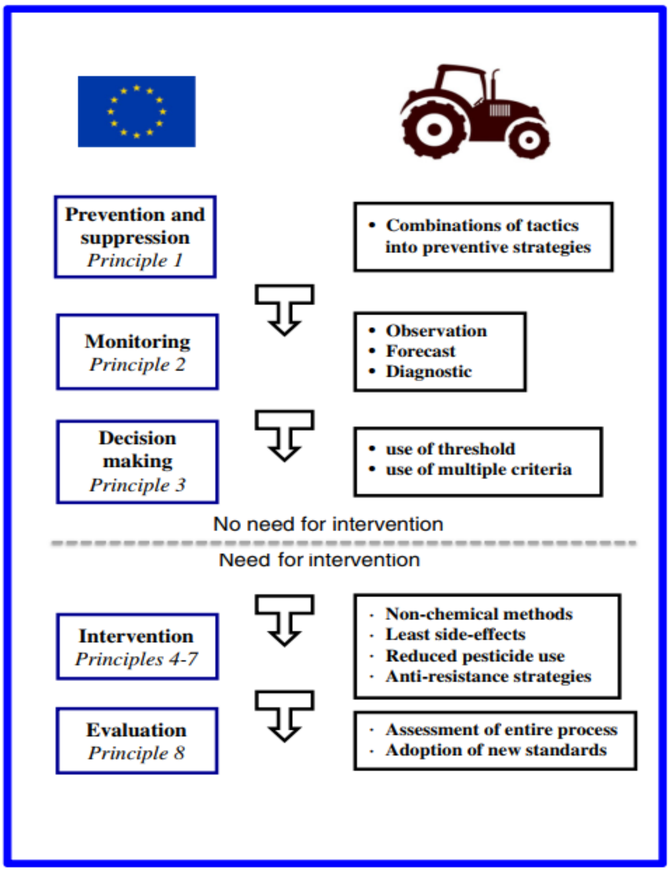
The eight principles of IPM and their sequencing

Several principles and application strategies of IPM have been developed. Barzman *et al.* (2015) identified and organised eight principles of IPM, which are described below:

- Principle 1: The prevention and elimination of pests, including the use of crop rotations, appropriate cultural techniques (false seedbeds, sowing date and density etc.), the use of resistant/tolerant varieties, establishing balanced fertilisation, liming, irrigation and drainage programmes, introducing hygiene measures to prevent the spread of pests, and the protection and reinforcement of beneficial populations;
- Principle 2: Monitoring;
- Principle 3: Decision-making based on monitoring and thresholds;
- Principle 4: Preference given to non-chemical methods over chemical methods;
- Principle 5: Pesticide choice (the least dangerous possible);
- Principle 6: Reducing pesticide use;
- Principle 7: Strategies preventing the emergence of resistance;
- Principle 8: Evaluation of crop protection measures.

These principles are applied in a logical sequence, with the first principles having to be introduced before the following ones (Figure 2-19) (Barzman *et al.*, 2015). Principle 1 on the prevention and elimination of pests implies an initial re-design of the cropping system. Principles 2 and 3 on monitoring and decision-making are introduced once the system has been established, with the decision on measures to be introduced (principle 3) taking into account the results of monitoring (principle 2). If a curative intervention is chosen, principles 4 to 7 offer several options starting with those with the least impact. Finally, principle 8 addresses evaluation, with the aim of evaluating actions in order to improve the system that has been established.

Figure 2-19: The logical order behind the eight principles of IPM (Source: Barzman *et al.*, 2015)



Strategy for implementing actions: The pyramid of Integrated Pest Management

IPM principles and strategies have been represented in the form of a crop protection pyramid (see, for example, Naranjo, 2001) (Figure 2-20). This pyramid represents actions to be prioritised (avoidance strategies) at the base of the pyramid and others to be used only as a last resort at the top of the pyramid (Figure 2-20). The top of the pyramid within the dotted lines corresponds to the conventional paradigm of crop protection centred on the use of chemical pesticides, based on pest monitoring and the definition of intervention thresholds.

More recently, the presentation of the principles of IPM in the form of a pyramid has been reformulated in the literature (Lundin *et al.*, 2021). Lundin *et al.* (2021) combine pollination management with integrated crop protection (Figure 2-21) to build a pyramid of Integrated Pest and Pollinator Management (IPPM).

The shape of the pyramid illustrates a multi-step decision support system, where priority is given to preventive (or proactive) actions at the base of the pyramid while curative (or reactive) actions at the top are not given priority and are implemented only if preventive actions are insufficient to manage pests or maintain damage below thresholds (ibid.). Actions at the base of the pyramid employ ecological processes based on biodiversity, and involve landscape and crop management. Actions at the top of the pyramid replace biodiversity-based practices with external inputs, such as synthetic pesticides and abiotic inputs. Monitoring is at the centre of the pyramid and highlights the actions that farmers need to implement (ibid.).

Figure 2-20: IPM represented in the form of a pyramid (Source: Naranjo, 2001)

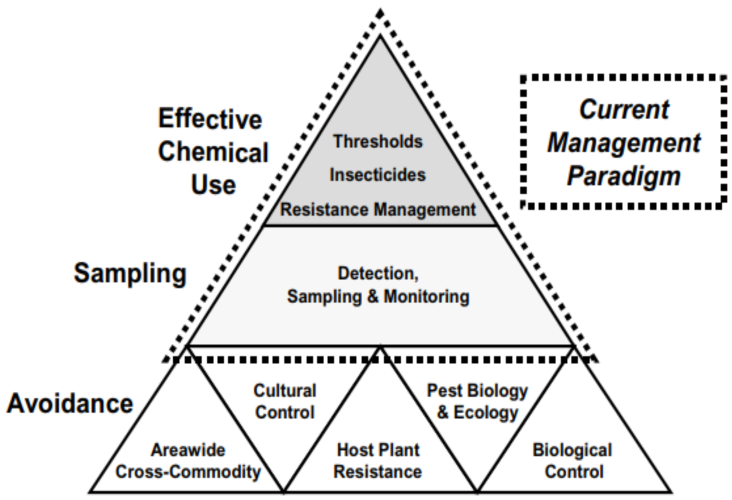
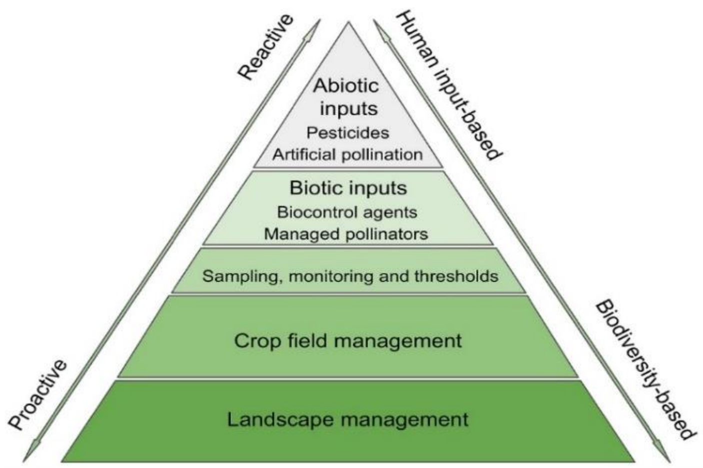


Figure 2-21: Pyramid of Integrated Pest and Pollination Management (Source: Lundin *et al.*, 2021)



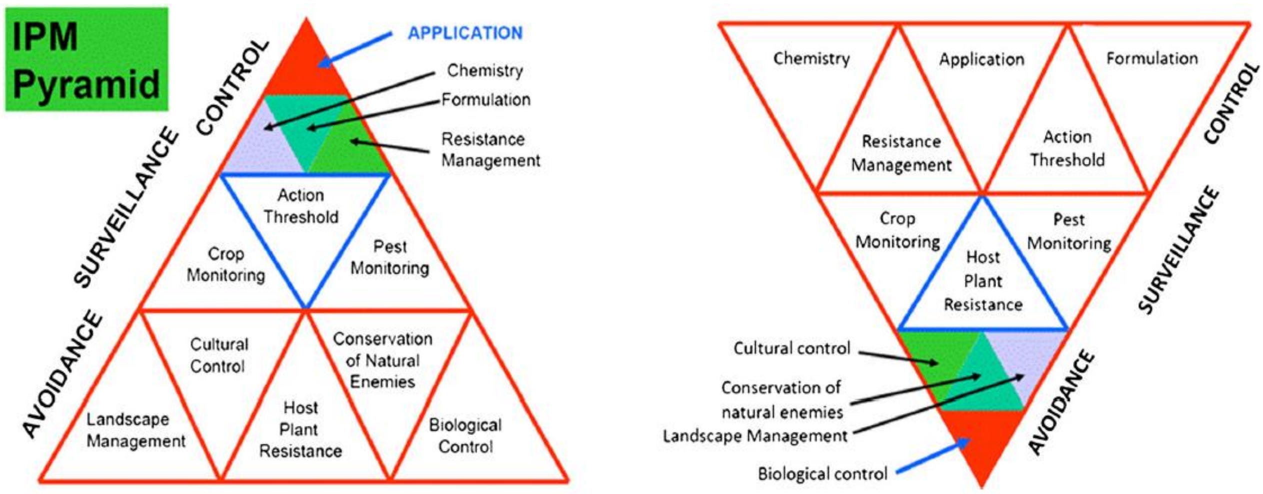
The limits of Integrated Pest Management

Despite the promotion of IPM since the 1950s, in particular through European Directive SUD (2009/128 EC), its principles have still not been widely adopted (Jacquet and Jouan, 2022b; Deguine *et al.*, 2021).

Reflecting on the low impact of IPM principles in the reduction of chemical pesticide use, Hokkanen (2015) redefines the dominant mode of pest management in conventional agriculture. He represents it as an inverted pyramid (Figure 2-22), where pest management is mainly based not on prophylaxis but on pest control using synthetic pesticides, producing major effects on the unsustainability and instability of these cropping systems.

The failure of the dissemination of IPM to reduce pesticide use can be explained by several factors: the profusion of IPM definitions and interpretations which make the concept of IPM vague, the gap between IPM concepts and its practice, and a lack of understanding of the ecological concepts underpinning IPM (Deguine *et al.*, 2021). Moreover, IPM often presents a juxtaposition of crop protection techniques and not a real integration of different crop protection methods (Stenberg, 2017). Ehler (2006) considers that IPM is often applied not as *Integrated Pest Management* but rather as *integrated pesticide management*, in other words a set of tools providing for a rational use of pesticide applications based on monitoring and thresholds. This vision of IPM leads to crop protection that is always centred on chemical pesticides (Ehler, 2006).

Figure 2-22: The reality gap in pest management: the ideal IPM promoted for more than 50 years (left), and the reality of ordinary pest management (Source: Hokkanen, 2015)



Deguine *et al.* (2021) identify six barriers to the large-scale adoption of IPM:

- A lack of knowledge among farmers, especially of basic ecological concepts.
- Risk aversion, with IPM being perceived as risky compared to pesticide use.
- Conflicts of interest between agricultural advisers and the lobbying of agrochemical companies.
- The lack of technologies adapted to local contexts.
- The lack of clear and effective policies.
- The lack of collective and interdisciplinary action.

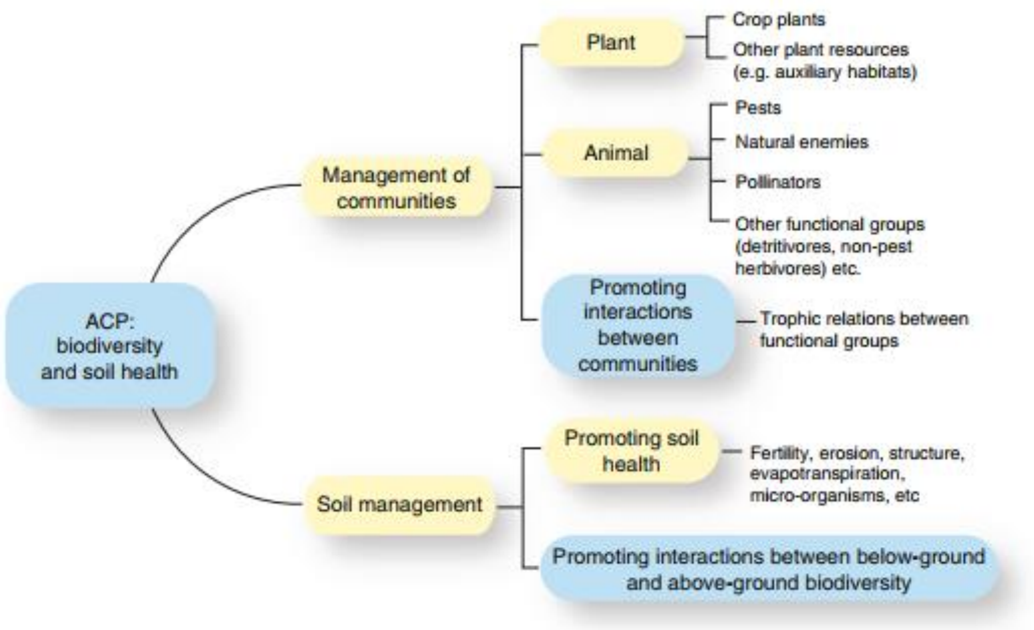
Agroecological Crop Protection (ACP)

Crop protection based on agroecology

Agroecological Crop Protection (ACP) stems from agroecology and makes it possible to apply the principles of agroecology to crop protection (Deguine *et al.*, 2021). While agroecology was developed in the 1970s, its application to crop protection emerged from the 2000s (Deguine and Ratnadass, 2017). In the book 'Agroecological Crop Protection' (2017), Deguine *et al.* present the principles of ACP and examples of its application.

Like agroecology, ACP builds on the ecological functions of ecosystems by improving ecosystem health (Deguine *et al.*, 2021). In order to improve the health of ecosystems, ACP seeks to develop interactions between the different communities of living beings within ecosystems (ibid.). For this, ACP relies on two pillars, which are biodiversity and soil health, and seeks to introduce the management of ecological communities and soil (Deguine and Ratnadass, 2017) (Figure 2-23). The management of ecological communities and soil is based on the diversification of plants over time and space and on the improvement of soil quality (organic matter and its biological function) through sustainable and ecological cultivation practices (ibid.). In addition, ACP recommends limiting as much as possible all practices that could negatively affect biodiversity and ecosystem health, such as the use of chemical inputs and monocultures (Deguine and Ratnadass, 2017).

Figure 2-23: The two pillars of ACP: biodiversity and soil health
(Source: Deguine and Ratnadass, 2017)



The agronomic application of Agroecological Crop Protection

Based on agroecological principles applied to crop protection, Deguine *et al.* (2009) suggested a crop protection strategy that has been further developed by Deguine and Ratnadass (2017). An essential phase of this strategy is the implementation of preventive measures across space and time, in other words:

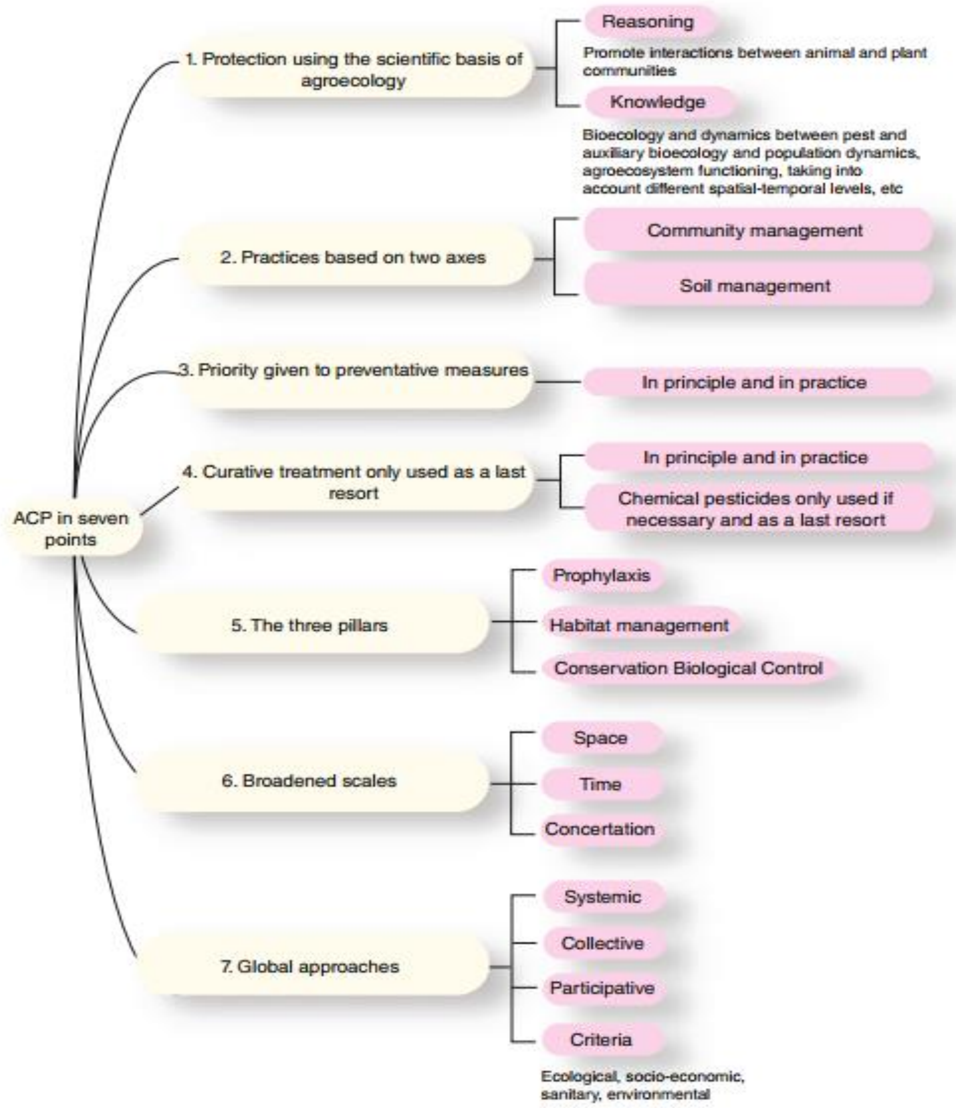
- The cultivation of healthy plants and maintenance of healthy soil through various practices that favour biological regulations. These include the use of adapted varieties, sustainable fertilisation and irrigation, reduced tillage and the temporal diversification of vegetation.
- The reduction of pest populations and the reinforcement of beneficial populations (from the plot to the agroecosystem) through the management of habitats at the edges of plots and intra-plot plant diversification, in particular the use of trap plants and push-pull techniques.
- The use of concerted practices over time and space within agroecosystems.

This strategy means that different spatial and temporal scales must be taken into account, ranging from the plot to the agroecosystem (Deguine and Ratnadass, 2017). Finally, Deguine and Ratnadass (2017) propose seven characteristics of Agroecological Crop Protection (Figure 2-24).

These seven characteristics correspond to:

1) The use of the scientific basis of agroecology;
2) The two axes of practices (biodiversity and soil health);
3) Priority given to preventative measures;
4) The use of curative treatments only as a last resort;
5) The three pillars of ACP which are prophylaxis, habitat management and conservation biological control;
6) Broadened scales (spatial, temporal and concertation);
7) Global approaches.

Figure 2-24: The seven main characteristics of Agroecological Crop Protection (Source: Deguine and Ratnadass, 2017)



Synthesis on IPM and ACP

IPM and ACP are two crop protection strategies, developed by the scientific community and applied in the field, which are designed to limit pesticide use in crop protection. They have points in common such as the prioritisation of prophylaxis practices, the mobilisation of ecosystem functions and the use of chemical pesticides as a last resort. Nevertheless, ACP goes further in its reflection by basing crop protection on the good health of the agroecosystem, which involves not only avoiding pests but also ensuring good management of biodiversity and soil health. Pesticide use is no longer restricted in order to avoid pollution and its negative impacts but is avoided because it can call into question the very basis of crop protection, *i.e.* the health of the ecosystem.

These two approaches show that a crop protection strategy without chemical pesticides requires a re-design of the cropping system and therefore the exploration and combination of existing and future practices. Crop protection without chemical pesticides can rely on some elements of IPM and ACP. As such, production systems in organic farming, which employ the principles of agroecology, provide, to a certain extent, possible routes for thinking about systems without chemical pesticides.

Conclusion

We have seen that for decades crop protection in Europe and many other parts of the world has been based primarily on the use of chemical pesticides. This has made it possible to increase greatly agricultural production, but has created cropping systems dependent on chemical pesticides and more sensitive to pests. Furthermore, this dependence on pesticides concerns not just cropping systems, but the entire food system. However, since the 1990s, the negative impact of chemical pesticides on the environment and human health has become a major societal concern. Therefore, many measures have been introduced to limit their use without, however, calling into question existing uses in cropping systems in conventional agriculture. Agricultural systems aimed at limiting the use of pesticides have been promoted in European policies through the Integrated Pest Management (IPM) model and, more recently, other models have been conceptualised and experimented with, such as agroecological crop protection (ACP). At the same time, cropping systems and specific sectors without synthetic pesticides have developed, in particular through organic farming certification and labelling.

Crop protection without chemical pesticides can rely on some elements of IPM, ACP and organic farming. However, the impossibility of using chemical pesticides (and the possibility of using mineral fertilisers) to protect cultivated plants forces us to rethink crop protection in depth, as we will see in the following sections (2.3, 2.5 and 2.6).

2.3. Plant resistance, plant-soil and plant-plant interactions for crop protection strategies without chemical pesticides

Author: Jean-Louis Drouet

Table of contents

Introduction

The selection of plants began with agriculture when people settled down about 10,000 years ago. By cultivating plants for food, they empirically chose the most beautiful seeds of the plants that they found most interesting.

At the end of the 19th century, the first crosses of selected parents opened the way to so-called **‘classical’ breeding**, which aims to genetically improve cultivated plants to correct their defects (*e.g.* their susceptibility to various pests) by creating new varieties (*i.e.* improved and reproducible populations; *e.g.* Gallais, 2015). By selecting plants capable of recognising genotypes of pests that are common in cultivated plots, genetic (or varietal) improvement has two main types of objectives (Aubertot and Savary, 2005):

- **Increased genetic resistance** to the pest, which helps to prevent, slow down, or make its reproductive cycle less efficient; this resistance cancels out or reduces the pest's rate of reproduction;
- **Morphological characteristics** that make the host plant in its stand less vulnerable to damage from a given pest population level.

Knowledge of the genomes of cultivated plants has progressed greatly in the 20th century thanks to the **development and use of biotechnologies**. This has led to a better understanding of plant resistance mechanisms against pests and to the selection of more resistant varieties, still using ‘classical’ approaches.

The concepts and mechanisms of **resistance/defence and immunity of cultivated plants to pests**, as well as the **interactions between cultivated plants and pests**, are the subject of paragraph 2.3.1.

In addition to these major historical trends, other breeding approaches have developed over the last few decades:

- So-called **'participatory' approaches**, developed by farmers in relationship with researchers, aim to create varieties that meet the needs expressed by farmers who are not satisfied with the varieties produced by classical breeding;
- Breeding strategies have also evolved over the last 20-30 years, taking into account the **immune defence mechanisms of plants** (experts of the thematic group ‘strengthening plant resistance‘, workshop on 2020, December 14th – see Table A2 in the Appendix of the report).

More recently, weak signals have been identified that could prove promising for protecting crops against pests without using chemical pesticides. Two types of interactions, for which knowledge is still only very partial, have been identified and should be integrated into future breeding programmes

- **Interactions between cultivated plants and their microbiome**, developed in paragraph 2.3.2;
- **Interactions between cultivated plants and neighbouring plants**, developed in paragraph 2.3.3.

2.3.1. What is plant resistance?

2.3.1.1. Some definitions

The **‘genetic resistance' or 'varietal resistance'** of a plant refers to the ability of a plant (or crop variety) to resist a pest by blocking or reducing its power of infection and multiplication (Lannou, 2021a). The resistance of a plant is determined by its genes. A **gene** is a piece of hereditary information located on a chromosome at a given locus. **Alleles** are the natural variants of the same gene. The **genotype** (resp.

phenotype) is the set of genetic (resp. apparent) characteristics of an individual. A **major resistance gene** is a gene that confers a resistance that is generally qualitative and very strong. A **sensitivity gene** is a gene that makes infection by a pathogen possible. The **great plasticity of the plant genome** is at the origin of very variable characteristics, allowing plants to adapt continuously to changes in their environment and to external aggressions. While we talk about **resistance, and also epidemics, for pests and pathogens,** this is not the case for **weeds**, for which we talk rather about **crop suppressive capacity** (*i.e.* the capacity of crops to suppress weeds), **crop tolerance to weeds** because weeds are at the same trophic level as crops, or **invasive plants**. Current varieties perform well in terms of potential yields and poorly in terms of their weed suppressive capacity. It is also **preferable to talk about 'crop resistance' or 'plant population/stand resistance'** rather than 'plant resistance' (expert workshop, December 2020).

Resistance, observed in the form of the phenotype of a plant confronted with a pest and thought to be the result of a relatively simple genetic determinism, is in fact the result of a **complex set of molecular mechanisms**, governed by a large number of genes and regulated by multiple interactions. This complexity, even though it has been perceived for years, is only beginning to be understood and explained by researchers. It requires us to go beyond reductionist approaches studying a given process on individual plants in a particular environment, and to move towards a **systemic approach** mobilising the concept of the **phytobiome**. This concept considers not only the plant and its microorganisms but also the plant in its abiotic (*e.g.* climate) and biotic (*e.g.* neighbouring plants) environment and the integration, which is still poorly taken into account, of the plant in its wider environment (biotic and abiotic). For example, a systemic approach would make it possible to mix varieties or associate cultivated species to favour the regulation of weeds that are disadvantaged by competition for access to resources of the environment. The levers that can be mobilised are therefore not only at the scale of the plant but also at larger scales (*e.g.* agricultural practices at the plot scale such as tillage or inputs) (expert workshop, December 2020).

The component of resistance that has really been understood by pathologists and plant breeders in the 20th century is actually only the most visible part of it, which is called specific resistance, or **qualitative (or total) resistance**, with a simple, often monogenic (*i.e.* determined by a single gene) determinism and an equally simple expression, which is the total absence of disease. **Quantitative (or partial or incomplete) resistance** allows some expression of the disease and its effect is on the efficiency of the infection, the development *in planta* or the rate of multiplication of the pest; it is usually, but not always, of polygenic determinism (*i.e.* determined by several genes) In virology, **extreme resistance** occurs when the inhibition of virus accumulation in the infected cell is very early, without cell death. The **durability of resistance** is the length of time that resistance provides satisfactory epidemiological control in a disease-supportive environment (Lannou *et al.*, 2021). **Resistance bypass** by the pathogen (Barbacci and Raffaele, 2021) occurs when minor variations in the 'molecular key' carried by the pathogen can render the plant's detection system of the pest inoperative (Raffaele and Kamoun, 2012).

The more recently used concept of **plant immunity** broadens the notion of resistance and refers to the **set of biological functions that enable plants to resist pests**. Resistance involves various immune mechanisms. Plant immunity corresponds to a systemic vision of plant health and also integrates adapted agricultural practices and, above all, the use of all beneficial biological regulations and biocontrol practices. It allows for coexistence between hosts and their pests in natural systems, *i.e.* a form of equilibrium that is constantly evolving, generally without major accidents. However, the cultivation of plants can create a disruption in this balance, in favour of the pests (Lannou, 2021b). The concept of **agroecological immunity**, which is even more recent, has been defined by the idea of taking into account all external simulations of plants and understanding how they influence the behaviour and health of the crop (RMT BESTIM, 2020).

The **vulnerability** of a plant corresponds to the **degree to which a plant is susceptible to damage from disturbances** (after Urruty *et al.*, 2016). Although the term vulnerability was not commonly used when pesticides were used systematically without considering alternative solutions, it is now used more frequently (*e.g.* frequent returns of pests to crops are a factor of vulnerability; expert workshop, December 2020). **Few vulnerability indicators** are currently available. To study vulnerability to pest epidemics, it is necessary to consider both the probability of their occurrence and the magnitude of their potential consequences. The current trend in agriculture is to focus on the most frequent and least serious epidemics and to ignore the extremely rare but serious epidemics (expert workshop, December 2020). The vulnerability of a plant also refers to the **plasticity of the plant's resistance**, which depends on its pedoclimatic environment and agricultural practices. Although it has been observed for a long time, the study of this plasticity is an emerging field of research and is linked to the concept of agroecological immunity.

Plant tolerance to a pest is the **ability of a plant to grow and reproduce as a healthy plant while infected by a living pest**. The tolerance of the plant decreases as its vulnerability increases. The terms 'tolerance' and 'resistance' refer to two different concepts and the processes involved in tolerance and resistance are different. The term 'tolerance' is not defined in the same way by a plant pathologist working on fungal diseases, a weed scientist studying weeds, or a virologist working on perennial plants. It is preferable to talk about resistance, which is the capacity of plants to block their infection or to reduce the multiplication of pests (see above), as opposed to tolerance, which is the capacity of a plant or a stand to compensate for the damage caused by an infection or a pest (expert workshop, December 2020). However, tolerance may seem promising because it often applies to several stresses and therefore does not subject pests to a single selection pressure that leads to varietal resistance bypasses. These two types of mechanisms (resistance and tolerance), as well as a third one called '**escape**', which consists in **limiting the exposure of sensitive organs or plant stages to the stress**, can all contribute to reducing the harmfulness of a pest.

Another term that also joins those of resistance and tolerance is **resilience** (see Section 2.4).

2.3.1.2. Resistance/defence mechanisms of plants against pests

Over the course of evolution, plants have developed a complex immune system that enables them to survive in the face of pests and sometimes unfavourable environmental conditions, particularly in the current context of climate change, which favours the emergence of new epidemics (Roby, 2021). Research over the last 30 years has led to a **better understanding of the molecular mechanisms underlying plant immunity**, revealing unexpected complexity and robustness. In the case of an interaction between a plant and a pest, a succession or cascade of events takes place, starting with the recognition of the two partners, followed by the transduction of signals emitted at the interface, which will condition the final response, namely the implementation of defence reactions (Aubertot and Savary, 2005).

A first line of **passive defence** is formed by all the **physical barriers** (*e.g.* cuticle, cell wall, spines, fine excrescences of the epidermis called trichomes) and **chemical barriers** (*e.g.* phenols, lignin of the walls, secondary metabolites). These pre-existing defences constitute a first barrier to protect the plant (Favery and Coustau, 2021) but **do not guarantee a sufficient level of security** (Trémousaygue and Deslandes, 2021). The plant can also mobilise additional levels of defence, general or specific, which are based on direct or indirect recognition of the pests. Knowledge of the interaction, defence and resistance mechanisms of plants to insects and nematodes is still limited to a few plant species and a few pests. Some pests have adapted their aggression strategy by producing 'signal' molecules called '**effectors**' or '**elicitors**' (from the Latin *elicere* meaning to provoke or induce) that bind specifically to membrane receptors on a plant and **prevent or reduce the plant's immune responses**. According to Rouxel *et al.* (2021), the term effector in a broad sense can refer to any molecule produced by a pathogen that has an 'effect' (*i.e.* an action) on a molecule or molecules of another organism. Long before the term pathogenesis effector was first mentioned in the literature (Rosqvist *et al.*, 1994), work based on biochemical approaches had identified different types of molecules produced by bacterial or fungal pathogens that have effects on plants.

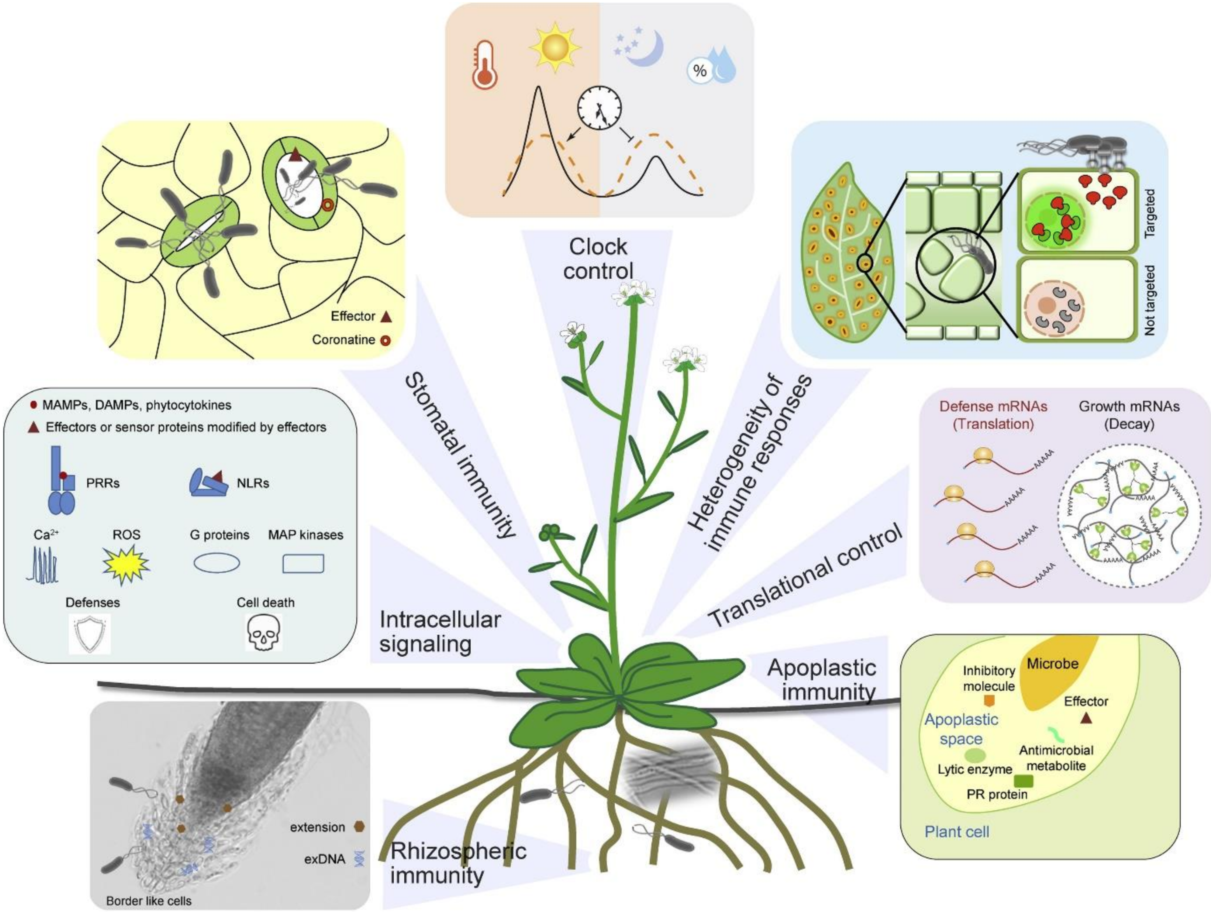
In response to the presence of elicitors, plants have also developed **active defence mechanisms** that can be **molecular**. The 'signal' molecule produced by the pest can indeed induce the stimulation of the plant's defence genes and trigger the production of **defence molecules** such as phytoalexins (*e.g.* phenolic compounds, terpenoids, polyacetylenes) or **compounds involved in signalling the aggression** to other cells, or even to the whole plant by systemic action (*e.g.* salicylic acid, ethylene, jasmonic acid). Stimulation of defence genes can also lead to the accumulation of pathogenesis-related defence proteins (or PR proteins, *e.g.* protease inhibitors). These proteins can inhibit some of the infectivity factors of the pest (*e.g.* proteases, polygalacturonases) and even attack some of their vital structures (*e.g.* parietal structures and plasma membranes; Klarzynski and Fritig, 2001). The study of these mechanisms has led to a better understanding of the steps leading to the incompatible reaction between a pest and a resistant host plant (Dangl and Jones, 2001).

Resistance induction of a plant consists in **stimulating natural defence mechanisms** present in the plant but in a latent state. **Natural defence stimulators** (NDS) or **plant defence stimulators** (PDS) are substances (*i.e.* molecule or mixture of molecules, of natural or synthetic origin, organic or mineral), capable of triggering the natural defence mechanisms of plants before attack by pests (*e.g.* Hammerschmidt *et al.*, 2001). Few SDN/SDP are currently on the market (*e.g.* chitosan, which is a polyoside derived from chitin, harpin, which is a peptide produced by the *Erwinia* bacterium, and glycosphingolipids extracted from the membrane of fungi; Benhamou and Rey, 2012). However, their efficacy against insects or nematodes remains poorly documented and requires further studies (Favery and Coustau, 2021). **Plant defence stimulators can act synergistically or antagonistically with plant growth biostimulants**. According to the official definition from the harmonised EU regulation 2019/1009, a **plant biostimulant** is a product that stimulates plant nutritional processes independently of the nutrients it contains, with the sole purpose of improving one or more of the following characteristics of plants or their rhizosphere: nutrient use efficiency, tolerance to biotic stress, quality characteristics, availability of nutrients confined in the soil or rhizosphere. Biostimulants can be microorganisms (fungi, bacteria, *e.g.* mycorrhizae), plant extracts (*e.g.* amino acids, algae extracts) or mineral extracts (*e.g.* humic acids).

Plant defence mechanisms can also be **immune** (*e.g.* perception of non-self, which can be general or more specific depending on the nature of the molecules recognised) or **signalling** (*e.g.* transcription factors and hormonal response). **The molecular processes highlighted are complex** (Trémousaygue and Deslandes, 2021) and require subtle adjustments of cell metabolism to optimise the immune response without altering the development of the plant. After having been addressed by reductionist approaches, the study of plant immune defence mechanisms must now evolve towards **holistic approaches** (Zhang *et al.*, 2020; Figure 2-25). Trémousaygue and Deslandes (2021) recommend that **future breeding programmes mobilise the diversity of immunity mechanisms and combine them in order to develop immunity that is less easily bypassed by pests**. The use of precise molecular markers, potentially suitable for the introgression of interesting traits into cultivated varieties, could make it possible to identify natural variants meeting the desired selection criteria. Breeding programmes should aim to generate quantitative resistance, resulting in less selection pressure on the pest than total resistance, in order to protect crops more sustainably by limiting pest proliferation and the emergence of new aggression strategies.

Interactions between the host plant and the pest can also take place in a complex biotic context (Ravigné *et al.*, 2021). Indeed, the plant faces multiple pests, with more or less specific resistance mechanisms. Conversely, pests do not only interact with their hosts and their existence has direct and indirect repercussions on other ecosystem actors. Furthermore, the interaction between the plant and the pest can involve a third actor, which can be a second pest simultaneously infecting the same plant, known as **coinfection** (Tollenaere *et al.*, 2016), which is common in natural populations (Seabloom *et al.*, 2015). Coinfection often affects the symptoms on the plant in a positive or negative way (Tollenaere *et al.*, 2016), as well as the epidemiology and evolution of natural pathogen populations (Ravigné *et al.*, 2021).

Figure 2-25. Towards a holistic approach of plant immune responses (Source: Zhang *et al.*, 2020)



The workshop of 2020, December 14th made it possible to identify **three main types of mechanisms** (or approaches or strategies) for strengthening plant resistance to pests: i) stimulating plant defence mechanisms, ii) acting on genetic mechanisms of resistance to pests, and iii) using the natural genetic variability of plants:

- A first major approach consists in **stimulating plant defence mechanisms** (PDS) with molecules or microorganisms or other tools, but these approaches remain empirical and give more or less satisfactory results in field conditions, with trade-offs (synergistic or antagonistic) between plant resistance mechanisms and growth and development mechanisms. As mentioned above, the interactions between the plant and its biotic and abiotic environment are very complex and intervene in the genetic construction of the plant or the introgression of certain traits in the plant. It is thus necessary to take into account the biotic (*e.g.* microbiota) and abiotic environments of the plant (*e.g.* temperature, humidity) that favour the resistance of the plant and the durability of this resistance (and *idem* at the scale of plant populations and at even larger spatial scales);
- A second major approach consists in **acting on the genetic mechanisms of resistance** to pests by using genome editing techniques (*e.g.* CRISPR-Cas), which are being used on an increasing number of plants. The synthesis of small RNAs and small peptides present in the plant (including seeds) and used by the plant to defend itself is an avenue that should be further explored. However, these small RNAs remain difficult to manipulate within the European legislative framework. Other works are also currently developed: i) the search for combinations of genes favourable to plant resistance goes beyond the classic approach focusing on the major resistance genes that are very quickly bypassed by the pests, and ii) the inactivation of genes based on reasoning in terms of gain of resistance or gain of function. This technique is currently very promising in pathology for targeting and inactivating the plant's sensitivity genes;

- A third major approach consists in **using the natural genetic variability of plants** and is currently the subject of major work to avoid other biotechnologies that are more or less well accepted (see Lannou *et al.*, 2021).

In addition to these three main avenues presented above, the experts also stressed the need to **take greater account of the interactions, and all their complexity, between plants and their biotic and abiotic environment** (see above). These interactions include the role of interactions between plants (see 2.3.3), which influence immunity and resistance mechanisms, and which constitute a lever for agriculture without chemical pesticides, or the major role of the microbiota (see 2.3.2) in the immunity and resistance of plants to pests. For example, the microbiota could help the plant to withstand several strains of pathogens by developing partial resistance, which is generally more durable and at the same time less specific and effective for several pathogen species or several strains of pathogens within the same pathogen species.

2.3.1.3. The limits of resistance due to its bypass by pests

The evolutionary implications of species interactions have been known since Darwin (1862; interaction between the orchid called ‘Madagascar star’ and a pollinating butterfly). **Coevolution** (Ehrlich and Raven, 1964) between cultivated plants and pests is antagonistic because reproduction of one species (the pest) is at the expense of the other (the host plant). Over time, **coevolution favours the development of a resistance (or immune defence) system in the plants**, which leads to the avoidance or limitation of the effect of the infection. In return, **pest populations acquire more sophisticated, rapid and recurrent mechanisms of infectivity and aggressiveness** that bypass the plant immune system (Dawkins and Krebs, 1979). Intensive agricultural systems have become vulnerable to pests that have **bypassed varietal resistance** (Ravigné *et al.*, 2021).

According to Saintenac *et al.* (2021), the most obvious successes of breeding for disease resistance concern a **few genes or sources of resistance exploited by breeders and farmers**. These genes or sources of resistance have proven to be effective in the long term, despite intensive use, in many regions and in the presence of high pathogen pressure (*e.g.* resistance genes in wheat or rice against fungi, resistance genes in rice, chilli, potato or tomato against viruses, resistance gene in soybean against a nematode). **Qualitative resistance** (high efficiency and simple determinism) has been the basis of genetic improvement for resistance throughout the 20th century and some of the biotechnological innovations have significantly increased the competitiveness of agricultural production on the international market, especially in emerging economies, despite the opposition they still encounter (Aubertot and Savary, 2005; papers by the Commonwealth Agricultural Bureau International (CABI), the American Phytopathological Society (APS) and the European Commission Research Centre (JRC)). But the rapid deployment of new varieties over large areas has imposed a sudden and very strong selective pressure on pest populations that has constrained crops very differently from wild populations. According to Barrett (1985), breeding for disease resistance, by focusing on a very particular form of resistance, would have artificially increased the importance of the so-called 'gene-for-gene' interaction in agriculture, compared to plant immunity in wild populations (Lannou, 2021b). The gene-for-gene model radically shaped the thinking of pathologists and plant breeders until recently, before they turned their attention to the **quantitative traits of crop-pest interactions** and their mechanisms.

One of the main failures in the use of resistant varieties is the adaptation of target pests through **resistance bypass**. These are particularly frequent, rapid and extensive in the case of qualitative and single-gene resistances. **Quantitative polygenic resistances are generally considered to be more durable**, partly because of lower selection pressure on pest populations and more complex evolutionary trajectories for pest adaptation to resistance. However, counter-examples show total or partial bypassing (called erosion) of quantitative resistance. An interesting avenue for sustainability could be the combination of a major resistance gene and quantitative resistances (Palloix *et al.*, 2009). Resistance bypasses can lead to rejection of the variety by farmers, which then forces breeders to identify new sources of resistance and introduce them into new varieties, which is a long, costly and genetic resource-intensive process. It is therefore essential to protect the effectiveness of resistance through appropriate management.

2.3.1.4. How to overcome resistance bypasses?

The race for arms

The need to continuously introduce new qualitative resistance genes (alleles) into varieties leads to an '**arms race**' (or 'Red Queen theory' with 'boom and bust' cycles) **between plant breeders and pests** (Ravigné *et al.*, 2021). Breeders may then seek to combine genetic engineering and gene accumulation by **pyramiding** (*i.e.* a strategy of accumulating several resistance genes in the same variety), with genomic methods of searching for new genes in wild species close to the cultivated species. However, even if infectivity genes are expensive for pests, the renewal of varieties in annual production does not stop the pest's arms race, especially as the different varieties introduced are often protected by the same resistance genes. By using current and future technological means, allowing real-time measurement of epidemics, monitoring of the genetic diversity of pest populations and rapid and efficient genomic selection of plants, it should be possible to accelerate, at least for annual crops, the development time and deployment of new resistant varieties (Ravigné *et al.*, 2021).

However, given the scarcity of genetic resources and diversity in wild species, engaging in a simple arms race with pests seems misleading. Other solutions should be sought in strategies for managing resistant varieties. One proposal would be to promote a ‘trench warfare’ strategy in agriculture, in order to **favour the sustainability of resistance**. This could be done by increasing the genotypic diversity of resistance genes in a plot or in a landscape or a region. In addition, it could be interesting to vary the proportions of different resistance genes from year to year at a given location, according to temporal management. The sustainability of qualitative and quantitative resistances could be maximised by **breeding varieties that combine qualitative and quantitative resistances** (Brun *et al.*, 2010). However, quantitative resistances should be selected with care by identifying the infection cycle component of the pest and ensuring that it is not tolerance at the individual plant level, otherwise counterproductive results may be obtained as a result of pest adaptation (Trémousaygue and Deslandes, 2021). These mechanisms have been shaped by the evolution of plants in interaction with pests and are now used by breeders to create more resistant varieties (Ravigné *et al.*, 2021).

Global changes (*e.g.* climate change, changes in practices) will also play a role in the regulation of pest populations (see Section 2.4) and interact with the levers for reducing phytosanitary pressure and the genetic levers for improving plant resistance. Given the evolutionary dynamics of interactions between cultivated plants and pests, the virulence-avirulence-resistance-sensitivity responses place cultivated plants in contexts of sensitivity or vulnerability such that they always lose out to pests (expert workshop, December 2020). This raises the question of the effect of global changes on the dynamics of pests and how to select by pyramiding genes with a partial quantitative effect rather than selecting on a single gene with a total qualitative effect that will be quickly bypassed.

The interest of wild plants in finding new resistances

The natural compartment (also called wild compartment) has long been considered as a simple reservoir of infectious disease emergences, but it is also a reservoir of knowledge and avenues for improving the design and deployment of resistant varieties (Ravigné *et al.*, 2021). Understanding the origin of infectious diseases, their epidemiological dynamics and their adaptation dynamics is needed for designing sustainable cropping systems (Zhan *et al.*, 2015). Many of the answers to researchers' questions lie not in cultivated systems (agroecosystems), but in natural ecosystems (Morris *et al.*, 2009; Desprez-Loustau *et al.*, 2016). Many associations between crops and pests are actually recent and result from the adaptation of a pest from the natural environment onto a crop (*i.e.* host hopping; Giraud *et al.*, 2010). This phenomenon can occur when a crop is established in contact with a wild ecosystem or as a result of accidental transport of the pest outside its original geographical range. The continuous increase in the movement of plant products (seeds, grafts, live plants) for trade, consumption or planting means that these accidental introductions now account for the majority of cases of emerging infectious diseases (Anderson *et al.*, 2004).

In the case of these recent associations between cultivated plants and pathogens, understanding the biology of the pathogen and predicting its fate in the crop compartment may logically require studying the functioning of pathogen populations in their native environment, and the host with which they have co-evolved. The wild compartment sometimes contributes to epidemics by harbouring plants on which the pathogens persist, or which are obligatory to complete the parasite cycle. For example, the agent of wheat stem rust, *Puccinia graminis*, has a secondary host in barberry (*Berberis vulgaris*), which is essential for sexual reproduction and winter survival of the fungus (Jin, 2011). This wild reservoir can exchange pathogens with the cultivated compartment during epidemics. In another example, grapevine golden flavescence, caused by the bacterium *Candidatus Phytoplasma vitis*, has alders and clematis as a wild reservoir (Malembic-Maher *et al.*, 2020). While studies on pathogens of cultivated plants are numerous, studies on pathogens in the wild compartment are still rare. The study of the wild compartment remains difficult, especially because of the limited genetic resources. For example, only 6% of known viruses have been isolated from the wild compartment (Malmstrom *et al.*, 2011). This knowledge deficit is particularly clear in the case of emerging diseases (Desprez-Loustau *et al.*, 2016).

One can imagine that in 2050 it will be able to mimic in the cultivated plant the immunity developed by a wild plant or a related plant, for example by replacing an allele from the wild or related plant, so that the cultivated plant can defend itself like the wild plant against a pest. This could be achieved by sequencing the genetic resources of the wild or related plant and by genetic modifications of the crop's pest resistance traits. Such genetic modifications could be achieved using Crispr-Cas9 technologies or other methods that will have been developed by 2050. However, the yield or fruit production of the wild plant would remain low, as it allocates its resources mainly to defence and survival. The wild plant could be considered as a service plant that would not be harvested but could provide an immunity service to nearby cultivated plants. One could then imagine plot configurations with cultivated plants in the centre and service (wild) plants at the perimeter of the plot, thus constituting a physical barrier to pests. One could also imagine that service plants compete with weeds for access to resources (expert workshop, December 2020).

2.3.2. Interactions between cultivated plants and their microbiome

In cultivated plots, plants are constantly developing in association with microorganisms, some of which (*e.g.* bacteria, fungi, viruses) cause varying degrees of damage to crops and penalise harvests and yields, while others benefit crops by improving their nutrition, stimulating their development, or strengthening their resistance/immunity to pests. Among crop protection strategies, knowledge of the interactions between cultivated plants and microorganisms in their environment, as well as an understanding of how cultivated plants can benefit from the presence of phytobeneficial microorganisms, is a weak but promising signal for biological control of cultivated plants, especially against insects and diseases.

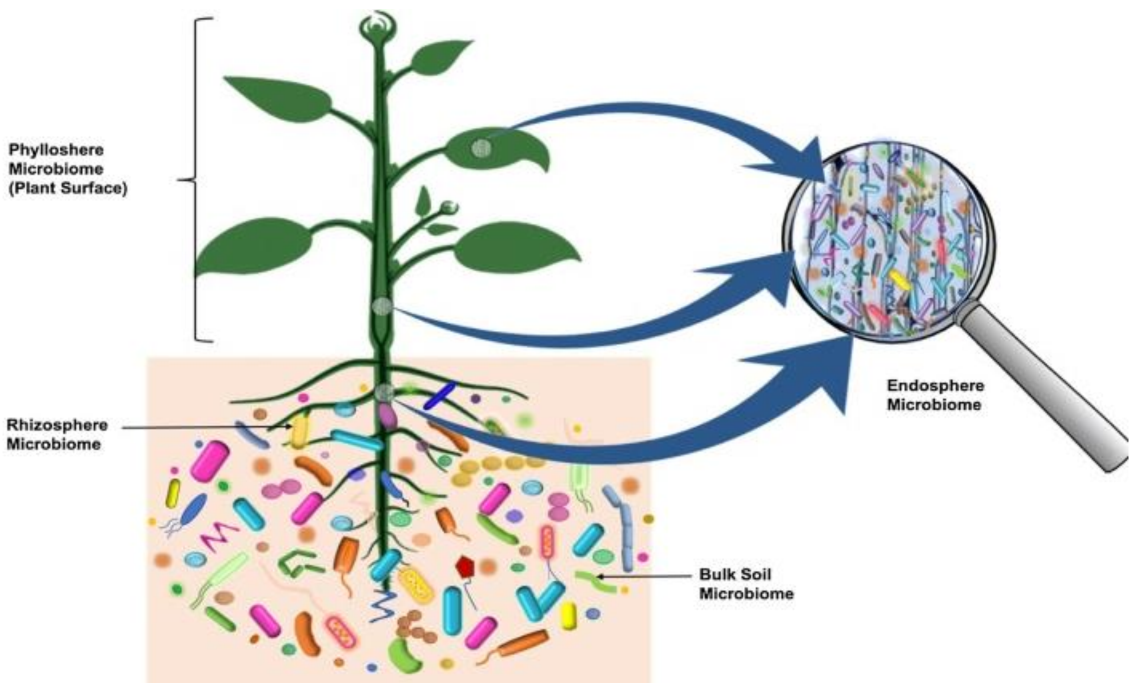
2.3.2.1. Some definitions

The **microbiota** is the set of microorganisms living in a specific environment (called microbiome) on the surface or inside a host (Lannou *et al.*, 2021). A **symbiont** is an organism living in symbiosis with another organism (*i.e.* in a reciprocal beneficial interaction). A microorganism is **endophytic** when it develops within a plant, without negative consequences for the plant. Recent work indicates that multicellular organisms (*e.g.* animals and plants) and their associated unicellular organisms (*e.g.* microbes) can be considered as super-organisms, or holobionts (in ancient Greek, *holos* means whole and *biont* means unit of life; Gilbert, 2019; Suarez and Stencel, 2020). However, the definition and concept of a holobiont is still debated. A **holobiont** can be defined as an ecological unit of a group of organisms that come together based on their evolutionary capacity to achieve a common goal, which is the survival of the holobiont (Sharifi and Ryu, 2021). The **holobiome** includes all living organisms, their genetic material and primary and secondary metabolites, as well as the molecules produced in a particular habitat (Berg *et al.*, 2020; Sharifi and Ryu, 2017). The **microbiome** includes the microbial community living in a particular habitat and its metabolites, mobile genetic elements and relic DNA (Berg *et al.*, 2020). The microbiome helps the holobiont to survive during biotic and abiotic stresses. The presence and abundance of specific microbial species in the microbiome changes during successive phases of plant ontogeny and during biotic/abiotic stresses (Carrión *et al.*, 2019; Cotton *et al.*, 2019; Edwards *et al.*, 2018; Gu *et al.*, 2016).

A distinction is made between the **microbiomes** of: i) the **rhizosphere**, at the interface between the soil and the roots, where telluric pathogens circulate, ii) the **phyllosphere**, in the leaves in direct contact with aerial pathogens, iii) **other microenvironments within plants** (in the anthers, seeds, internal tissues) (Figure 2-26; Dastogeer *et al.*, 2020).

Figure 2-26. The 'Plant Microbiome' consists of diverse microbial communities on the outside surface and in internal tissues of the host plant (Source: Dastogeer *et al.*, 2020)

The rhizosphere, endosphere, and phyllosphere constitute the major compartments of plant microbiome. The soil microbiome is an important source of the plant microbiome.



2.3.2.2. The importance of microbial diversity and the microbiome for cultivated plants

The rhizosphere contains a large number of microorganisms that are considered phytobeneficial. These microorganisms are not always active and, although they colonise the plant roots well, their potential effects on the crop are not well expressed. According to Ravigné *et al.* (2021), the study of plant-associated microbial diversity and proteins produced by microbes and plants shows that **plants form intimate associations with certain microbes and microbes form associations with each other that can be relatively stable and influence plant health** (Vorholt, 2012; Berg *et al.*, 2014). For example, the phyllosphere appears to be dominated by non-pathogenic bacteria belonging to a few major phyla (Proteobacteria, Bacteroidetes and Actinobacteria). These bacteria show specific adaptations for interaction with plants (*e.g.* use of certain sugars and amino acids) and for interaction with other bacteria (*e.g.* formation of clusters; Vorholt, 2012). Thus, the phenotype of plants results from interactions between the plant itself and the microbes it hosts (*i.e.* the holobiont). Diseases, even if caused by an identified primary agent, are the result of **interactions between several microbes and the host** (*i.e.* the pathobiome, Vayssier-Taussat *et al.*, 2014).

According to Mougel *et al.* (2019), **plant-associated microbial communities** have a **huge and still untapped potential to improve plant resistance to abiotic and biotic stresses and *in fine* crop yields** (Trivedi *et al.*, 2017). The results obtained on new functions of plant microbiota have led to increased research efforts on plant-associated microbial communities for sustainable agricultural production. Molecules produced by microbes have the potential to replace chemical inputs (fertilisers and pesticides) used in conventional agriculture. Specifically, the diversity and composition of the microbiota can have a strong effect on stress tolerance (Bernardo *et al.*, 2017), plant health (Mendes *et al.*, 2011) and pest/pathogen control (Bartoli *et al.*, 2016; Lachaise *et al.*, 2017). At a more functional level, **plant microbiota recruitment** appears to be a **fine process involving the plant's innate immune system controlling the hosting of beneficial microbes while eliminating pathogens** (Hacquard *et al.*, 2017). Furthermore, the **root microbiota can stimulate or prime the plant immune system** by strenghtening plant defences against a broad spectrum of pathogens (Bakker *et al.*, 2018).

A growing body of research is focusing on the associations and relationships between microbiota and host plants (Tian *et al.*, 2020). Applications of microbes and microbiota to improve crop productivity and pest resistance require further research. Various genes in microbes related to hormones (*e.g.* strigolactones) and nutrient uptake similar to nitrogen uptake should be studied to find out the mutual link with host plants. Work on microbiota interacting with cultivated plants should combine basic and applied research approaches and address: i) mutualistic symbioses of fungal and bacterial microbes with host plants, ii) plant diseases caused by environmental microbiota, iii) mechanisms to improve crop growth, productivity, resistance and yield quality, or iv) allelochemical effects between plants and microbiota (Tian *et al.*, 2020). Research is also needed on fundamental issues such as the detection of phylogenetic signals that could be phytobeneficial or the modes of action (synergistic and antagonistic) of microbes modulating host plant immunity (Vannier *et al.*, 2019).

Research on microbiomes has mainly focused on those of cultivated plants, whereas the **microbiomes of wild plants** are only beginning to be described and analysed (Ravigné *et al.*, 2021). Cultivated and wild compartments differ in the composition and functions of soil microbiomes (Ravigné *et al.*, 2021): **cultivated plants have fewer symbiotic relationships and their microbial communities are less diverse than in wild plants** (Cordovez *et al.*, 2019). Conversely, comparisons of cultivated and wild plant viruses have shown that virus diversity may be lower in wild populations than in cultivated populations (Bernardo *et al.*, 2018). These authors point to the lack of knowledge on microbial diversity and suggest that natural and cultivated microbiomes function differently and are an important component of the pathogen environment.

2.3.2.3. The holobiont concept

The **holobiont** concept has emerged in recent years as a theoretical and experimental framework for studying **interactions between hosts and their associated microbial communities in all types of ecosystems** (Simon *et al.*, 2019). Beyond the individual plant, this concept mobilises **all the holobionts present in the plot and the landscape** (*e.g.* pathogens including fungi, pests including insects, all microorganisms and macroorganisms in the cropping system). So far, research on the holobiont concept has mainly focused on pathogens, and work is beginning on pests (mainly insects), with very little work on weeds. However, the identification of phytobeneficial microorganisms is difficult because the corresponding genes are distributed in a large number of taxa present in soils and are often still very poorly known, notably due to the lack of available tools. The current trend is to apply the knowledge acquired on a limited number of members of the corresponding functional group to the whole taxon (expert workshop, December 2020). A better understanding of holobionts and of the interactions between host plants and associated microbial communities should enable breeding programmes to evolve towards **more systemic selection of functional holobionts**, including the selection of microbial communities beneficial to cultivated host plants. It is also a question of being able to **monitor and control holobionts** in order to activate the appropriate levers at the right times (*e.g.* genetic improvement of cultivated plants, cultural practices, particularly organic amendments, inputs of microorganisms; see Section 2.5) to strengthen the immunity of cultivated plants.

2.3.2.4. The importance of the microbiome in plant communication

According to Sharifi and Ryu (2021), the **plant-associated microbial community** (*i.e.* the **microbiota**) plays an important role in **plant communication**. Plants decipher complex situations in their habitat by detecting environmental stimuli and molecular patterns associated with microbes, herbivores and other hazards. The perception of these cues generates inter/intracellular signals that induce changes in plant metabolism and physiology. **Signals** can also be transferred between plants through different mechanisms, which Sharifi and Ryu (2021) classify as wired and wireless communications. Wire communication involves transfers of direct signals between plants, via mycorrhizal hyphae and parasitic plant stems. Wireless communication involves the emission of volatile compounds by plants, as well as root exudates caused by microbes and insects, which allow communication between plants without physical contact (*i.e.* allelopathic communication).

Symbiotic associations between plant roots and fungi are extremely common, with arbuscular **mycorrhizal symbiosis** occurring in over 70% of plant species (Cosme *et al.*, 2018). Plants are thus inevitably interconnected via mycorrhizal fungi in a '**common mycorrhizal network**' (CMN) that could transfer signals between plants via the outer surface of hyphae, cytoplasmic flow or electrical signal conduction (Barto *et al.*, 2012; Johnson and Gilbert, 2019). For example, it has been suggested that signalling molecules (*e.g.* jasmonic acid) can be transferred through the CMN, thereby initiating the defence of neighbouring plants against pathogen infection (Song *et al.*, 2010) and herbivory by aphids or caterpillars (Babikova *et al.*, 2013; Song *et al.*, 2014). The role of CMN is still poorly documented and, so far, only its effect on plant competitiveness through nutrient transfer and growth promotion has been demonstrated (Delavaux *et al.*, 2017; Parniske, 2008; Smith and Smith, 2012). In general, there is a **knowledge deficit on the interactions between plant microbial populations and pathogens**. Studies have so far mainly focused on binary interactions between plants or between plants and microorganisms. The challenge is now to address the complexity of these interactions, which are influenced by a large number of biotic and abiotic factors (expert workshop, December 2020).

The microbiota would be an essential lever for strengthening plant immunity and protection, and evidence is still needed to demonstrate this. The experts mentioned several hypotheses such as the **recruitment by the plant of specific microorganisms** that will help it to resist in the event of biotic or abiotic stress (*i.e.* the 'cry for help' hypothesis). For example, in a stress situation, the plant will modify its exudation profile and acidify the rhizosphere, which will allow the recruitment of beneficial microorganisms. Other hypotheses concern the **modification of the microbiota** by the plant itself and neighbouring plants in order to allow the plant to modify its physiology and respond to stress, or the **establishment of fungal highways** (*e.g.* mycorrhizae) that would allow the transfer of microorganisms or metabolites between plants. The 'cry for help' hypothesis requires the existence of a **reservoir of microbial diversity** from which the plant can recruit. The composition of this reservoir depends on a set of agroecological factors including soil and climatic conditions, as well as and agricultural practices. Certain practices carried out to date may have caused the disappearance of certain phytobeneficial microbial species and eliminated their interactions with cultivated plants. **The inoculation of exogenous microbial strains or consortia**, as well as their monitoring and control, would then be avenues to develop in order to reintroduce such phytobeneficial microbial species and re-establish their interactions with cultivated plants. Some phytobeneficial microorganisms in the rhizosphere have given priority to social relationships with each other and the introduction of a set (*i.e.* consortia) of microorganisms working in synergy could thus produce more interesting results for the host plant than the introduction of a single type of microorganism. The increase in knowledge of the interactions between plant immunity and associated microbial communities (endophytes, rhizosphere and phyllosphere) by 2050 should make it possible to **select varieties that are more adapted and resistant to local agropedoclimatic conditions** (expert workshop, December 2020). The geographical location of varieties will also have to be re-evaluated in the light of climate change (see Section 2.4).

Beyond its effect on crop protection, the microbiota would also have a multiservice role (*e.g.* strengthening the immunity and tolerance of cultivated plants to pests and abiotic stresses, contributing to the acquisition of nutrients, acting on phenotypic plasticity during flowering, germination and abiotic stress; expert workshop, December 2020).

2.3.2.5. The impact of cultural practices on the microbiome

The impact of cultural practices on soil and plant microbiota has been little studied to date and the knowledge to be acquired should make it possible to develop intelligent cultural practices aimed at eliminating chemical pesticides and to consider microbiota as a new green generation of products (Mougel *et al.*, 2019).

Varietal mixtures or species associations have a role in the development of phytobeneficial microbial communities. Work in theoretical ecology has shown the value of **varietal mixtures to improve crop productivity and limit the development of pathogens** (Litrico and Violle, 2015). **Plant species associations** can significantly **alter the abundance and composition of soil microbiota**, with a beneficial effect on crop growth and production (Mougel *et al.*, 2019). The supply of biostimulants could enhance the ability of a plant to absorb nutrients, regulate its physiological state and resist biotic and abiotic stresses. Biostimulants, even if they act at the foliar level and at low rates, could also act on the root system and modify, positively or negatively, the microbiota of the rhizosphere. Non-pathogenic soil microorganisms with a proven phytobeneficial role could be mobilised to stimulate or prepare the plant to respond to a biotic or abiotic stress. They may already be present in the rhizosphere and be known as facilitators such as PGPR (Plant Growth Promoting Rhizobacteria).

Without asking farmers to become microbiologists, cultural practices should also aim to **favour the phytobeneficial microbial communities already present in the soil by mobilising the appropriate levers** (*e.g.* organic amendments, planting intercrops, setting up long rotations, choosing inputs that do not damage the existing microbiota). For example, too high levels of mineral fertilisation can lead to soil acidification that is unfavourable to trophic symbioses. Such limits should be integrated into the reflections on technical itineraries (expert workshop, December 2020).

Conventional and organic agricultural systems have a **large impact on the diversity and composition of soil microbiota**, which is more heterogeneous in organically managed systems than in conventionally managed ones (Lupatini *et al.*, 2017). For example in wheat, the abundance of key fungal taxa (*i.e.* arbuscular mycorrhizal fungi) is much higher in organically grown plants than in conventionally grown ones (Banerjee *et al.*, 2019), and bacterial communities are mainly structured by management type (Hartmann *et al.*, 2015). Other work has shown that the diversity of microbial community is higher with organic amendments in organic agriculture than with mineral fertilisation in conventional agriculture (Hartman *et al.*, 2018).

2.3.2.6. The seed microbiome

Part of the plant microbiota is transmitted vertically, especially through seeds. The development of **solutions based on seed microbiota to strengthen plant immunity and protect crops** appears to be a promising avenue, but little is known about the processes and functions performed by microbial consortia and their effects on seed immunity and vigour (Barret *et al.*, 2019). A few studies have shown that seed microbiota could improve seed germination, but their role in protecting plants from pathogens is still unknown (Escobar-Rodriguez *et al.*, 2019). New approaches using synthetic microbial communities (SynComs) could explore the causal links between the microbiota and the host plant (Vorholt *et al.*, 2017).

However, only a very small part (about 1%) of the microbiota can be transmitted vertically from the seed to its progeny, and the microorganisms present at the beginning of the plant's life will gradually disappear during the plant's development. Moreover, seeds are sterilised in current practices, which breaks the chain of transmission of their microbiota. The weight to be given to the seed microbiota must therefore be relativised to that of the agropedoclimatic conditions (expert workshop, December 2020).

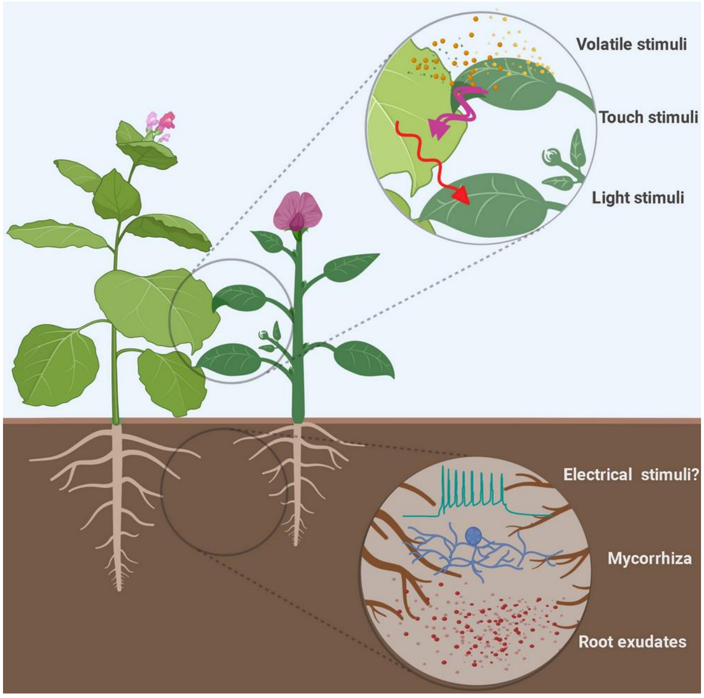
2.3.3. Interactions between cultivated plants and other plants (cultivated, related, wild, weeds)

Until the early 1980s, plants were traditionally considered passive, affected by their neighbours only through indirect effects on resource availability (Pierik *et al.*, 2013). **Interactions between cultivated plants and other plants (cultivated, related, wild, weeds) have always been neglected** (Vicherová *et al.*, 2020). However, over the last 30-40 years, **a growing body of work has shown that plants sense, respond to and interact with their neighbours**. These interactions are often quite subtle and slow and can also be unintuitive and surprising (Bilas *et al.*, 2021). Just as the interactions between cultivated plants and their microbiome, the interactions between cultivated plants and their neighbours are still poorly understood but constitute a promising weak signal for crop protection against pests and especially against weeds present in cultivated plots.

2.3.3.1. Mechanisms for detecting neighbouring plants

Probably the most important and durable biotic stress that a plant can encounter is that of its neighbours, especially weeds, which represent a direct threat to access to resources (light, water, mineral nutrients). Above ground, plants have well-described responses to poor light quality or shading, whether generated by plants or not (Roig-Villanova and Martínez-García, 2016). Root growth responses to soil nutrient availability have been widely characterised (*e.g.* Shahzad and Amtmann, 2017) and will inevitably be triggered if neighbouring plants deplete the environment of nitrate and phosphate (*e.g.* de Kroon *et al.*, 2003; Nord *et al.*, 2011; Schenk, 2006). Plants may also respond passively to the presence of neighbouring plants simply because of reduced resource availability in the environment (Pierik *et al.*, 2013; Schenk, 2006). Recent work highlights that plants have multiple mechanisms by which they can actively detect neighbouring plants (Figure 2-27; Bilas *et al.*, 2021), using 'cues' (*i.e.* information produced by neighbouring plants that allows them to be detected; Karlovsky, 2008; Shelef *et al.*, 2019).

Figure 2-27. Mechanisms of neighbour detection by plants (Source: Bilas *et al.*, 2021)



Several studies have shown that plants are able to distinguish between genetically related and unrelated individuals (*i.e.* kin recognition), and exhibit more cooperative behaviour towards their relatives (*i.e.* positive kin discrimination; Anten and Chen, 2021). The effects of kin recognition go far beyond reducing competition for resources between related plants and involve interactions with symbionts (*e.g.* mycorrhizal networks). Kin recognition therefore likely has important implications for the evolution of plant traits, plant population diversity, ecological networks, microbial communities and ultimately plant immunity. Selection on kin is potentially promising for crop breeding as it could produce varieties with less competitive traits and thus better population performance (Anten and Chen, 2021).

Two complementary levers could be used to select on interactions between neighbouring plants and strengthen their immunity and phytobeneficial microbial communities (expert workshop, December 2020; see 2.3.2), on the one hand by acting on mechanisms exogenous to the cultivated plant (essentially antagonisms or competitions between neighbouring species, or between microbial species and pathogens present in the phytobiome), and on the other hand by modulating the functions of the endophytic microbiota (on the surface or in the tissues of the plants).

2.3.3.2. The different types of signals between neighbouring plants

Interactions between neighbouring plants are considered in this paragraph as signals (light in quantity and quality, chemical or allelopathic through aerial volatile compounds and root exudates, mechanical through touch; Bennett, 2021). However, **knowledge is still lacking on interactions between**

neighbouring plants, particularly on the mechanisms, traits of interest and genes involved (Bilas *et al.*, 2021), in order to be able to take them into account in varietal improvement programmes and to assess their potential contribution to pest regulation in field conditions (expert workshop, December 2020).

Light signals

Plant organs absorb, reflect and scatter incoming solar radiation, thus reducing photosynthetically active radiation (PAR), the light red:far red ratio (R:FR ratio) and blue light (Bilas *et al.*, 2021). This creates a **signal of the presence of neighbouring plants**, distinct from **fluctuations in the quantity and quality of ambient light**. Plants are extremely sensitive to these light quality perturbations and can use light signals to detect each other over large distances in the absence of shading (Roig-Villanova and Martínez-García, 2016).

Light signals generated by neighbouring plants are detected by the now well-known **plant photoreceptors**, including phytochromes highly sensitive to far red light and phototropins sensitive to blue light. Leaf tips are the primary site of light signal detection, making it less likely that self-shading will trigger these responses (Pantazopoulou *et al.*, 2017). Urban *et al.* (2017) found that **UV-C light flashes** have the potential to prime plant defences on a wide range of crops and pathogens. Working on strawberry powdery mildew as well as downy mildew and grapevine powdery mildew, these authors showed that such flashes (rates and treatment frequencies) are more effective than continuous PAR radiation, which would suggest the existence of specific physiological responses. Moreover, unlike other elicitors, these flashes seem to have only moderate direct stimulating effects on plant defences. This work on the responses of plants to their neighbours shows that they actively **interact with each other by sending and receiving light signals** (Huber *et al.*, 2021).

Volatile organic compounds (VOCs) as aerial chemical signals

Plants can detect the presence of neighbouring plants and respond quickly to potential competition or threat by emitting VOCs. For example, an indication of the proximity of an emitting plant can be 'inferred' by a receiving plant due to the rapid diffusion rate of highly volatile compounds compared to moderately volatile compounds (Baldwin, 2010; Heil and Karban, 2010; Ninkovic *et al.*, 2019). VOC emissions would be very effective over short distances, whereas they would fade rapidly over longer distances (Heil and Adame-Álvarez, 2010). The simple nature of VOC signals would also allow eavesdropping by unrelated neighbours (Karban *et al.*, 2003; Ninkovic *et al.*, 2013).

Knowledge is still lacking on the VOCs involved and the mechanisms involved in distinguishing between neighbouring plants, as well as on the perception of VOCs by neighbouring plants. Moreover, recent studies have shown that **VOC detection by plants is mainly associated with defence priming, rather than with the plant's response to the presence of neighbouring plants** (Bilas *et al.*, 2021).

Root exudates as underground chemical signals

Plants exude large amounts of organic molecules into the soil (Bais *et al.*, 2003), which play a number of functional roles such as conditioning the soil by modifying its adhesive properties or pH (Vives-Peris *et al.*, 2020). Plants also release **signalling molecules that promote the formation of beneficial symbioses with microorganisms, suppress pathogens and act allelopathically** (Ehlers *et al.*, 2020; Rolfe *et al.*, 2019). These compounds can persist in the soil due to low rates of oxidation and photodecomposition (Karlovsky, 2008) and change, through plant-soil feedback, the properties of the soil in a way that is noticeable to both the neighbouring plants in place and their progeny (Hu *et al.*, 2018; Van der Putten *et al.*, 2013).

Plants can detect the mixture of chemicals exuded by other plants, in the absence of actual neighbouring plants or any nutrient depletion, and can respond with changes in root architecture and growth (Biedrzycki *et al.*, 2010; Kong *et al.*, 2018; Semchenko *et al.*, 2014; Yang *et al.*, 2018; Bilas *et al.*, 2021). Exudate gradients in the soil could therefore provide information on the proximity of neighbouring plants, as well as their physiological status, and could thus allow roots to precisely avoid neighbouring roots (Fang *et al.*, 2013). **Root exudates have regularly been suggested as key factors in the apparent ability of plants to distinguish self/non-self and kin/non-kin** (Biedrzycki *et al.*, 2010; Semchenko *et al.*, 2014; Yang *et al.*, 2018). The candidates suggested so far (*e.g.* jasmonic acid) seem likely to be generic signals, involved in triggering broad responses such as allelopathy (Kong *et al.*, 2018). For example, strigolactones are a class of phytohormones that are also exuded into the soil and play a broad signalling role in the rhizosphere, including promoting the formation of mycorrhizal associations (Waters *et al.*, 2017). In another example, the molecule Dimboa, secreted by maize roots to warn neighbouring plants, is also an antifungal molecule acting through the recruitment of phytobeneficial microbiota. Not all exuded molecules are phytobeneficial and a major unresolved issue is the production of molecules that are toxic to undesirable neighbouring plants and not toxic to the plant itself (expert workshop, December 2020).

Touch as a mechanical signal

Plants are naturally exposed to mechanical stresses by a range of factors (*e.g.* wind, insects, physical obstacles) and **mechanisms allow them to sense and respond to these mechanical stresses**, which can be seen as a 'touch' response (Hamant and Haswell, 2017). These mechanical stresses may be able to stimulate plant defence (Li and Gong, 2011). **The effectiveness of the mechanical stimulus depends on the length** (*i.e.* rate, *e.g.* transient bending exerted on the stem) **and repetitiveness** (*i.e.* frequency) **of the signal** and less on the force applied (Coutand and Moulia, 2000; Anten *et al.*, 2010; Coutand *et al.*, 2010). Plants are sensitive to even light touch of neighbouring plants, which is a quick indicator of their presence (Markovic *et al.*, 2016). These tactile stimuli are perceived with great sensitivity by leaf trichomes and root tips (Massa and Gilroy, 2003; Zhou *et al.*, 2017). Plant-generated touch is clearly distinct from other mechanical stimuli, as touch, wind and mechanical damage evoke distinct molecular responses (Anten *et al.*, 2010; Markovic *et al.*, 2016). Responses to touch result in stronger plant growth allowing the plant to move away from neighbouring plants or acclimatisation of the plant to its neighbours through the production of stronger structures giving them a competitive advantage over their neighbours.

The touch of neighbouring plants appears to play a particularly important role in **priming plants for other interactions**, and has been found to modify both the **release of VOCs and root exudates** (Elhakeem *et al.*, 2018; Markovic *et al.*, 2016). Touch remains a very simple cue and its supposed role in transmitting information about the identity of neighbouring plants has not yet been demonstrated (Bilas *et al.*, 2021).

Sound as an acoustic signal

Very recent work showed that stressed plants emit airborne sounds that can be detectable by other organisms and opens avenues for understanding plants and their interactions with the environment (Khait *et al.*, 2023).

Conclusion

The contribution of biological and genetic levers to crop protection has historically been achieved through **varietal improvement** methods. Since the end of the 19th century with the first crosses of plants with pest resistance traits, **methods and technologies have continued to progress** in order to produce cultivated varieties with total (or qualitative, often monogenic) resistance genes that can be rapidly bypassed by pests, as well as cultivated varieties with partial (or quantitative, polygenic) resistance genes that are less easily bypassed by pests. Given the **rapid bypass of resistance genes in this arms race** between the crop and its pest, classical breeding methods tend to produce **resistance that is not very durable** and thus show their limits.

Research on the resistance of cultivated plants has recently focused on the concept of **plant immunity**, which considers all the biological functions that enable plants to resist pests. This concept corresponds to a **systemic vision** of plant health and takes into account the **interactions, and coexistence, between the host plant and its pest**. More recently, it has been extended to the concept of **agroecological immunity**, which takes into account all the interactions between the host plant and its biotic and abiotic environment. The knowledge to be acquired on plant immunity and the complex interactions between the cultivated plant and its immediate environment (*i.e.* within the plot) and more distant environment (*i.e.* at the scale of landscapes) opens up a promising avenue for **biological crop protection**, in particular by **stimulating/strengthening the plants' defence mechanisms**. In addition, the knowledge acquired or to be acquired on **wild plants**, which present a much greater genetic diversity than that of cultivated plants and which have developed defence mechanisms against pests under natural conditions, could be mobilised to strengthen the immune system of cultivated plants. Wild plants could also play the role of **service plants**.

Other work has also been undertaken recently to better understand the complexity of crop populations interacting with their biotic environment other than their pests. This work focuses in particular on i) the presence of **microorganisms potentially beneficial to cultivated plants** and ii) the presence of **neighbouring plants** with which they can **interact through the emission or reception of positive/attractive or negative/repulsive signals** (*i.e.* light signals in quantity and quality, chemical or allelopathic signals through aerial volatile compounds and root exudates, mechanical signals through touch). Knowledge still needs to be acquired on the mechanisms underlying these complex interactions between cultivated plants and their microbiome on the one hand and between cultivated plants and their neighbours on the other hand. This knowledge will make it possible to understand the way in which cultivated plants can **take advantage of these interactions to strengthen their immunity to pests** and *in fine* to **mobilise these interactions in future 'biological' crop protection strategies** (*e.g.* selection of functional holobionts, inoculation of microbial consortia, selection of varietal mixtures and associations of cultivated and wild species).

2.4. Effects of climate change on pests and pest x crop interactions, and resilience of cropping systems

Author: Jean-Louis Drouet

Table of contents

Introduction

According to the International Plant Protection Convention (IPPC, 2021), climate change poses a unique challenge to plant health. It will affect ecosystems and crop production systems worldwide, impact on international trade flows of crop products, and also influence the infectivity, severity and distribution of pests worldwide. In particular, climate change will pose an extraordinary test to the global plant health community and its ability to provide effective and coordinated science-based solutions.

The first paragrah of this Section provides definitions of key terms related to climate change, including average trends to 2050, bioclimatic factors considered, climatic hazards and extreme events, and resilience of cropping systems, including terms such as robustness, adaptability, stability, vulnerability or transformability of cropping systems. The second paragrah presents a synthesis of the work carried out over the last 30 to 40 years, mainly based on experimental approaches, on the effects of bioclimatic factors on pests and on interactions between host plants and pests. The third paragrah describes attempts to model these effects and climate change on pests and host-plant interactions. The fourth paragrah presents some mitigation and adaptation measures to climate change. The fifth paragrah identifies knowledge and research gaps. Finally, given the multiplicity of pests and interactions between host plants and pests, the high spatial variability of climatic factors and the increased frequency of future climate hazards and extreme events, the sixth paragrah identifies some ways to develop greater resilience of cropping systems to climate change.

2.4.1. Definitions

2.4.1.1. Climate change, climate hazards, extreme events

According to IPPC (2021), the term '**climate change'** refers to the combined global average increase in surface air temperature and ocean surface temperature over a 30-year period. According to the IPCC (2018) report, global warming is likely to reach 1.5°C or even 2°C between 2030 and 2052 compared to the period 1850-1900, which serves as a proxy for pre-industrial temperatures, if it continues to increase at the current rate (Figure 2-28). The trend increase in temperatures, as well as in greenhouse gas concentrations (notably CO_2 but also N_2O and CH_4) and pollutants (ozone O_3, ammonia NH_3, nitrate NO_3, etc.), is characterised by a long time span and wide spatial scales. Climate change is projected to have a negative impact on production if temperature rises locally by 2°C or more above late 20th century levels, although there may be beneficial effects in some parts of the world, particularly at high latitudes and altitudes. These **regional differences** include **increase in mean temperature in most continental** and oceanic regions, **heat extremes in most populated areas**, **heavy precipitation events in several regions**, and the **likelihood of droughts and precipitation deficits in some regions** (Figure 2-29).

In addition to these extreme events, **climate hazards** will become increasingly frequent with climate change and will be characterised by short time scales and relatively small spatial areas: storms (strong winds and heavy rain), droughts (summer heatwaves, winter mildness), floods, etc. In Europe, extreme weather events and climatic hazards have already led to fluctuations in the quality and quantity of harvested products, and yield losses have reached such a level that they threaten the existence of farmers (Life-AgriAdapt, 2020). Figure 2-30 shows the main impacts of climate change in each region of Europe (adapted from EEA, 2017). At the global scale, food and fibre production and plant biosecurity, which includes all strategies to assess and manage risks posed by infectious diseases, quarantine organisms, invasive alien species and living modified organisms in natural and managed ecosystems, will also be affected (Gregory *et al.*, 2009; Stack *et al.*, 2013).

Figure 2-28: Global surface temperature increase relative to the period 1850-1900 (Source: IPCC, 2021)

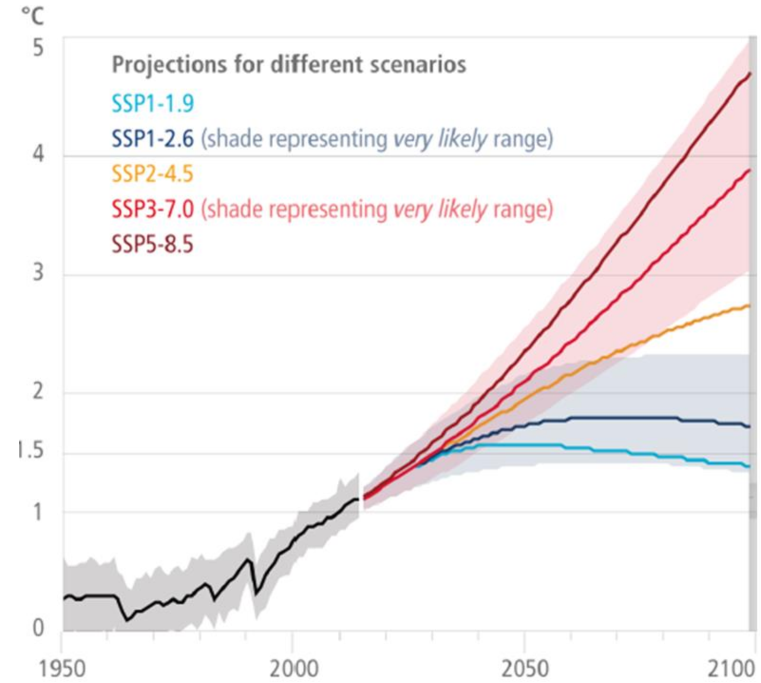


Figure 2-29: Annual mean temperature change (°C) relative to the period 1850-1900 (a) and annual mean precipitation change (%) relative to the period 1850-1900 (b) (Source: IPCC, 2021)

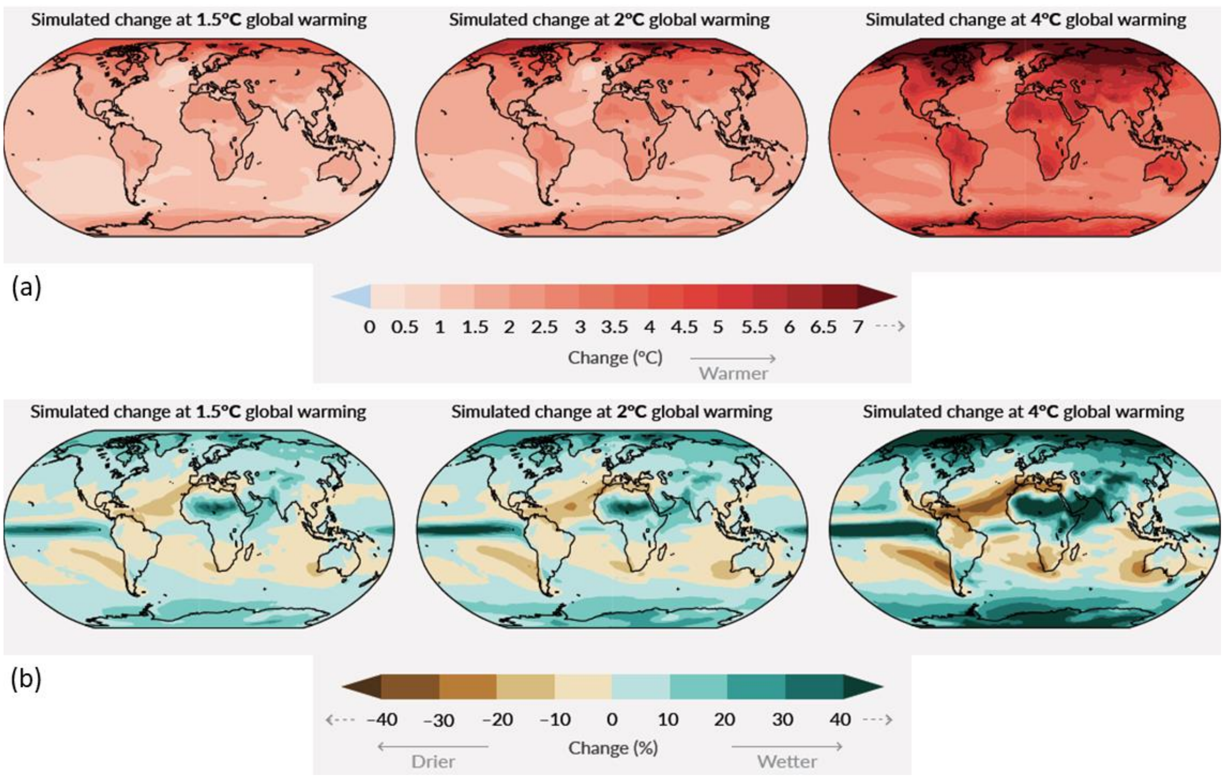
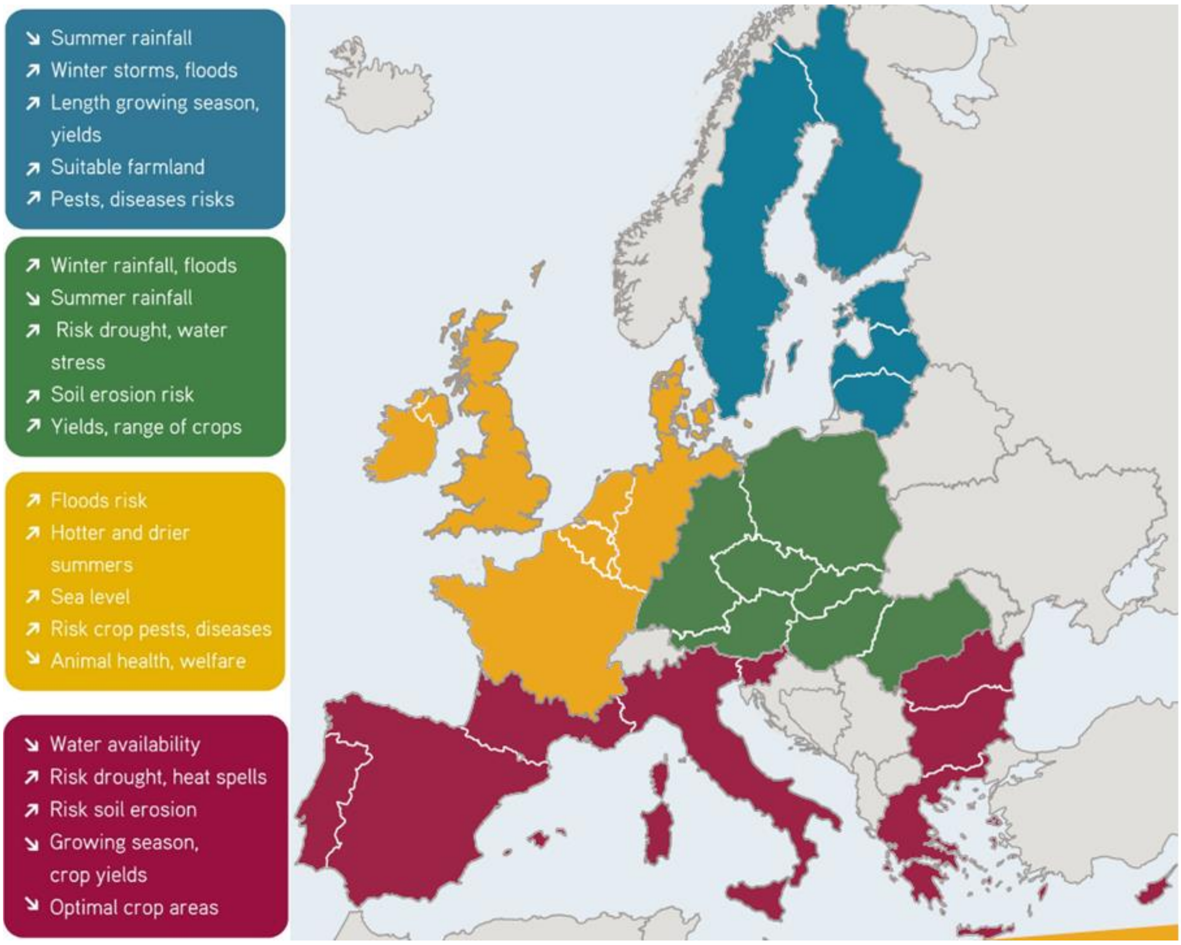


Figure 2-30: The four climate risk regions in Europe and the risks in each of them
(Source: Adapted from EEA, 2017)

Blue: Northern region, Yellow: Atlantic region, Green: Continental region, Red: Southern region.



The (micro-)meteorological factors affecting the functioning of pests and plants (crops and weeds) are temperature, precipitation and relative humidity, as well as concentrations of atmospheric gases (CO_2, O_3 and other pollutants).

The increasing frequency of climatic hazards and extreme events remains unpredictable and makes local/regional predictions of different climatic factors highly uncertain. As a result, the nature and extent of the impact of climate change on pests and their interactions with host crops will vary depending on the capacity of cropping systems and natural ecosystems to adapt and evolve. It is therefore essential to strengthen the resilience of these systems, in relation to their robustness, stability, adaptability, transformability and vulnerability.

2.4.1.2. Resilience, robustness, adaptability, stability, vulnerability, transformability

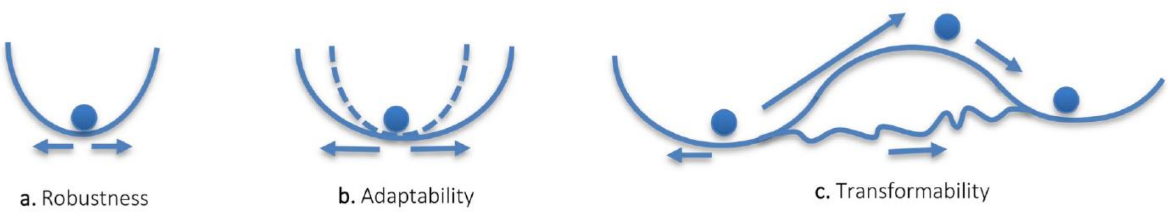
The term '**resilience**' is increasingly pervasive in scientific and policy debates. The popularity of this concept comes at a time when biophysical, social and economic conditions are seen as increasingly volatile, unpredictable and uncontrollable (Darnhofer, 2014), partly in relation to the impacts of climate change (IPCC, 2021). The term 'resilience' comes from the Latin 'resilire', which means 'to bounce back'. In the sciences, it appeared in 1858 to designate in mechanics the capacity of a material to resist the application of a force (rigidity) and to absorb it by deforming (ductility). Holling (1973) later used it in his seminal paper on **systems ecology**, highlighting in particular that ecosystems generally have **several stable regimes**; for example, a lake can be clear or turbid, *i.e.* dominated by algae (Scheffer and Carpenter, 2003). In this context, **resilience is the ability of an ecosystem to remain within a domain bounded by critical thresholds of a given regime** (Gunderson and Holling, 2002), avoiding a shift to an alternative regime that is characterised by different structure, function, identity and feedbacks (Walker *et al.*, 2006). An **ecosystem** should not be understood as a state of equilibrium, but as a **dynamic and constantly changing system, especially in response to disturbances**. One of the most widely used definitions of resilience was then given by Folke *et al.* (2010) as 'the **ability of a system to absorb disturbance and reorganise itself while undergoing change, so as to retain essentially the same function, structure and feedbacks, *i.e.* the ability to change in order to maintain the same identity'**.

The term resilience has been used in many disciplines, with various meanings and connotations (Darnhofer, 2014). Several resilience frameworks have already been developed and applied to components of agricultural systems (Meuwissen *et al*., 2019), such as farms (*e.g.* Darnhofer, 2014; Herman *et al*., 2018), people (Coutu, 2002), businesses (Reeves *et al*., 2012), supply chains (Leat and Revoredo-Giha, 2013; Stone and Rahimifard, 2018) and social-ecological systems (Walker *et al*., 2004; Folke *et al*., 2010; Stockholm Resilience Centre, 2015). These various meanings all have in common an emphasis on the ability to respond effectively to change, particularly unpredictable and sudden change.

According to Darnhofer (2014), resilience encompasses buffering capacity, adaptive capacity and transformative capacity. Meuwissen *et al.* (2019) also distinguished three resilience capacities for cropping systems (Figure 2-31):

- **Robustness** is the ability of the cropping system to withstand (un)anticipated stresses and shocks;
- **Adaptability** is the ability to change the composition of inputs, production, marketing and risk management in response to shocks and stresses, but without changing the structures and feedback mechanisms of the cropping system;
- **Transformability** is the ability to significantly alter the internal structure and feedback mechanisms of the cropping system in response to severe shocks or sustained stress that makes it impossible to maintain the *status quo*; such disruptions can result in changes in the functions of the cropping system, they can occur after tipping and collapse points have been reached and also result from a sequence of small incremental changes (Termeer *et al.*, 2017).

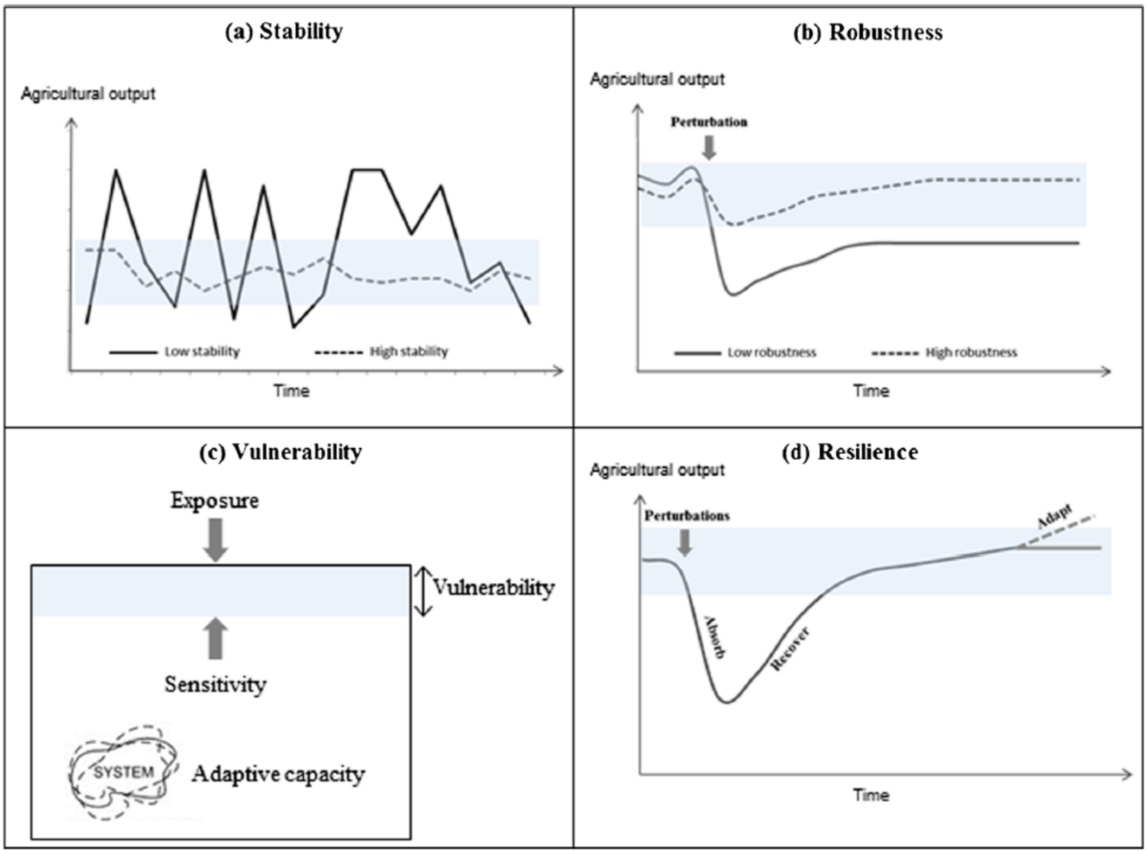
Figure 2-31: Illustration of the three resilience capacities of cropping systems (Source: Meuwissen *et al.*, 2019, adapted from Holling *et al.*, 2002)



In a less encompassing way, Urruty *et al.* (2016) presented the notion of resilience of cropping systems by distinguishing it from the notions of robustness, stability and vulnerability (Figure 2-32):

- **Resilience** *per se* is the ability to absorb change and anticipate future disturbances through adaptive capacity;
- **Robustness** is the ability to maintain desired levels of crop production in the face of disturbances;
- **Stability** is characterised by the constancy of crop production over long periods of time or across various spatial environments;
- **Vulnerability** is the degree to which cropping systems are susceptible to damage from disturbances.

Figure 2-32: Illustration of the concepts of stability, robustness, vulnerability and resilience (Source: Urruty *et al.*, 2016, adapted from Mumby *et al.*, 2014 and de Goede *et al.*, 2013)



Darnhofer's (2014) definition is in line with other definitions of resilience in an agricultural context. For example, the OECD (2020), like other major institutions (Resilience Alliance (Folke, 2016), JRC (Manca *et al.*, 2017), IPCC (2018) and FAO (2018)), has defined **resilience as the capacity of a system to absorb disturbances, adapt and transform in response to adverse events**. Darnhofer (2021) notes that it is not always clear how these three aspects of resilience (absorbing, adapting, transforming) are conceptually linked (Gallopín, 2006; Cutter *et al.*, 2008; Folke *et al.*, 2010; Miller *et al.*, 2010; Alexander, 2013; Klein *et al.*, 2003). Furthermore, **resilience tends to be understood as the maintenance of a system**, which gives it an ambivalent relationship with change, particularly transformative change, which by definition leads to a fundamentally new system (Folke, 2016). It is therefore **unclear whether adaptive capacity is an aspect of resilience or whether resilience and adaptability are two distinct concepts that exist side by side**. A number of publications seem to indicate that they are distinct by explicitly referring to either resilience or adaptive capacity, as do, for example, the FAO (2018) or the IPCC (Jones, 2019). This is in line with Urruty *et al.* (2016) who indicate that the key levers for a transition towards more stable, robust, less vulnerable or more resilient cropping systems can be summarised in two broad categories: i) increasing the intrinsic diversity of cropping systems and ii) increasing their adaptive capacity. These key levers are in line with the five generic principles proposed by the Resilience Alliance (2010) to strengthen the resilience of cropping systems:

- **Diversity**, including both functional diversity (Kerner and Scott, 2014) and response diversity, the latter referring to different responses to disturbances (Reidsma and Ewert, 2008; Carpenter *et al.*, 2012);
- **Modularity**, *i.e.* the internal division of the system into independent but connected modules (Carpenter *et al.*, 2012) with potentially different functions;

- Openness, which refers to the connectivity between systems (Carpenter *et al.*, 2012);
- The **closeness of feedbacks**, *i.e.* the response of one part of the system to changes in other parts of the system (Walker and Salt, 2006), where institutions and social networks shape information and material flows;
- **System reserves**, *i.e.* the stocks of resources in terms of natural, economic and social capital that a system has access to when under stress and shock (Kerner and Scott, 2014); these provide a buffer to compensate for the loss or failure of system functions (Biggs *et al.*, 2012); larger and more diverse reserves generally confer greater system resilience (Resilience Alliance, 2010).

For the following of this foresight study, we chose to characterise the resilience of cropping systems by their robustness (linked to the internal structure of the system) and adaptability (related to actions external to the system) to pests in a context of climate change.

2.4.2. Effects of bioclimatic factors on pests and pest x plant interactions

Over the last 30-40 years, several studies have sought to assess the effects of several factors (increasing temperatures, CO_2 concentration, ozone or ultraviolet B radiation, changing water or moisture conditions) on the incidence and severity of plant pathologies (IPPC, 2021). Studies have focused on pests affecting field crops such as wheat, barley, potato, soybean or rice (Bregaglio *et al.*, 2013; Evans *et al.*, 2008; Launay *et al.*, 2014; Luck *et al.*, 2011; Mikkelsen *et al.*, 2014), horticultural crops (Gullino *et al.*, 2018; Koo *et al.*, 2016), including tropical crops (Ghini *et al.*, 2011), and forests (Battisti, 2008; Jactel *et al.*, 2019; Sturrock *et al.*, 2011).

The effects of climate change on pest species are complex and are characterised by direct effects on pests and indirect effects, especially on host crops, as well as interactions between these effects. Any change in warming and other climatic and atmospheric conditions in a given location can have direct or indirect effects on insect pests, pathogens and weeds. Possible direct and indirect effects on pests include i) changes in their geographical distribution (expansion or contraction) or increased risks of pest introduction, due to climate change and also to increased international trade; ii) changes in their seasonal phenology (*e.g.* the timing of spring activity, the synchronisation of pest life cycle stages with their host plants and natural enemies); and iii) changes in different aspects of population dynamics, such as overwintering and survival, population growth rates or the number of generations of polycyclic species (Juroszek and von Tiedemann, 2013a; Richerzhagen *et al.* , 2011).

In general, all important stages of the life cycle of insect pests, pathogens and weeds (survival, reproduction and spread) are more or less directly influenced by temperature, relative humidity, amount or quality of light, wind or any combination of these factors. The physiological processes of most pest species are particularly sensitive to temperature variations (Juroszek *et al.*, 2020). For example, high temperatures can particularly favour the spread of plant viruses and their insect vectors until their upper temperature threshold is reached (Trebicki, 2020).

2.4.2.1. Approaches used

Studies over the past 30-40 years that have sought to assess the effects of several bioclimatic factors have relied on various research approaches.

Experimental approaches consist of **experiments to examine the effects of changing one or more meteorological parameters**. They can provide useful information about the effects of climate change on pests and diseases, but few such studies have been able to realistically reproduce climate change (Chakraborty and Newton, 2011; Ingram *et al.*, 2008; Loustau *et al.*, 2007; Luck *et al.*, 2011; Pautasso *et al.*, 2012).

Other studies using approaches in the natural environment have examined **species along latitudinal or altitudinal gradients as an indicator of climate change over time**. These approaches include research along an altitudinal gradient including low to high elevation sites (Betz *et al.*, 2020; Garibaldi *et al.*, 2011), with associated changes in air temperature and humidity, and work conducted in different habitats along a latitudinal gradient (*e.g.* in temperate, semi-arid and subtropical climatic conditions (Bairstow *et al.*, 2010; Scalone *et al.*, 2016). The first approach has the advantage of having an identical photoperiod along the altitudinal gradient. In the second approach, the photoperiod is likely to vary along the latitudinal gradient. In tropical regions, for example, days are shorter and nights longer in summer and vice versa in winter, unlike in temperate regions. These differences in photoperiod must be taken into account when interpreting the results. Nevertheless, this type of approach is useful for identifying broad trends over wide environmental gradients and across a range of climatic regions under real conditions. Such studies can also help to determine whether a given species is restricted to a specific climate or whether it is widespread and likely to spread to warming areas (Juroszek and von Tiedemann, 2013a).

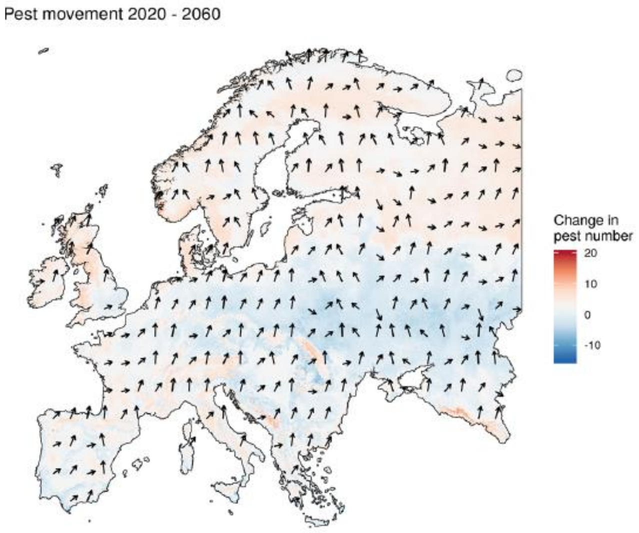
In addition to these empirical experimental approaches, **meta-analyses of datasets** have been carried out to identify general trends in the response of certain pests when exposed to changing climate variables (Koricheva and Larsson, 1998; Massad and Dyer, 2010; Vilà *et al.*, 2021). In addition, long-term datasets from field observations have been used to study the effects of climate change that are already noticeable due to warming in recent decades (Altermatt, 2010; Huang and Hao, 2020; Jeger and Pautasso, 2008). These long-term datasets can serve as a baseline for future studies (Huang and Hao, 2020; Robinet and Roques, 2010) as they can help researchers distinguish between impacts due to climate change and those resulting from other factors (Garrett *et al.*, 2016, 2020). Some researchers have tried to **refine predictions of the effects of global warming on insects by combining data from long-term datasets, large-scale experiments and computer modelling** (Diamond, 2018; Lehmann *et al.*, 2020; Grünig *et al.*, 2020). For example, according to Figure 2-33, the evolution of climatic suitability for host plants shows a gradient towards higher latitudes while the evolution of climatic suitability for insect pests does not show a clear gradient between south and north, probably due to the complexity and diversity of climatic niches of pest species. Therefore, the dynamics of the evolution of insect pest species are likely to be more idiosyncratic than that of their host plants with climate change. Furthermore, the number of insect pest species in central and north-eastern Europe would tend to decrease, due to the difference in climatic niches between cold-adapted and warm-adapted insect pests. Cold-adapted host plant species would tend to move further north with increasing temperatures, while there would be fewer warm-adapted host plant species.

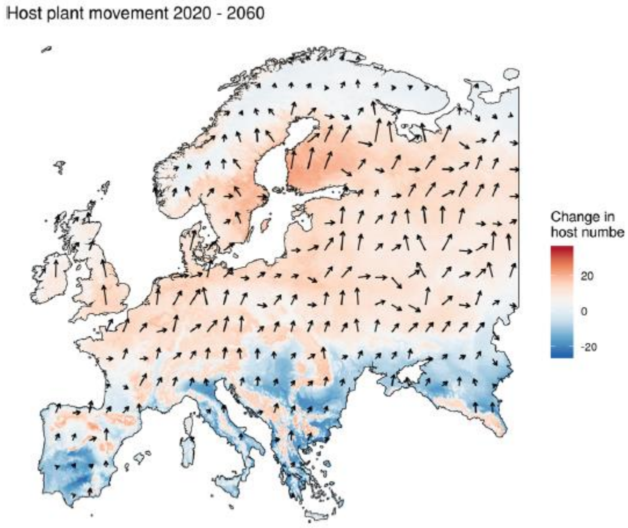
Other studies have focused on meta-analyses of data from laboratory studies. Using this type of approach, Fussmann *et al.* (2014) concluded that **higher trophic levels** (*e.g.*, predators) are **more sensitive to climate change than lower order organisms** (*e.g.*, plants or herbivorous insects). This type of information is useful when studying the impact of the changing role of natural enemies on insect pest dynamics and biological control in the context of climate change, a topic on which very little field data are available (Thomson *et al.*, 2010).

Finally, other studies have relied on **expert advice** or generated **simulation models** to predict how projected changes in climate or atmospheric composition will affect the distribution, prevalence, severity and control of pests and other organisms (see 2.4.3).

Figure 2-33: Climatic suitability shift for pests and host plants (Source: Grünig *et al.*, 2020)

Arrows show for each grid cell the average direction of climatic suitability shift over all species. For each species, we calculated the direction from where each newly suitable grid cell can be reached from its closest suitable grid cell in the previous time step. The length of the arrows is proportional to the number of new colonisations of each grid cell. The coloured maps show the change in total number of pests (left) and host plants (right) with suitable conditions during the time step of 2020-2060. Red shadings indicate an increase of the number of species with suitable climate; blue shadings indicate decreasing numbers. Climatic suitability shift and change in number of species are shown for the RCP8.5 scenario.





2.4.2.2. Effects of bioclimatic factors on insect pests and insect pest x crop interactions

This paragraph is mainly based on the synthesis by Gagnon *et al.* (2011).

Direct effects

Studies on the effects of climate change on insects focus on **phytophagous insects** since they dominate local biodiversity, interact with more than one trophic level (host plant and natural enemy) and can have a major economic **impact** on agriculture (Ladanyi and Horvath, 2010).

The **effects of climate change on insects** are closely linked to the increase in **temperature**, an important climatic parameter regulating their development rate. Other bioclimatic parameters also have a role in the effects on insect biology, such as **precipitation, wind and increased CO_2 concentrations**.

Single-factor effects

The development of insects, which are poikilothermic organisms, is directly influenced by external climatic conditions, particularly **temperature**, which regulate the rate of their metabolism (Andrewartha and Birch, 1954). Foliar insects are more affected by temperature than soil insects where temperature variations are less pronounced (Bale *et al.*, 2002).

Most studies show an increase in the **growth rate of insect pests** with increasing temperatures (Fuhrer, 2003; Patterson *et al.*, 1999). Others have observed a decrease in the impact of some pests, such as the decrease in cereal aphid populations in Great Britain in response to increases in temperature and atmospheric CO_2 concentration (Newman, 2006).

Several studies have demonstrated an increase in **voltinism** with climate change (Porter *et al.*, 1991, on the European corn borer; Altermatt, 2010, on 250 European lepidopteran species). Trnka *et al.* (2007) argue that corn borer populations will be able to develop two generations per year by 2025, whereas only one generation per year was observed from the data available to them. These authors indicate that voltinism is under genetic and also environmental control, with interactions between **degree-day sums** and **photoperiod** that can affect the diapausing stages of the insects and limit multivoltinism under warmer conditions (Tobin *et al.*, 2008).

Under temperate climatic conditions with cold winter temperatures, Zhou *et al.* (1995) showed that **winter survival** would be the dominant factor affecting the phenology of five aphid species, and that a 1°C increase in mean winter temperature would bring forward the migration time by 4 to 19 days depending on the species. This phenological change would allow aphids to feed over a longer period of time, thus increasing plant damage and the risk of virus transmission. According to Gagnon *et al.* (2011), temperature increases could eventually allow these southern species, or those that infest heated greenhouses, to escape and establish under altered temperate climatic conditions.

According to climate scenarios, the **distribution range** of the European corn borer could expand up to 1200 km northwards, or by 165-500 km for every 1°C increase in temperature (Porter *et al.*, 1991). Other **mathematical modelling** has shown a redistribution (expansion to the north and/or reduction to the south) of species range (Jeffree and Jeffree, 1996) and relative abundance (Olfert and Weiss, 2006b). **Resource availability**, **migratory properties** of a species, **species interactions** and **habitat fragmentation** may also play a role in the distribution of a species (Lawton, 1995).

Rainfall, and in particular flooding, can affect insect **oviposition** (the act of depositing eggs in the most suitable environment for optimal hatching), as well as **insect survival** on the ground. Staley *et al.* (2007) showed that an increase in **rainfall pattern** could increase the incidence of the pest Agriotes lineatus, a wireworm that attacks potatoes among other crops. **Droughts** lead to increased carbohydrate concentrations in plants, making them more attractive to insects (Ziska and Runion, 2007).

Wind can play a role in the dispersal of insects, which can travel great distances. But strong winds can disrupt the movement of insects such as the Colorado potato beetle and thus limit its spread (Boiteau, personal communication).

The direct effect of **CO_2** on insects is poorly documented. For example, Schroeder *et al.* (2006) showed that CO_2 can stimulate oviposition in insects such as the corn rootworm under high CO_2 conditions. Indirectly, changes in the feeding behaviour of some insects have been associated with **physiological and/or morphological changes in the host plant** under high CO_2 conditions.

Interactions between factors

Cannon (1998) suggested that the **interactions between all these factors**, which generally vary simultaneously, should be more frequently considered in studies. Those considering climate change often refer to temperature and CO_2, but many other factors may be involved such as wind, weather extremes, ozone and other pollutants (Lawton, 1995). These factors should also be taken into consideration in their interactions in order to know their effect on the complete life cycle of the insect.

Indirect effets

Increase in CO_2 concentration

Increasing CO_2 concentration increases the carbon/nutrient ratio of plants, which can have several effects on the plant x herbivorous insect interaction: i) modification of the **feeding behaviour** of the herbivorous insect, ii) modification of the **concentration of plant defence chemicals**, iii) **compensatory response of plants** to herbivory, iv) **competition between insect pests** (Coviella and Trumble, 1999).

The **decrease in plant quality** (decrease in nitrogen supply) could increase the **consumption rate of herbivorous insects** to obtain sufficient **nutrients**. On the other hand, an increase in CO_2 concentrations could attract more herbivorous insects, by increasing **carbohydrate** concentrations. For example, Ballhorn *et al.* (2010) showed an increase in the consumption of young lima bean leaves by the Mexican bean beetle at high CO_2 concentrations, which is thought to be due in part to the decrease in nitrogen-based defence compounds in the young leaves. Other studies have shown that the performance of herbivorous insects feeding on plants at elevated CO_2 concentrations is reduced (Cannon, 1998; Hunter, 2001). Wolfe *et al.* (2008) showed that a slowing down of the development of the herbivorous insect would increase its capacity for parasitism or predation. Unlike chewing insects, plant phloem-feeding insects such as aphids would not be negatively affected by increased atmospheric CO_2 concentration (Cannon, 1998; Flynn *et al.*, 2006; Hughes and Bazzaz, 2001). The **response of the herbivorous insect to an increase in CO_2 concentration** is therefore **variable depending on the insect species and also on the host plant** (Cannon, 1998; Fuhrer, 2003). The carbon/nutrient ratio hypothesis argues that the patterns of plant defence depend on variations in the nutrients available in the environment. Thus, in a more carbon-rich environment, carbon-based defence compounds will be produced, whereas a nitrogen-rich environment will predispose plants to synthesise nitrogen-based defence compounds. According to this hypothesis, an increase in atmospheric CO_2 concentration would cause an increase in carbon-based defence compounds in plants. The meta-analysis by Massad and Dyer (2010) also supports this hypothesis.

Increasing CO_2 concentration can also change the resistance of a plant to a herbivorous insect by changing its **chemical composition**. For example, Zavala *et al.* (2008) showed that in soybeans, an increase in CO_2 concentration decreases the concentration of cysteine proteinase inhibitors in the plant, a specific repellent for herbivorous beetles, which would result in a greater vulnerability of the plant to attacks by two common herbivorous insects of soybeans, the Japanese beetle and the corn rootworm. Dermody *et al.* (2008) showed an increase in the number of corn rootworms and aphids in soybeans grown under high CO_2 concentrations. **Volatile organic compounds (VOCs)** in plants allow herbivorous insects to locate and congregate on their host. Increased CO_2 concentration favours the production of these VOCs and could increase insect epidemics (O'Neill *et al.*, 2010a). It could also modify the composition of the substances of plant defence and thus modify plant x herbivorous insect interactions (O'Neill *et al.*, 2010b).

However, the effect of increasing atmospheric CO_2 concentration on plants and insects has often been criticised as **experiments conducted under controlled conditions** optimise other parameters (temperature, humidity) and **do not correctly reproduce the interactions between all climatic variables**. Mondor *et al.* (2010) have highlighted the variability of the response to CO_2 between different aphid genotypes, thus casting doubt on the generalisation of results within a single species. It is therefore important to target, for each system, the most determining factors in order to highlight the net effect of climate change (Lawton, 1995).

Synchrony between crops and insect pests

The **synchrony between the host plant and the insect pest** is the result of an evolutionary adjustment maintained over many years. In general, aphid eggs that emerge during host leaf break have better fitness than those that hatch earlier or later in the season and the fact that the insect pests are well synchronised with their host plant indicates that adaptation is possible (Dixon, 2003). **The rate of development of an insect is strongly related to that of the host plant**. At low temperatures, the host plant grows too slowly to support the development of the insect, whereas at high temperatures, the host plant grows too quickly (Bale *et al.*, 2002). Aurambout *et al.* (2009) showed the relevance of focusing on these two trophic levels when assessing the risk of introducing the pest *Diaphorina citri* into citrus orchards in Australia. The predicted temperature increases predict an increase in the number of generations of the pest causing a negative impact on citrus orchards. However, the temperature will shorten the period during which the host plant is susceptible to the pest and so the final impact should be less than if only the biology of the insect was considered.

2.4.2.3. Effects of bioclimatic factors on pathogens and pathogen x host plant interactions

Work on pathogens has mainly focused on **fungal pathogens** (aerial and soil), with very little work on bacteria, nematodes and viruses. The main effects that climate change could have on pathogens are changes in their **growth**, **reproductive rate** and **species survival**, **host plant sensitivity**, **geographical distribution of the host or pathogen** and the **effectiveness of pathogen control methods** (Chakraborty *et al.*, 2000; Harvell *et al.*, 2002; Rillig, 2007). The main bioclimatic factors influencing disease development are **temperature** and **humidity**, while CO_2 and O_3 have an indirect effect on pathogens via plant physiology (Boland *et al.*, 2004).

Climatic factors such as temperature, precipitation, CO_2 and O_3 all have an effect on pathogens, and these should also be considered in interaction (Luck *et al.*, 2011). In addition, several other factors should be considered in studies of pathogens and climate change (Garrett *et al.*, 2006 and 2011; Pautasso *et al.*, 2010): i) the effect of the pathogen on host survival, physiology, behaviour and reproduction; ii) the growth stages at which the host is vulnerable to the pathogen; iii) the proportion of individuals/biomass infected at a site; iv) the spatial extent and distribution of infection; v) the environmental thresholds for population response; vi) the frequency and duration of pathogen impact and vii) the effect of indirect interactions. A better understanding of host plant x pathogen interactions is needed to develop climate change adaptation measures to ensure food security (Chakraborty and Newton, 2011; Singh *et al.*, 2023).

Direct effects

Single-factor effects

With regard to **temperature**, milder winters will generally ensure better conservation of pathogens, thus increasing the amount of inoculum in the soil the following spring (Fuhrer, 2003). Warm weather with droughts may reduce the intensity of some pathogens. Some diseases, such as mildews, which develop at rather cool temperatures (between 10 and 24°C depending on the species) could be adversely affected by global warming. However, a study by Salinari *et al.* (2006) predicts an increase in the intensity of downy mildew infections in grapevines with projected climate change, *i.e.* increased temperatures and decreased precipitation.

Many plants grown at the limit of their developmental temperature may be disease-free since they are not able to grow under these cooler conditions at present. Increasing temperature would allow an expansion of the range of pathogens causing these diseases and an increase in the phytosanitary risks on these crops (Coakley *et al.*, 1999). Furthermore, the extension of the growing season would allow greater inoculum production for some species and increase the frequency and intensity of infections. However, some pathogen species are also sensitive to photoperiod, which will not be affected by climate change (Coakley *et al.*, 1999).

Moisture, whether in the form of **precipitation**, **dew** or **relative humidity**, is an essential factor in the development of most fungal infections. Increased precipitation is thought to favour the dispersal of spores of certain species, leading to a better spread of pathogens (Fuhrer, 2003). Since temperature increases of 2 to 3°C are predicted for 2050, water stresses could even occur in connection with increased transpiration in plants. In general, water stresses reduce the impact or symptoms of diseases during the warm season, but can also reduce the resistance of plants to diseases (Gregory *et al*., 2009).

According to Chakraborty *et al.* (2000), the effects of increased **CO_2 concentration** on pathogens can be either positive or negative for crops, but on average, disease incidence tends to increase with increasing CO_2. Among the most commonly cited elements is the increase in biomass and plant canopy density, thereby increasing relative humidity and increasing the dispersal power and fecundity of the pathogen. The direct effects of CO_2 on pathogens are less studied, but could nevertheless have a significant impact on the host plant. For example, a study by Melloy *et al.* (2010) showed that increasing CO_2 concentration increased the biomass of the fungus *Fusarium pseudograminearum* in wheat. However, the pathogen's response to CO_2 is highly specific to the host plant x pathogen interaction. Eastburn *et al.* (2010) observed an increase in the severity/intensity of brown spot in soybeans (*Septoria glycines*) at high CO_2 concentrations (550 ppm), while the incidence of downy mildew (*Peronospora manshurica*) in the same crop was reduced.

Ozone O_3 is not thought to affect pathogens directly (Manning and Tiedemann, 1995), but it can have an effect by increasing or decreasing the susceptibility of a plant to the enemy (Fuhrer, 2003). The interaction between ozone and the pathogen depends mainly on the timing of ozone exposure, the phenological stage of the plant and other factors predisposing to infection (Fuhrer, 2003; Manning and Tiedemann, 1995). While ozone is perceived negatively, some authors consider it as an ally that can protect the plant from a pathogen attack by eliciting the plant's defence reactions (Sandermann *et al.*, 1998).

One might think that soil pathogens would be less influenced by climate change since temperature and CO_2 variations are less important. However, depending on the type of pathogen (fungus, bacteria or nematode) and the biology of the microorganisms (overwintering in the soil or on residues), some of them could be influenced.

Soil fungal species (*e.g. Botrytis*, *Fusarium*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Sclerotinia, Sclerotium*, *Verticillium*) survive temperature extremes by means of structures such as sclerotia or microsclerotia, thick-walled spores (*e.g.* chlamydospores or oospores) (Boland *et al.*, 2004), or hyphae. Warmer winters are not expected to have a significant effect on **soil pathogenic bacteria**, while those surviving on the host or residues (*e.g. Erwinia amylovora*) or transmitted by vector organisms (*e.g. Erwinia stewartii*, transmitted by a species of beetle) may be advantageous (Boland *et al.*, 2004). Rising temperatures could increase the development rate of **nematodes** and thus lead to additional generations. Winter storage of nematodes is not expected to be affected by climate change, although for some species, such as the soybean cyst nematode, winter heat waves may reduce egg viability (Boland *et al.*, 2004). The decrease in root surface area of a nematode-infected plant would lead to an increase in water stress symptoms under drought conditions (Boland *et al.*, 2004).

Interactions between factors

Little work has been done on the interactions between pathogens and bioclimatic factors (Luck *et al.*, 2011).

Indirect effects

Indirect effects are mediated by host plants or by adaptations in crop management due to climate change (Juroszek *et al.*, 2020). A warming of the average air temperature, especially in early spring in temperate regions, could lead to host plant life cycle stages occurring earlier in a season (Racca *et al.*, 2015). This may affect pathogens that infect hosts at a particular life cycle stage (*e.g.* wheat pathogens such as Fusarium species that infect wheat during flowering; Madgwick *et al.*, 2011; Miedaner and Juroszek, 2021a). Adaptation measures for crop management in the face of climate change include introducing irrigation, stopping deep ploughing, shifting planting dates and planting more than one crop per year.

The **effects on the physiology of host plants** may in turn **alter their passive resistance** to disease. In addition, **climatic stresses caused by extreme events and the presence of pollutants**, such as ozone, reduce the resistance of a plant. More work needs to be done on changes (positive or negative) in the resistance, sensitivity or vulnerability of host plants to pathogens.

2.4.2.4. Effects of bioclimatic factors on weeds and weed x crop interactions

Unlike insects and pathogens, the risks associated with weeds are based more on increased trade leading to the introduction of new species than on climate change *per se*.

Concerning the competitive advantage of weeds over crops, it is also worth noting that, for decades, the genetic diversity of crops has been considerably reduced by the selection of traits resulting in yield increases, to the detriment of the adaptive capacity of these crops (Fernandez-Quintanilla *et al.*, 2008). In contrast, the **genetic background** of weeds remains **very diverse** and therefore, they have a much **greater phenotypic plasticity than crops** (Ziska and Runion, 2007). This high plasticity gives them a **clear advantage in their ability to adapt to climatic changes** (Wolfe *et al.*, 2008). Weeds have attributes that make them **difficult to control since their reproductive success is often very efficient**. These same traits give them a **competitive advantage by acclimating more easily to climatic variations** (Hovenden, 2007) and by **adapting to arid and extreme conditions due to climate change** (Edwards and Newton, 2007).

Direct effects

Climate change can have different effects on weeds. **Increases in CO_2 concentration** may alter plant physiology and thus alter interspecific competition between crops and weeds. **Temperature and precipitation are two important bioclimatic factors for the distribution of the species in a territory**.

Botanists distinguish between plants with C3 metabolism, C4 metabolism and CAM (crassulacean acid metabolism) plants (*e.g.* Ehleringer and Cerling, 2002). The set of chemical reactions in the Calvin cycle vary between these types of plants in the number and type of carbon molecules created by the plant, the storage locations of these molecules in the plant, and the ability of the plant to withstand low carbon atmospheres and higher temperatures. CAM or Crassulaceae plants (cacti and other succulents) are not in the scope of this foresight study.

C3 plants are the oldest and constitute the vast majority of the terrestrial plant species on which we depend for food and energy. They include cereals (wheat, barley, rye, rice, soybeans, etc.), vegetable crops (potatoes, spinach, tomatoes, etc.), fruit trees (apple, etc.). C3 plants convert CO_2 into a 3-carbon molecule (3-phosphoglyceric acid or PGA) by the enzyme Rubisco (ribulose bisphosphate carboxylase oxygenase).

C4 plants represent only about 3% of terrestrial plant species and are characterised by a biochemical modification of the C3 photosynthetic process. They convert CO_2 into a 4-carbon molecule by the enzyme PEP (phosphoenolpyruvate) carboxylase. This evolution has allowed C4 plants to have twice the photosynthetic capacity of C3 plants and to withstand higher temperatures, less water and less available nitrogen. Most grassland forage plants in the tropics, subtropics and warm temperate regions are C4, as are highly productive crops (maize, sorghum and sugarcane). C4 plants thrive in long growing sunny seasons.

These processes are directly relevant to studies on global climate change because C3 and C4 plants respond differently to changes in atmospheric CO_2 concentration and to variations in temperature and water and nitrogen availability. **C3 plants function less efficiently than C4 plants in warmer, drier and more erratic conditions**. C4 plants are able to photosynthesise at much lower atmospheric CO_2 levels than C3 plants, but they also respond more poorly than C3 plants to increased CO_2 levels. **C3 plants would thus benefit from the increase in CO_2 concentration**, which has a **fertilising effect** on the plant, accelerating its growth and photosynthetic rate (Fuhrer, 2003). This increase in CO_2 also allows for a **better efficiency of the plants in using water resources and a greater tolerance to drought** (less need to open the stomata since CO_2 is abundant). Considering only the effect of increasing CO_2

concentration, yields could increase by 10-30% for C3 plants and 0-10% for C4 plants (Ainsworth and Long, 2005; Seguin, 2007). On the other hand, **C3 plants could become more vulnerable to pathogens and insect pests**, resulting in reduced yields of C3 plants compared to C4 plants. **Climate change could also make it more difficult to control weeds, most of which are C4 plants** (14 of the 18 most problematic weed species worldwide are C4 plants; Fuhrer, 2003), **whose competitive advantage would be enhanced over C3 plants**. Indeed, in addition to affecting plant growth rate, increased CO_2 can lead to increased reproductive effort in weeds. This can result in an increase in pollen production, as demonstrated in common ragweed (Ziska and Caulfield, 2000), and thus improve the establishment power of the plant through increased seed production.

An **increase in temperature will favour C4 plants**. **Temperature and precipitation affect the geographical distribution of weeds** (Patterson *et al.*, 1999). Warmer temperatures will allow a migration of species, which are currently at the limit of their distribution, towards the poles and to higher altitudes. A simulation of habitats favourable for the development of weed species in cold winters, such as Kudzu (*Pueraria montana*), under climatic conditions at the 2020, 2050 and 2080 horizons, predicts a **northward expansion of the range of these species by ensuring better winter survival** (Wolfe *et al.*, 2008). Furthermore, when soil moisture is high, weed competition has less negative impact on yields.

Indirect effects

As with pests and pathogens, the **interactions between the different factors affecting weeds can be complex**. Increased CO_2 concentration can increase competition between weeds and crops, which can compromise crop yields by increasing weed growth and decreasing herbicide efficacy. For example, in soybeans, a decrease in yields would be caused by the increase in CO_2 that contributes to the increase in the biomass of Canada thistle (*Cirsium arvense*) and the decrease in the effectiveness of glyphosate (Ziska, 2010). Patterson *et al.* (1999) reported that high CO_2 concentrations would lead to increased rhizome and tuber growth (in C3 plants) making it more difficult to control perennial plants.

In another example, experiments simulating real field conditions with the FACE system have shown the complexity of interactions between weed growth and temperature, water and CO_2 under altered environmental conditions (Williams *et al.*, 2007), and other experiments have shown that water stress can alter the competitive relationships between weeds and crops under conditions of high CO_2 concentration (Valerio *et al.*, 2011). When the water regime is satisfactory, the growth of the C3 tomato (*Lycopersicon esculentum*) benefits more from the high CO_2 concentration than the C4 weed *Amaranthus retroflexus*, while under water stress conditions the opposite phenomenon occurs. Similar experiments (Valerio *et al.*, 2011; Williams *et al.*, 2007) conducted under controlled conditions and in the field suggest that the response of plants to high CO_2 concentration cannot be predicted based solely on the type of photosynthetic cycle (C3 or C4), as there are a range of complex interactions with various factors, including water availability and temperature. These findings are in line with a recently published meta-analysis (Vilà *et al.*, 2021), which aimed in particular to understand the combined effects of weeds and climate change on crops.

Although increasing temperature or changing other climatic factors could allow a greater success in establishing these species, their distribution range is mainly limited by good crop management (*e.g.* use of weed-free seeds) than by thermal limitation. The **issue is therefore multifactorial and requires an in-depth study of the various factors promoting the dispersion and establishment of weed species**. By observing the mechanisms of weed acclimatation and adaptation, it would be possible to develop different crop production approaches to modify or create environments that do not allow weed establishment or reproduction. It would also be possible to use the genetic background of the weeds to create cultivars carrying the gene of interest.

2.4.3. Modelling the effects of climate change on pests and pest x crop interactions

This paragraph is largely taken from the Gagnon *et al.* (2011) and IPPC (2021) syntheses.

Simulation models can be used to **predict the effects of climate change on pests** (Sutherst, 1991; Sutherst *et al.*, 2011) and to determine control tactics and strategies (Ghini *et al.*, 2008; Hill and Thomson, 2015; Salinari *et al.*, 2007; Shaw and Osborne, 2011). For example, one modelling approach is to **use 'climate matching', which involves studying a geographical area whose current climate is similar to the future climate of the area under consideration** (in this case, for the study of pest dynamics). The results are then **extrapolated to design a future scenario for the same area** (Sutherst *et al.*, 2000). Other modelling approaches use **long-term datasets** of weather parameters, pest distribution, crop development and prevalence to develop and validate **'pest-crop-climate' models** (Angelotti *et al.*, 2017; Madgwick *et al.*, 2011). Other recent examples of modelling-based studies take into account parameters such as voltinism for insect pests, the timing of plant flowering and the severity of associated diseases, as well as the overall distribution of weeds.

2.4.3.1. Simulation of future pest risks

The simulations presented here aim to determine future pest risks under different climate change scenarios. They mainly use **species distribution models, population dynamics models or hybrid models combining the two** (Table 2-3). The **climatic factors** studied are **temperature, precipitation and humidity, while elevated CO_2 concentrations are given little consideration** (Eastburn *et al.*, 2011; Juroszek and von Tiedemann, 2015). The **effects of climate change are probably easier to predict for pest species that are primarily temperature-sensitive. Predictions are trickier for pests whose reproduction and spread are strongly linked to water availability, wind and crop management**. This is particularly true for pests sensitive to interactions with other organisms, such as **pathogen vectors** (Trebicki and Finlay, 2019), except in cases where their interactions are studied in detail (Juroszek and von Tiedemann, 2013a) and therefore predictable.

The simulation results depend on the **materials and methods used** (*e.g.* the emission scenarios, the global and regional climate models, the pest-specific model, the used parameters; Miedaner and Juroszek, 2021a). All these elements shape the outcome of the pest risk projections (Gouache *et al.*, 2013; Juroszek and von Tiedemann, 2013b; Launay *et al.*, 2020) and need to be taken into account when analysing simulation results, such as those presented in Table 2-3. In addition, Miedaner and Juroszek (2021a) highlighted that the **impact of climate change on pest risk may vary between geographical areas** (*e.g.* between plains and mountains, north and south, summer and winter, hot and humid seasons and cool and dry seasons).

Considering that the increase in temperature is the factor with the greatest impact on the results, Juroszek and von Tiedemann (2015) suggested, on the basis of projections, that the **change (increase or decrease) in pest risk should be more noticeable at the end of the 21st century**. This assumption is consistent with the predictions that global warming will be greater at the end of the 21st century than at the middle or beginning of the century (*e.g.* with a global temperature increase of 3°C at the end of the century, compared to 2°C at the middle and 1°C at the beginning).

Table 2-3: Examples of possible effects of climate change on plant pests (insects, pathogens and weeds) in different climate zones (Source: IPPC, 2021)

CLIMATE ZONES	LIKELY EFFECTS OF CLIMATE CHANGE ON FUTURE PEST RISK (MAINLY 2050–2100)	REFERENCES
Boreal	More increasing insect pest and plant disease risk in **boreal forests**	Seidl *et al.*, 2017.
Temperate	More increasing insect pest risk in **agriculture and forestry**	Grünig *et al.*, 2020.
	More increasing insect pest and plant disease risk in **forests**	Seidl *et al.*, 2017.
	More increasing disease risk in **agriculture and horticulture** (mostly based on western European studies)	Juroszek and von Tiedemann, 2015; Miedaner and Juroszek, 2021a.
	Often poleward shift of insect pest and pathogen risk in different managed and unmanaged ecosystems	Bebber, Ramotowski and Gurr, 2013.
	Often range expansion of important insect pests in **agriculture and horticulture**	Choudhary, Kumari and Fand, 2019.
	More increasing risk of weeds in different managed and unmanaged ecosystems	Clements, DiTommaso and Hyvönen, 2014.
Subtropical	Increasing saturation of insect pest risk in **agriculture and forestry** in southern Europe	Grünig *et al.*, 2020.
	More increasing disease risk in **agriculture and horticulture**	Gullino *et al.*, 2018.
	Often range expansion of important insect pests in **agriculture and horticulture**	Choudhary, Kumari and Fand, 2019.

Geographical location plays a role in pest risk (Sidorova and Voronina, 2020). For example, a first simulation study of future pest risks induced by climate change predicted an increase in the risk of rice blast, caused by the fungus *Magnaporthe grisea*, in cool subtropical rice-growing regions such as Japan, whereas in hot and humid tropical regions, such as the Philippines, the risk of rice blast is expected to decrease in the future (Luo *et al.*, 1995 and 1998). For insect pests, Kocmánková *et al.* (2011) indicate, on the basis of their projections, that the European corn borer (Ostrinia nubilalis) and the Colorado potato beetle (*Leptinotarsa decemlineata*) are likely to **increase their distribution ranges in many parts of Europe, establish at higher altitudes and increase their annual number of generations due to projected temperature increases**. Furthermore, global warming could lead to temperature increases close to the **upper lethal limit for certain insect species, especially during the summer in temperate regions** (Bale and Hayward, 2010; Harvey *et al.*, 2020). This variation in impact depending on the geographical area means that generalisations should be made with great caution and that researchers should be very careful when extrapolating their results (Juroszek *et al.*, 2020).

Warmer and drier climatic conditions favour insect pests, while warmer and wetter climatic conditions favour pathogen pests. Seidl *et al.* (2017) published a comprehensive global analysis of the available results (more than 1600 unique observations) and concluded that about two-thirds of all observations show that the risk of abiotic (*e.g.* fire and drought) and biotic (*e.g.* insect pests and pathogens) stressors will increase in the forest sector worldwide. The same trend is expected for many crop diseases (Juroszek and von Tiedemann, 2015), insect pests (Choudhary *et al.*, 2019) and weeds (Clements *et al.*, 2014), with an increase in pest risk in most cases. Environmental organisations and plant protection services are currently debating **how to deal with pest infestations in national parks and protected areas**, as well as the tricky question of whether to **intervene in currently unmanaged ecosystems**.

2.4.3.2. Modelling the effects of climate change on pests and pest x crop interactions

Case of insect pests

Studies of the effects of climate change are mainly carried out on relatively short time scales (between 20 and 50 years). Changes in population turnover and local movements can be observed after 1 to 10 generations, whereas it would take 10 to 100 generations to observe population changes due to intra- or inter-specific competition (Lawton, 1995). Most **climate models** project an **increase in the distribution range of insect pests**, an **increase in the number of generations per year** and a **higher population density of insect pests** (Aurambout *et al.*, 2009; Bergant *et al.* 2006; Bergant *et al.*, 2005; Estay *et al.*, 2009; Hallett *et al.*, 2009; Jeffree and Jeffree 1996; Newman 2006; Olfert and Weiss 2006a; Olfert and Weiss 2006b; Porter *et al.*, 1991; Trnka *et al.*, 2007; IPPC, 2021; Table 2-4.a).

Adaptation to climate change can occur at different scales depending on the herbivorous insect and its host plant. In general, tree species **expand their distribution range** by 20-40 km over 100 years (Davis and Shaw, 2001), while for insects, poleward migrations of up to 240 km over a 30-year period have been recorded (Parmesan *et al.*, 1999). Thus, insects could migrate north, but find themselves facing **non-optimal hosts**, thus reducing their fitness. For example, one species of butterfly, *Erynnis propertius*, has adapted locally to different oak species (Pelini *et al.*, 2010). Climate change could promote the expansion of populations of this butterfly from the south to the north, where a different oak species grows. However, the mortality of the butterfly is increased when it consumes the northern host, thus limiting its expansion to these regions.

Case of pathogens

Few studies have focused on modelling the effects of climate change on pathogens. One of the particularities of pathogens is their high need for moisture throughout their life. However, the modelling of precipitation and relative humidity for the future has a greater range of uncertainty than the modelling of temperature. Differences in trends could be identified between the major regions of Europe (Figure 2-30), including i) a decrease in summer precipitation and an increase in winter precipitation and/or storms and floods in Northern and Eastern Europe, and also ii) increased risks of drought in Eastern Europe, iii) drier and warmer summers and increased risks of flooding in Western Europe, iv) increased risks of drought and heat waves in Southern Europe. But uncertainties about future precipitation and moisture conditions translate into a much more variable range of potential biological responses, as likely climatic conditions can vary from one extreme to the other between drought and flooding. Furthermore, pathogens have a very different biology from one species to another in terms of their responses to bioclimatic factors. It is therefore extremely difficult to make generalisations about the impact of climate change on pathogens (IPPC, 2021; Table 2-4.b).

Case of weeds

As with pathogens, there are few studies on the effect of climate change on weeds in agriculture. Some species will benefit from climate change by **increasing their seed production** (Edwards and Newton, 2007), **increasing their winter survival** (Wolfe *et al.*, 2008), **altering the timing of germination and emergence** (Thompson and Naeem, 1996) or increasing **their competitive power** (Ziska and Runion, 2007). The climate simulations used all show an **increase in the distribution range of species towards the north, or a redistribution of these species by decreasing the populations in the south** (Bradley, 2009; Bradley *et al.*, 2010; Jarnevich and Stohlgren, 2009; Jeffree and Jeffree, 1996; IPPC, 2021; Table 2-4.c).

Table 2-4: Examples of pest risk simulation studies where pest models have been crossed with climate change scenarios (Source: IPPC, 2021)

a) Case of insects

COUNTRY OR REGION	TIME SPAN OR SPANS	CROPS AFFECTED, PEST SPECIES AND PROJECTION OF CHANGE	SELECTED REFERENCE
		INSECTS	
Switzerland	2070–2099	**Multiple crops:** Brown marmorated stinkbug (*Halyomorpha halys*), which has a wide range of potential hosts, is projected to expand into higher altitudes, produce more generations per year, and be active earlier in spring.	Stoeckli, Felber and Haye, 2020.
Global	2050, 2100	**Multiple crops:** Area suitable for fall armyworm (*Spodoptera frugiperda*) is projected to increase.	Zacarias, 2020.
Global	2050	**Tomato:** It is projected that several nations face a potential increase in two-spotted spider mite (*Tetranychus urticae*) outbreaks, while biological control by its key predator *Phytoseiulus persimilis* will not improve.	Litkas *et al.*, 2019.
United States of America, Midwest	2001–2050, 2051–2100	**Corn and soybean:** Pressure of nine different insect pests is projected to increase in general. Insect pests will move northward, because "optimal climatic conditions" will be further north.	Taylor *et al.*, 2018.
Global	2041–2060, 2061–2080	**Potato:** Expansion of Colorado potato beetle (*Leptinotarsa decemlineata*) into northern regions is projected.	Wang *et al.*, 2017.
Luxembourg	2021–2050, 2069–2098	**Oilseed rape:** *Meligethes aeneus* is projected to invade crops earlier in the year.	Junk, Jonas and Eickermann, 2016.
Scandinavia and central parts of Europe	2011–2040, 2071–2100	**Forest trees, spruce:** Increased frequency and length of late-summer swarming events of the European spruce bark beetle (*Ips typographus*) is projected. A second generation in southern Scandinavia is possible and a third generation in the lowlands of central Europe.	Jönsson *et al.*, 2011.

b) Case of pathogens

		PATHOGENS (DISEASES)	
France	2020–2049, 2070–2099	**Wheat:** Risk of leaf rust (caused by *Puccinia triticina*) is projected to increase.	Launay *et al.*, 2020.
France	2020–2049, 2070–2099	**Apricot:** Risk of blossom blight and twig blight (caused by *Monilinia laxa*) is projected to decrease or increase, depending on the cultivar grown (early vs late flowering).	Tresson *et al.*, 2020.
China, central	2030s, 2050s, 2070s, 2080s	**Kiwi:** Area favourable for bacterial canker (caused by *Pseudomonas syringae*) is projected to increase.	Wang *et al.*, 2018.
Brazil	2011–2040, 2041–2070, 2071–2100	**Grapevine:** Area favourable for downy mildew (caused by *Plasmopara viticola*) is projected to decrease across Brazil, although there are differences across regions or states.	Angelotti *et al.*, 2017.
Italy	2030 2050 2080	**Grapevine:** Increased importance of downy mildew (*Plasmopara viticola*), due to more spring days with favourable conditions, with earlier attacks and more treatments needed.	Salinari *et al.*, 2006.
Germany, south-west	2050, 2100	**Sugar beet:** Risk of Cercospora leaf spot (caused by *Cercospora beticola*) is projected to increase.	Kremer *et al.*, 2016.

c) Case of weeds

		WEEDS	
Global	2050	For 32 invasive weed species, the area suitable for growth is projected, in general, to decrease on a global scale. However, in European countries, northern Brazil, eastern United States of America, and south-east Australia, the suitable area is projected to increase for most of these 32 weed species.	Shabani *et al.*, 2020.
Global	2041–2060, 2061–2080	Suitable habitat of prickly nightshade (*Solanum rostratum*) is projected to expand into the circumpolar latitudes.	Wan and Wang, 2019.
Global	2050	Area suitable for lantana (*Lantana camara*) is projected to increase, although there will be considerable variation among continents.	Qin *et al.*, 2016.
Global	2100	Area suitable for rigid ryegrass (*Lolium rigidum*) is projected to increase in North America, South America, Europe and Asia, while in Africa and Oceania it is projected to decrease.	Castellanos-Frías. *et al.*, 2016.
Europe	2010–2030, 2050–2070	Area suitable for common ragweed (*Ambrosia artemisiifolia*) is projected to expand northward and is projected to continue to be limited by drought stress in southern Europe.	Storkey *et al.*, 2014.

2.4.4. Knowledge gaps and research needs

IPPC (2021) mentions examples of gaps in research on climate change in relation to plant pests. Some of the knowledge gaps it cites have been selected from the work of Juroszek and von Tiedemann (2013a) and Juroszek *et al.* (2020), with a focus on recent publications, post-2010, in order to demonstrate that the research gaps are still relevant. In general, the examples presented apply to insect pests, pathogens and weeds:

- Potential opportunities for **crop protection** are not sufficiently studied (Sutherst *et al.*, 2007);
- The **effects of climate change on natural enemies and antagonists** and their consequences for pest management remain poorly understood (Eigenbrode *et al.*, 2015), especially for below-ground pests;
- **Below-ground species** are less studied than above-ground species; indeed, most work to date on the potential effects of climate change on pests has focused on above-ground pests rather than below-ground pests, despite the importance of below-ground pests in below-ground processes and their influence on soil health (Chakraborty *et al.*, 2012; Pritchard, 2011);
- **Pests in unmanaged systems are less studied than those in managed systems** (Anderson *et al.*, 2004);
- Research is **limited to a few particularly important pest species**; many other species are less studied or not studied at all (*e.g.* **bacteria and viruses are much less studied than airborne fungal pathogens**; Frank, 2020; Jones, 2016);
- **Long-term datasets** are needed to disentangle the potential effects of climate change on insect pests and pathogens from confounding factors such as changes in management (Garrett *et al.*, 2016, 2020);
- Many more studies are needed to examine the **interactions between temperature, water and CO_2** (simulation of future real-world conditions, *e.g.* using open-air CO_2 enrichment methods; Tenllado and Canto, 2020; Vilà *et al.*, 2021);
- **Biotic interactions in the different trophic levels** are poorly known, including the adaptive capacities of species (Van der Putten *et al.*, 2010);
- It would be useful to establish a **comprehensive summary of the results of studies already carried out in the fields of agriculture and horticulture** (Juroszek *et al.*, 2020);

- A better understanding of the effects of climate change on **ecological processes, especially at the local level**, will allow **general principles to be integrated** into control measures (Macfayden *et al.*, 2018); for example, in the case of grapevine insect pests, it has been proposed that future control of these insects should be based on a solid body of field data both on the pests themselves and on their antagonists under conditions of climate change (Reineke and Thiéry, 2016);
- It would be useful to **evaluate current plant protection methods** in relation to projected climate change scenarios (Delcour *et al.*, 2015);
- Simulations of future pest risks should be more frequently correlated with **crop models to provide information on potential yield losses**; similarly, possible adaptation and mitigation measures should, if possible, be integrated into the modelling (Juroszek and von Tiedemann, 2015);
- More research on **adaptation and mitigation measures** would be useful to minimise the increase in risk (Hoffmann *et al.*, 2019);
- Frameworks need to be established to adapt **decision support systems to changes in weather frequency** or even to **entirely new scenarios** (Garrett *et al.*, 2020).

2.4.5. Mitigation, adaptation and resilience to climate change

2.4.5.1. Mitigation and adaptation of cropping systems to climate change x pests

With a few exceptions (*e.g.* Gouache *et al.*, 2011), simulations of pest risk have not incorporated measures that farmers might adopt to mitigate or adapt to a potential increase in pest risk (Juroszek and von Tiedemann, 2015). Nevertheless, there is a whole range of possible mitigation and adaptation options in agriculture that should be considered, not only by farmers, but also in simulation models to inform future decisions. Further development of adaptation-based pest management tools will increase the chances of successful adaptation strategies in the future (Macfayden *et al.*, 2018).

Most scientists think that **improving host plant resistance** (and crop competition with weeds) is a very effective way to adapt crop protection to future climate conditions (Juroszek and von Tiedemann, 2015; Miedaner and Juroszek, 2021a and 2021b). It is essential to have drought-, temperature- and pest-resistant varieties. Other solutions include **adjusting the sowing period**, **lengthening crop rotation**, **improving pest forecasting systems**, **adjusting agronomic practices such as irrigation and fertilisation**, and **providing targeted advice** (Juroszek and von Tiedemann, 2015). Interestingly, several other potential crop protection adaptation measures, such as **modifying the microclimate**, **varying the sowing density** or **directly affecting the microclimate** (*e.g.* CO_2 capture), are not addressed at all in the literature on pest risk simulations.

In the agriculture and forestry sectors, **climate-smart strategies for pest management may also be needed** (Heeb *et al.*, 2019; Lipper *et al.*, 2014). Integrated pest management generally includes a wide range of direct and indirect pest management measures (Heeb *et al.*, 2019; Juroszek and von Tiedemann, 2011). These measures are presented in Table 2-5.

Table 2-5: Examples of hypotheses on how changes in atmospheric composition and climate might influence certain tools or strategies for controlling plant diseases (Source: IPPC, 2021)

CONTROL STRATEGY	TOOL	EXPECTED EFFECTS OF CHANGED CLIMATE	POTENTIAL OF TOOL FOR ADAPTATION
Avoidance	Barrier to entry (quarantine)	Climate-mediated change in pathogen dispersal – frequency, abundance, distance, speed.	Altered efficacy of quarantine practices likely. New phytosanitary measures, including the use of international (IPPC) standard treatments, will be needed.
Preventive	Crop rotation	No direct effect; diversity in cropping systems will remain important to reduce risk of disease.	Crop species better adapted to local climatic conditions are possibly required.
Preventive	Plant residue management	Potential increase in crop biomass through the CO_2 fertilizing effect, unless high temperature and drought counterbalance the fertilizing effect.	Innovative approaches needed to reduce inoculum level and saprophytic colonization.
Preventive	Sowing or planting date	Adjustments likely to be necessary; simple and cheap method to escape biotic and abiotic stress; however, disadvantages also possible.	Appears to be a powerful tool (often mentioned in the literature).
Preventive	Host plant resistance	Temperature dependent resistance may be overcome by pathogens; changes in plant morphology and physiology may affect resistance; potentially accelerated pathogen evolution may erode disease resistance prematurely.	Altered efficacy of host-plant resistance likely (higher, same, and lower efficacy depending on resistance (R) gene, pathogen population, etc.).
Preventive	Cleaning machinery and tools	Presumably no major effects.	Phytosanitary methods will remain important.
Preventive	Use of healthy seeds and plantlets	Presumably no major effects.	Preventive methods will remain important.
Preventive	Input levels (e.g. amount of irrigation)	Presumably higher temperatures will result in increased irrigation of more crops and in more regions.	Water conservation may demand efficient technologies such as drip irrigation, thereby reducing risk of foliar diseases.
Preventive or curative	Field monitoring and use of decision-support systems	Presumably no major effects.	Field monitoring and decision-support systems will remain or become more important.
Preventive or curative	Soil solarization (covering soil, usually with a plastic sheet, to trap solar energy in order to reduce pests in the soil)	Global warming may facilitate the use of this tool (it may be effective in more plant-pathogen systems and regions, heat may reach deeper soil layers, and duration of mulching period may be shorter).	Altered efficacy likely, but generally positive effects.
Preventive or curative	Antagonists, biological control agents	Presumably, vulnerability of biological control agents will be higher due to climate variability.	Altered efficacy likely (higher, same or lower, dependent on product, environment, management, etc.).

These measures include:

- **Quarantine** (biosecurity);
- Other phytosanitary measures, *e.g.* the **use of healthy seeds and seedlings**;
- **Biological control** (Eigenbrode *et al.*, 2015), natural regulation and enhancement of ecosystem services (FAO, 2016);
- Development of **more effective control methods for pathogens in crop residues**; these methods can be combined with already well-established practices, such as crop rotation, to avoid saprophytic colonisation of crop residues by pathogens and to reduce the transfer of inoculum from one cropping season to another (Melloy *et al.*, 2010);
- **Ploughing** can also be an effective way of **getting rid of diseased crop residues** (Miedaner and Juroszek, 2021b), although conservation agriculture is probably more suitable in drought-prone areas; ploughing does, however, require more fuel and therefore leads to more CO_2 emissions than no-tillage;
- **Shifting cropping areas** has also been suggested as a possible adaptation in the event of a disaster scenario, *e.g.* in the case of oilseed rape (Butterworth *et al.*, 2010) or in the case of broad beans in Egypt, where their cultivation was moved from the centre of the country to the

cooler Nile delta region in the north to escape the adverse effects of virus diseases, probably due, at least in part, to global warming;

- **Careful monitoring and early detection of pest arrival** to optimise timing of interventions (Heeb *et al.*, 2019; Strand, 2000); indeed, FAO (2008) stated that a key component of any strategy to address the hazards of pest introduction in the context of climate change must be surveillance and monitoring to detect new pest introductions; this led the IPPC to focus its work in recent years on surveillance and detection of pests, the publication of a guide on surveillance (IPPC, 2016) and the development of a series of diagnostic protocols to detect and identify pests; FAO (2016) emphasised the **need for farmers in particular to participate in surveillance and risk prevention schemes** where they exist;
- The use of expertise and '**citizen science**' to detect new plant health threats is also a promising avenue (FAO, 2016).

In addition, the increasing frequency of **climatic hazards** will lead official services to thoroughly review the design and implementation of surveillance and monitoring programmes. According to ISPM No. 6, the **compatibility of the pest with the climate and other ecological conditions of the area concerned** is one of the factors that determine which sites to monitor. However, there are still **many unknowns as to which climatic conditions are suitable for the establishment of different species**. The effects of climate change on the distribution of species are not yet well known, while the effects of climate change on microclimates and the species they support are currently being discussed and studied. Some studies indicate that microclimates can help combat species extinction by creating so-called 'microrefuges' (Suggitt *et al.*, 2018), but the **state of knowledge on the effects of climate change on microclimates and their ecology remains insufficient** and further research is needed to determine more precisely the future climatic conditions to which organisms in microclimates will be subjected (Maclean, 2020).

The choice of adaptation strategies also depends on their **cost**. Srivastava *et al.* (2010) conclude that lower-cost adaptation strategies, such as **changing sowing dates and cultivar types**, should be considered to **reduce the vulnerability of** crop **production to climate change**. However, the value of **changing sowing and harvesting dates** depends on a number of factors, such as potential yield loss, **location of the crop**, **farmer and consumer preferences** for cultivars and market conditions (Wolfe *et al.*, 2008). More costly adaptation measures may also be required (Juroszek and von Tiedemann, 2011), such as more effective control methods for pathogens in crop residues or the establishment of monitoring systems.

2.4.5.2. Towards greater resilience of cropping systems to climate change x pests

In his seminal article, Holling (1973) emphasised that a **resilience-based management approach would 'stress the need to keep options open and to design systems capable of absorbing and accommodating future events, whatever unexpected form they may take'**. As it became clear from the 2000s onwards that the dynamics of many ecosystems are strongly influenced by human activity, the literature has focused on '**socio-ecological resilience**', to emphasise that the social system and the ecosystem are coupled, interdependent and co-evolving (Berkes and Folke, 1998; Berkes *et al.*, 2003; Liu *et al.*, 2017). It has thus informed research on adaptive co-management and social learning (Plummer, 2013). Concepts related to social-ecological resilience have been applied to agroecosystems, for example identifying thresholds and their interactions at plot, farm and regional scales (Anderies *et al.*, 2006; Kinzig *et al.*, 2006; Walker *et al.*, 2009; van Apeldoorn *et al.*, 2011).

Half a century after Holling (1973), Darnhofer (2021) notes that the **prevailing trend is to understand resilience as the ability to maintain the current state** and not to effect transformative change (as defined in Folke *et al.*, 2010; see 2.4.1.2); maintaining the current state has several implications in the agricultural context:

- The **tendency to seek to maintain the current state presents change in negative terms**: change is understood to be induced by shocks, stresses, disturbances or undesirable events; it implies that **stability is preferred to change** which, beyond a certain point, is often undesirable;
- The **emphasis on external drivers of change** has minimised internal drivers, implying that the system is in dynamic equilibrium unless disturbed by external events;
- **Transformative change**, *i.e.* engaging in new paths of development, **is often sidelined because new ways of thinking and operating** that **lead to unfamiliar development trajectories** are not the focus of attention; the implicit objective is usually to enable the current system to function as well as possible, not to transform it; this objective hinders the study of shocks as opportunities for change, the study of internal drivers as essential to understanding a system's trajectory, and the consideration of transformational change as a means of achieving a more desirable system than the current one; taking the particular case of farmers who would like to maintain the function of their farm (*i.e.* to provide for the family, produce food and fibre and maintain the productivity of the land they manage), they could consider doing so by changing the structure, identity and feedbacks of their cropping system, for example by moving from intensive to low external input systems (Coquil *et al.*, 2014; Gosnell *et al.*, 2019; Tittonell, 2020).

Darnhofer (2021) also questions why such a one-sided application of the concept of resilience has occurred, despite the fact that **resilience is recognised as complex**, context-specific and highly dynamic (Rittel and Webber, 1973) and Holling (1973) emphasised the need to expect the unexpected and keep options open. It appears that **current approaches to resilience-based management seem to reduce resilience to a simple variant of risk management** (see OECD, 2020). Furthermore, **the complexity of resilience makes it difficult to operationalise and measure with simple indicators** (Armitage *et al.*, 2012). The many efforts to develop standardised tools and assess resilience using composite indicators are not yet able to take advantage of unpredictable dynamics or engage in transformative change. These findings concur with those of Urruty *et al.* (2016) who mention that the **operationalisation of resilience concepts in empirical assessments remains limited due to their multidimensional nature** and the fact that they are **not directly observable** (Callo-Concha and Ewert, 2014). These authors point out that the situation is even more complicated when assessments focus on time-bound events, such as drought, or on gradual disturbances such as climate change. They also stress the urgent need for better knowledge of the models and metrics available to quantify the capacity of cropping systems to cope with various types of disturbance. Meuwissen *et al.* (2019) also indicate that it is still unclear how to assess resilience and related concepts at the level of cropping systems where farms might cooperate across sectors, where non-farming populations are adjacent to farmers, where farmers contribute to multiple value chains, and where required functions change in response to changing consumer and societal preferences.

Some studies have already been done to propose indicators and metrics. For example, based on the principle that agroecosystems are too complex for resilience to be accurately measured, Cabell and Oelofse (2012) defined 13 **indicators of resilience based on behaviour within agroecosystems**. The identification of one or more of these indicators suggests that it is resilient and has the capacity to adapt and transform. The absence of these indicators identifies intervention points for managers and stakeholders to build resilience where vulnerability exists. Starting from the observation that the many definitions or measures of resilience proposed in the literature were mainly discipline-centric, Béné and Doyen (2018) sought to develop a **generic metric applicable to all disciplines and different interpretations of resilience**. They proposed a continuum of five categories of resilience responses (resistance, coping strategies, adaptation, adaptive preference and transformation) which they then reframed into a generic metric using viability analysis (*i.e.* a mathematical formalism that draws on dynamical systems and control theory). This generic approach goes beyond resilience as the ability of a system to return to its initial state to resilience as the ability to transform the system.

Climate change, and more broadly global changes and their impacts on cropping systems, highlight the need for a paradigm shift from resilience aimed at maintaining the current state to resilience aimed at transformative change. Such a shift implies the implementation of **holistic approaches in farms, landscapes and territories**. The mitigation and adaptation measures developed in paragraph 2.4.5.1 are examples of measures to be implemented at the farm and landscape levels. Farmers will also be able to take advantage of Web 2.0 resources and other new technologies to make the exchange of up-to-date information faster and easier (Lamichhane *et al.*, 2015). These authors also suggest that more collective approaches including dissemination and involving other stakeholders will help to address the challenge of developing more robust cropping systems and that local human and financial resource gaps can be overcome by pooling resources across borders. In implementing such an approach, cropping systems, dissemination, research and public policy act in coordination for more efficient and resilient food production systems.

In another example inspired by Tendall *et al.* (2015) on the resilience of food systems, CEREMA (2020) has proposed a compass of territorial resilience (Figure 2-34) which constitutes a framework for reflection and action beyond that of resilience to climate change alone. A **resilient territory** can be qualified through its **capacity to react/adapt in the short and medium term**, but also its **capacity to learn and reorganise in the long term**. The proposed framework is intended to help the actors of a community or a territory (city, inter-commune, district, department, region, watershed, natural park, coastal fringe, etc.) to strengthen their resilience in order to better anticipate, act, bounce back, transform themselves over time and, in fine, reduce their vulnerabilities. It can help build local actions that promote the resilience of their territory, whatever the type of shock or disturbance: hazards, shocks, chronic stresses, slow pressures (economic, demographic or environmental changes), unknown threats, etc.

Figure 2-34: Compass of territorial resilience organised into 6 principles and 18 levers (Source: CEREMA, 2020)

Conclusion

In recent decades, research on the biology of climate change has expanded considerably, particularly in the last decade. In general, most studies point out that the **pest risk from insects, pathogens and weeds will increase in cropping systems under climate change**, especially in the currently coldest areas, such as the Arctic and boreal regions, and also in temperate and subtropical regions. This increase in pest problems will affect managed ecosystems (agriculture, horticulture, forestry, etc.), semi-managed ecosystems (national parks, etc.), and probably also unmanaged ecosystems.

The main trends up to 2050 regarding climate change and its effects on pests and pest-crop interactions can be summarised as follows (Figure 2-35):

- **climate change**: average **increase in global temperatures** (by 1, 1.5, 2 or even 4°C) and **CO_2 concentrations**, increase in **precipitation** (and humidity) in the boreal and temperate latitudes of northern Europe but decrease in the temperate and subtropical latitudes of southern Europe, **spatial and temporal variations in climatic factors**, with **high uncertainties**, due to the increase in **extreme events** (heat waves and droughts, heavy precipitation and floods, storms, etc.) and **climatic hazards**;
- the effect of climate change **on different types of pests** and on **interactions between pests and host crops**:
    - **insect pests** whose physiology and dynamics are mainly influenced by **temperature**, but also by **humidity** and **wind**, and by **interactions** that will be affected by conditions of temperature, humidity, drought and CO_2 concentration in particular; the effect of climate change on these interactions may produce a positive effect by maintaining or reinforcing the **synchrony** between the pest and the host plant, or, conversely, a negative effect by desynchronising the stages of the insect pest's life cycle from those of the host plant;
    - **pathogens** are mainly influenced by **temperature** and **humidity**, which affect the whole life cycle of the pathogen, including its development and dispersal, inoculum production and maturation, and infection conditions; as with insect pests, climate change may have an effect on the **interactions** and **synchrony** (or asynchrony) between the pathogen and the host plant;
    - **weeds**, whose growth and development depend, like crops, on **temperature**, **precipitation** and **CO_2 concentrations**, but which, unlike crops, have a much **more diversified genetic background**, which gives them **greater adaptability than crops to climatic variations and hazards and to extreme events**; furthermore, while **crops** (mostly with C3 metabolism) **would be advantaged by an increase in CO_2 concentration**, **weeds** (mostly with C4 metabolism) **would be more tolerant and therefore better adapted to warmer and drier conditions**;
- the effects of climate change which are **common to the different types of pests, with changes in**:
    - **geographical distribution ranges of pests** (and crops) with **latitude** and **altitude** in relation to global temperature increase; pest distribution ranges may expand in boreal and temperate latitudes and/or shrink or disappear in subtropical and temperate latitudes; in the new agro-pedo-climatic contexts generated by climate change, there could also be an **increased risk of introducing pests that could become invasive**, including insect pests or weeds that serve as **secondary hosts** for pathogens;
    - **seasonal phenology**, especially the timing of spring activity; all stages of the pest life cycle will be affected by climate change, which will also disrupt, positively or negatively, the **developmental synchronies between pests, their host plants and their natural enemies** (see above);
    - the **dynamics of pest populations**: increase in winter survival, population growth rate, number of generations in a season, etc.

Figure 2-35: Main trends up to 2050 regarding climate change and its effects on pests and pest-crop interactions

Climate change to 2050 in Europe

- Temperature and CO_2 increase, droughts in mid-latitudes
- More climatic hazards and extreme events

Insect pests

- Mainly **temperature** on insect physiology and dynamics
- Also humidity, drought, wind, CO_2 on insect and host plant physiology
- **Synchronism** between insect pest and host plant

(Fungal) pathogens

- Mainly temperature and humidity on pathogen development and dispersion, inoculum production and maturation, infections conditions

Weeds

- Effects of CO_2, temperature and precipitation
- Large genetic diversity and greater adaptability than crops to climatic variations and extreme events

Changes common to all pests:

Geographical distribution of pests (especially in latitude and/or elevation in relation to temperature): range expansion or reduction or loss, increased risk of (invasive) pest introduction…

Seasonal phenology: timing of spring activity, synchronisation of pest life-cycle events with their host plants and natural enemies…

Population dynamics: overwintering and survival, population growth rates, number of generations during a season…

Use **climate correspondence** to simulate pest distribution

Uncertainties due to **climatic hazards, extreme events** and their **geographical ranges and variations**

Generalization/extrapolation difficult for the same type of pest

Beyond these major trends for each type of pest, it should be noted that the numerous studies conducted on the effect of climatic factors on pests and on interactions between pests and crops show results that are specific to the pest and the plant studied, and to the agro-pedo-climatic conditions of the study. These specific results cast doubt on their generalisation for the same type of pest (insect pest, pathogen or weed) and even within the same species. **Generalisations should therefore be considered with great caution**.

The data show that **all climates and ecosystems will be impacted**, not only **by changes in average bioclimatic conditions** (particularly temperature and CO_2 concentration), which are predictable and have been on a trend for several decades, but also by the **increasingly frequent occurrence of extreme events and climatic hazards** that are currently **unpredictable** and make local/regional forecasts of the various climatic factors **highly uncertain**. As a result, the nature and extent of the impact of climate change on pests and their interactions with host crops will vary according to the **capacity of production systems and natural ecosystems to adapt and evolve**. Further research is needed on the biophysical effects of climate change on pests and their interactions with crops. Given the complexity of cropping systems, and more broadly of socio-ecosystems, it also seems essential to focus efforts on **strengthening the resilience of these systems in the context of climate change**, and more broadly of global change, with in particular organisational transformations at the territorial level. **Compromises will have to be made between the different facets of resilience**, between strengthening the robustness of current systems and transforming them into territorial systems and organisations better adapted to climate change, or between the different levels at which resilience can be applied, for example strengthening the robustness of a value chain by forcing the adaptation or transformation of its actors.

Climate change is already forcing **changes in plant protection strategies**, and this trend is set to increase. Climate-smart pest management requires **holistic approaches at farm, landscape and territorial levels**, and relies heavily on the use of control methods that **enhance mitigation and strengthen resilience**, of which **curative and preventive plant protection measures** are key factors. **Surveillance** and **monitoring** activities (with the development of indicators including resilience indicators) of plant health threats at national, regional and international levels are essential and need to be strengthened to develop preventive measures and contain plant health threats.

2.5. Towards crop protection strategies without chemical pesticides: Six modes of action for crop protection without chemical pesticides

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This Section has been reviewed by Anaïs Tibi (INRAE, DEPE).

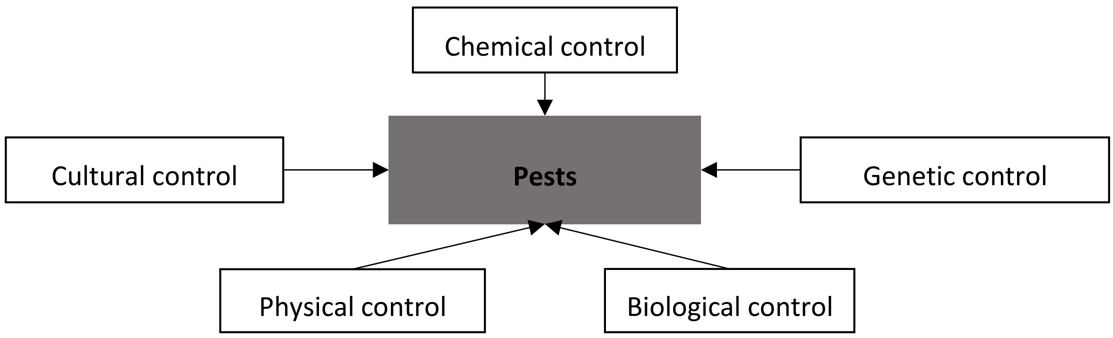
Table of contents

Introduction

Before building hypotheses of crop protection without chemical pesticides, we conducted a survey and a collective work in workshops to identify modes of action to manage pests without using chemical pesticides. The term pests cover animal pests, pathogens and weeds.

The modes of actions have been inspired by Aubertot *et al.* (2005), Attoumani-Ronceau *et al.* (2011) and Laget *et al.* (2015) who present different methods to manage pests that are summarized in Figure 2-36.

Figure 2-36: Different methods of managing pests (Source: Adapted from Aubertot *et al.*, 2005)



In Figure 2-36, chemical control is the use of chemical plant protection products to reduce pest population. Genetic control corresponds to the use of resistant or tolerant species to pests. Biological control involves the use of biocontrol products based on natural mechanisms. Physical or mechanical control acts directly on pests via physical methods (weeding, nets etc.). Cultural control consist of using of agricultural practices to limit pest development (crop rotation, intercropping etc.) (Laget *et al.*, 2015).

The modes of action, presented in this chapter, were defined during two thematic groups of experts (see Table A2 in the Appendix of the report) and adjusted based on reviews conducted by the project team. As a result, six modes of action were defined (Table 2-6). They emphasise several dimensions such as temporal and spatial management of pests, landscape level, diversity within the field, and the difference between prophylaxis and control.

The thematic group 'Reducing pest pressure' discussed and presented the five modes of action: 1) biocontrol; 2) physical control; 3) temporal management through cropping practices; 4) spatial management of crop diversity within the field; 5) management of the landscape. The thematic group 'Strengthening plant resistance' added a sixth mode of action: plant breeding (6). Each mode of action includes different levers of action. The levers corresponding to the six modes of action are summarised in Table 2-6.

The six modes of action act on pest populations or on plant-pest interactions. They involve various strategies to manage pests without chemical pesticides:

- Acting directly when pests are present (biocontrol, physical control);
- Avoiding sensitive phases of plant growth and pest population development (temporal management through cropping practices, spatial management of crop diversity within fields);
- Acting on the different phases of the life cycle of pests and that of their natural enemies (temporal management through cropping practices, spatial management of crop diversity within the field, management of the landscape);
- Strengthening the plant resilience to pests.

Table 2-6: The six modes of action for crop protection without chemical pesticide

Modes of action	Levers of action
Biocontrol	Microorganisms
	Macroorganisms
	Chemical mediators
	Natural substances
	Plant defence stimulators and biostimulants
Physical control	Thermal, electromagnetic, pneumatic and acoustical control
	Physical barrier
Temporal management through cropping practices	Temporal diversification (crop sequences, cover crops)
	Cropping calendar
	Fertilisation and irrigation
	Management of (grass) cover, residue, litter, and manure
	Management of tree architecture
	Soil tillage and weeding
Spatial management of crop diversity within the field	Intraspecific diversification (varietal and population mixtures)
	Interspecific diversification (intercropping and agroforestry)
Management of the landscape	Composition of the landscape
	Configuration of the landscape (spatial arrangement of landscape elements)
Plant breeding	Pest resistance and new selection objectives: microbial processes, varietal mixtures, species association (intercropping, agroforestry, annual and perennial crops), rootstock-graft association, other non-production services

Linked to those six modes of action, epidemiological surveillance also has a central position in pest management. It is not a mode of action in itself because it does not allow direct action on pests. Nevertheless, epidemiological surveillance is a tool for mobilising the different levers of action.

In this section, the six modes of action and their levers of action to manage pests without chemical pesticide are presented. The last paragraph introduces epidemiological surveillance. It should be noted that, in parallel of this work, a collective scientific assessment was carried out by INRAE on plant diversification to protect crops (Tibi *et al.*, 2022; Vialatte *et al.*, 2023). In this context, a complete review of the scientific literature was carried out on the effects of diversification of cultivated and non-cultivated plants (at the field or landscape scale) on pests.

2.5.1. Biocontrol products

In this paragraph, we present the different biocontrol agents and products, divided into four categories: macroorganisms (insects or nematodes), microorganisms (viruses, bacteria, fungi or oomycete), chemical mediators (pheromones or keiromones), and natural substances of plant, animal, microorganism or mineral origin (Busson *et al.*, 2022).

The term "Biocontrol" has different definitions. It does not have the same meaning in English (Biocontrol) and in French (Biocontrôle) (Deguine and Ledouble, 2022). In English "biocontrol" and "biological control" have the same meaning (ibid.). The three main types of biological control are classical biocontrol and augmentative biocontrol, which relies on the use of microorganisms and macroorganisms, and conservation biological control (Eilenberg *et al.*, 2001). It represents only a part of the French "biocontrôle" that also includes chemical mediators and different natural substances

(Amichot *et al.*, 2022). The official French definition of "biocontrôle" is "*a set of plant protection methods based on the use of natural mechanisms. Alone or in combination with other means of plant protection, these techniques are based on the mechanisms and interactions that govern the relationships between species in the natural environment*" (Xicluna, 2022).

Conservation biological control is developed in paragraph 2.5.5. Here, we focus on biocontrol agents and products (macroorganisms, microorganisms, chemical mediators and natural substances). The effectiveness and environmental effect of these products are discussed.

2.5.1.1. Use of macroorganisms

Introduction of macroorganisms by acclimation

This technique can also be called "classical biological control" because it is one of the oldest biocontrol strategy, considered since the 19th century (Eilenberg *et al.*, 2001; Borowiec and Sforza, 2020). Eilenberg *et al.* (2001) define this technique as "*the intentional introduction of an exotic, usually co-evolved, biological control agent for permanent establishment and long-term pest control*". It is used to control insect pests or weeds (Eilenberg *et al.*, 2001). It was originally used to control introduced invasive pests and restore a host/natural enemy balance, but it is now also successfully applied against native pests (ibid.).

The classical biological control strategy was widely used until the 1970s with an increasing number of introductions, but since the 1970s the number of introduction has decreased (Cock *et al.*, 2016). Although only 10% of introductions provide effective biological control after establishment (ibid.), introductions, when successful, can provide real agronomic and economic benefits (van Lenteren, 2012; Borowiec and Sforza, 2020). The deployment of acclimation strategies relies on public funding (van Lenteren, 2012)

The different steps of classical biological control are: exploration of the native pest area to find a potential natural enemy, importation of exotic macroorganisms and evaluation of their biological traits, and introduction into the natural environment (Borowiec and Sforza, 2020).

However, the introduction of exotic species can have negative impacts. For example, the Asian lady beetle, *Harmonia axyridis*, used for biological control, has become an invasive species in North America and Europe (Koch and Galvan, 2008; Roy and Wajnberg, 2008). This Asian lady beetle has impacts on non-target arthropods, threatens native biodiversity, inflicts damages on fruit production and invades households (ibid.). Another example is the introduction of weevil *Rhinocyllus conicus* in North America for biological control of true thistles. It has become an invasive species and has negative impacts on native plants and insects (Gassmann and Louda, 2001). Nevertheless, the impact of introduced agents on non-target species seems to be rare (Suckling and Sforza, 2014; van Lenteren *et al.*, 2006), and the occurrence of trade-related invasive species is much higher (Borowiec *et al.*, 2011). To limit the risks to non-target species, Louda *et al.* (2003) made six recommendations: "*avoid using generalists or adventive species; expand host-specificity testing; incorporate more ecological information; consider ecological risk in target selection; prioritize agents; and pursue genetic data on adaptation*". Long-term monitoring (8-10 years) is also needed (Borowiec and Sforza, 2020).

Augmentative biological control with macroorganisms

Augmentative biocontrol concerns the release of endemic microorganisms and macroorganisms (Eilenberg *et al.*, 2001). We focus on microorganisms in another paragraph.

Augmentative biocontrol is based on repeated releases of natural enemies of pests (Bout *et al.*, 2020). Those organisms are mass-reared in biofactories to be released in large numbers in fields and achieve "*an immediate control of pests*" (van Lenteren, 2012). In contrast to acclimation biocontrol, augmentative biocontrol is developed by private companies for commercial purpose. In Europe, three major companies are leading the market: Koppert, Bioline AgroSciences and Biobest (van Lenteren, 2012; Bout *et al.*, 2020).

Augmentative biological control can be subdivided in two methods: inoculation and inundation (Eilenberg *et al.*, 2001). Inoculation refers to "*the intentional release of a living organism as a biological control agent with the expectation that it will multiply and control the pest for an extended period, but not permanently*" and inundation to "*the use of living organisms to control pests when control is achieved exclusively by the released organisms themselves*" (ibid.). In practice, there is a *continuum* in augmentative biocontrol strategies between inoculation and inundation (Bout *et al.*, 2020).

Augmentative biocontrol is mainly used for high-value added productions, in greenhouses (*e.g.* vegetables, ornamental plants), or outdoor (*e.g.* strawberries, vineyards) (van Lenteren *et al.*, 2018). However, for field crops, the introduction of *Trichogramma brassicae* in maize fields successfully controls the European corn borer (Razinger *et al.*, 2016).

Macroorganisms may have difficulties in establishing and maintaining themselves, as they do not have enough resources (lack of preys, hosts, alternative food or nesting sites or shelters), which limits their effectiveness (Bout *et al.*, 2020). One solution is to provide alternative resources, for example by establishing companion plants hosting lays and hosts, or by directly providing resources (eggs, pollen, etc.) (ibid.).

There are also risks linked to augmentative biocontrol, as the introduced organisms may cause crop damages and interfere with other natural enemies (Bout *et al.*, 2020). There are very few studies on the dispersal of massively inundated auxiliaries and their potential long-term effects on non-target species (ibid.).

The sterile insect technique

According to the FAO terminology, the sterile insect technique is a "*method of pest control using area-wide flood release of sterile insects to reduce reproduction in a field population of the same species*". The released sterile males inseminate wild females, which lay sterile eggs that die prematurely (Oliva *et al.*, 2020).

The sterile insect technique is generally used as a component of area-wide integrated pest management, a program that aimed at preventing large-scale pest populations (Klassen and Curtis, 2005). It requires cooperation of a large number of actors (Oliva *et al.*, 2020). The sterile insect technique can be used to eliminate or contain native pests or invasive exotic pests, but also to prevent a pest invasion (Hendrichs *et al.*, 2005). This technique has advantages: (i) it is very specific to one target insect and is not expected to have impacts on non-target organisms (Oliva *et al.*, 2020); (ii) its effect ends as soon as the releases are stopped (ibid.); (iii) it becomes more effective over time (*i.e.* as the ratio of sterile to fertile insects increases, the sterile insect technique is more powerful) (Klassen, 2005). However, this technique has also limits: i) it can only control one species; ii) it is not suitable for crises (*i.e.* it acts on reproduction and not on viability); iii) it is not suitable for all scales and pest insects (Oliva *et al.*, 2020). In addition, mass-releases can generate high variability of population density and have impacts on non-target species (*i.e.* species that interact with the sterile insect or that are in competition for food) (ibid.). There is also a possibility of gene flow between the released insects and the wild population (sterile insects are not always 100% sterile) (ibid.). These effects are not studied (ibid.).

2.5.1.2. Use of microorganisms

Augmentative biocontrol with microorganisms

Microorganisms can be used for an augmentative biological control strategy (see above). A large number of microorganisms are identified as potential biocontrol agents for plant diseases, insect pests and weeds (van Lenteren *et al.*, 2018). Only a small part is commercialised (Bardin and Nicot, 2020). In 2019, 49 strains of microorganisms were registered with a marketing authorisation in the European Union. These were strains of fungi, bacteria, virus and oomycetes (ibid.). These authorised strains are in descending order of strain number: fungicide, insecticide, bactericide, elicitor and nematicide, but there is no herbicide (ibid.). Nevertheless, some bioherbicides derived from microorganisms are marketed worldwide, mainly in the USA and Canada (Cordeau *et al.*, 2016).

The effectiveness of microorganism biocontrol agents is variable under field conditions (Bardin and Nicot, 2020). These authors list the factors that affect the effectiveness of microorganisms:

- Variability of the environmental context: variable microclimatic conditions affect the survival, establishment and activity of microorganism agents;
- Agricultural practices as the choice of varieties, fertilisation and the use of plant protection products;
- Quality of the products and mode of application;
- Characteristics, inoculum and population of the target pest.

In addition, there are many effectiveness issues related to the conditions of introduction of these microorganisms. Products are often deactivated for storage and require an activation period that is often overlooked, and the environmental context of introduction can be highly variable (expert workshop, November 2020). The effectiveness of some products is only evaluated on a fraction of pests, but in the field, it may vary according to the geographical area (ibid.).

Microorganisms used as plant biostimulants

Plant biostimulants are not biocontrol products *per se*. Nevertheless, they encompass a broad category of products, including microorganisms (Yakhin *et al.*, 2017). Although biostimulants do not act as biological agents to control pests, there are related to biocontrol agents. Microorganisms applied on plant can have a dual function of biocontrol agent and biostimulants (du Jardin, 2015). Moreover, the European regulation on biostimulants is the same as that for plant protection products (EC No 1107/2009) (ibid.).

Du Jardin (2015) defines a plant biostimulant as "*any substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrients content*", "*by extension, plant biostimulants also designate commercial products containing mixtures of such substances and/or microorganisms*".

Microorganism biostimulants come from bacteria, yeasts and fungi, they can include living and/or non-living microorganisms and their metabolites (Yakhin *et al.*, 2017). Biostimulants have various positive impacts on plant: activating the metabolism of nitrogen or phosphorus released from soils, stimulating soil microbial activity, stimulating root growth, enhancing plant establishment, stimulating plant growth and mitigating the negative effects of abiotic stress factors on plants (ibid.). The mode of action of biostimulants is not well known (ibid.).

Many microorganisms used in the field fall into the category of plant biostimulants. We can mention biostimulants based on well-known and used microorganisms. Mycorrhizae, which form arbuscules, are fungi that establish symbioses with plant species and enhance their nutritional efficiency, water balance, protect them from biotic and abiotic stresses and enhance interactions with the plant community (du Jardin, 2015). *Rhizobia* are nitrogen-fixing bacteria that form root nodules in legumes to fix atmospheric nitrogen, which benefits the plant (Hendriksen, 2022). The "plant growth-promoting rhizobacteria" are also intracellular endophytes that promote plant growth by improving water and nutrient uptake and tolerance to biotic and abiotic stresses (Backer *et al.*, 2018).

Plant defense stimulators: Microorganisms that induce systemic resistance

As with biostimulants, plant defense stimulators do not control pests, but some biocontrol agents based on microorganisms also induce systemic resistance of plants to specific pests (Amichot *et al.*, 2022; Bardin and Nicot, 2020). Indeed, beneficial microbes produce different compounds (molecular patterns associated to pathogens or microbes) and elicitors, which are recognized by plants and induce immune mechanisms to confer systematic resistance to the plant (Pieterse and al., 2014). This resistance involves a physical state of the plant called "priming" in which the plant can activate strong and rapid cellular defenses in the event of pest invasion (Pieterse *et al.*, 2014; Conrath *et al.*, 2006).

Impacts of microorganism introductions

The impacts of microorganism biocontrol agents on the environment is poorly studied and the few studies show a moderate impact (Amichot *et al.*, 2022). Nevertheless, they can persist until a few years in the environment (ibid.), which questions the risk associated to an invasion of microbial inoculants that could disrupt ecosystem services and plant-microbe interactions or evolve into parasites or pathogens (Jack *et al.*, 2021).

2.5.1.3. Natural substances

Natural substances are provided by plants, animals, microorganisms or minerals. Their mode of action can be direct or via the stimulation of plant defense (Amichot *et al.*, 2022).

Natural substances of plant or seaweed origin

Plant-based biopesticides can be prepared directly by farmers or be commercialized industrial products (Sigwart and Lavoir, 2020).

Plant-based biopesticide substances are diverse. Amichot *et al.* (2022) and Sigwart and Lavoir (2020) cite a few major biopesticides that are marketed and used. Pyrethrum, produced naturally by asteraceae, which is neurotoxic to insects. Vegetable oils, such as rapeseed and sunflower oils, which asphyxiate insects. Essential oils that are used as insecticides. Pelargonic acid that is used as a herbicide. Maltodextrin that acts like vegetable oils on insects.

Most part of these products have low persistence in the environment and are considered as low-risk substances (Sigwart and Lavoir, 2020). Nevertheless, most are non-selective and can impact non-target insects (ibid.). Essential oils can be toxic to mammals (Duran-Lara *et al.*, 2020). For example, nicotine and retonine are derived from plants but they have been removed from the market due to their effects on mammals and human health (Sigwart and Lavoir, 2020, Amichot *et al.*, 2022).

Natural substances of animal origin

There are few substances derived from animals, the majority is used as repellent against wild game (*e.g.* blood meal, sheep fat, fish skeleton) (Amichot *et al.*, 2022). Some of them are also plant defense stimulators (ibid.).

Natural substances of microorganism origins

Some natural substances contain yeast extracts, acetic acid, beer, or other fermentation products (ibid.).

Natural substances of mineral origin

These substances can be mineral oils (*e.g.* paraffin oil), pure elements or salts and derivatives (sulfur, phosphate, ferric sulphate, etc.) (Amichot *et al.*, 2022). Mineral biopesticides can be used as antifungal, insecticide, defoamer or molluscicide (ibid.). Sulfur is one of the most widely used biocontrol products (ibid.).

2.5.1.4. Chemical mediators

Chemical mediators are synthetic molecules identical to pheromones or kairomones produced by insects (Amichot *et al.*, 2022). Insects use these molecules to communicate. They have a major role in their behaviour (feeding, reproduction, social relations) (Montagné *et al.*, 2020).

Pheromones are used to monitor pest populations. Traps containing synthetic pheromones lures baited and trapped insects, informing them of the presence of specific insects and the beginning of their seasonal flight period (Witzgall *et al.*, 2010). The use of insecticides can then be adapted to this information (ibid.).

Another use is mass trapping and annihilation or the “attract-and-kill” approach (Anton and Jacquin-Joly, 2020; Witzgall *et al.*, 2010). Insects are massively attracted in a high capacity trap by a chemical mediator lure and then killed (Anton and Jacquin-Joly, 2020). This technique has already shown its success in controlling beetle, fly or weevil populations (ibid.)

Finally, sexual confusion is an effective method using pheromones (Lance *et al.*, 2016). It consists of saturating the air with the species’ sex attractant pheromone in order to hinder the ability of males to locate females, thus reducing the incidence of mating and subsequently the insect population (ibid.). This technique is the most widely used among chemical mediators, but it requires a collective organisation to be implemented over a large area (Anton and Jacquin-Joly, 2020). It is employed on high-value crops because it is an expensive method, for example it is used in French and Italian vineyards against harmful lepidoptera (ibid.).

Chemical mediators are worthwhile for crop protection because “*they are species-specific, they are active in very small amounts, and the vast majority are not known to be toxic to animals*” (Witzgall *et al.*, 2010).

2.5.2. Physical control

Physical control is a set of practices that use physical methods for plant protection. It includes thermal control, electromagnetic control, pneumatic control, acoustical control and physical barriers. Mechanical weeding is also part of the physical control and it is developed in paragraph 2.5.3.

2.5.2.1. Thermal control

Thermal control consists of causing internal injuries on pests by lethal heating or by decreasing temperature below the freezing point (Aubertot *et al.*, 2005).

Thermal weed control

Thermal weed control consists of causing a lethal effect on the weed by increasing temperature through physical process (Bauer *et al.*, 2020). Different techniques are used for thermal weed control: flaming, electrical resistance, electromagnetic radiation, hot water, soil solarization, satured steam and hot foam (Bauer *et al.*, 2020; Peerzada and Chauhan, 2018). Soil solarization, saturated steam and hot foam are also use to control soil pathogens (Peerzada and Chauhan, 2018). Soil solarization is a soil sterilization through heat, it consists of using plastic mulches exposed to the sunlight during a long period to increase soil temperature (ibid.). It is used for high-value horticultural crops (lettuce, garlic, tomato, scash), as these crops compensate the high cost of solarization (ibid.).

Thermal weed control has been poorly developed in Europe, contrary to the United States (Peerzada and Chauhan, 2018). This technology plays an important role in organic agriculture (ibid.) and is seen as an alternative to chemical herbicide in conservation agriculture (Bauer *et al.*, 2020). However, high temperature may alter physical, chemical and biological proprieties of the soil (Peerzada and Chauhan, 2018).

Thermal control against insects and pathogens

Thermal control can also be used against insect pests and pathogens. It is particularly used in postharvest situations and it is more complicated to implement in the field (Vincent *et al.*, 2003). These authors describe different temperature control techniques: cold storage, which consists of decreasing temperature to store fruits and vegetables, heated-air treatments, hot water immersion, flaming, steaming and solar heating.

2.5.2.2. Electromagnetic control

Electromagnetic control is based on the interaction between electromagnetic radiation, or a current, and the matter constituting the target pests (Aubertot *et al.*, 2005). This electromagnetic radiation can be produced by irradiation, radio frequency heating or infrared heating (Vincent *et al.*, 2003).

2.5.2.3. Pneumatic control

Pneumatic control consists of using moving air (suction, blowing, or a combination of both) to eliminate undesirable insects from crops (Khelifi *et al.*, 2001). Pneumatic control is non-specific and have negative effects on beneficial organisms (Vincent *et al.*, 2003)

2.5.2.4. Acoustical control

Acoustical control consist of using noise to scare away pests. Bird scarers can be used to scare birds away by sound (Laget *et al.*, 2015).

2.5.2.5. Physical barriers

The objective of physical barriers is to prevent the arrival of pests by surrounding or obstructing the passage to the crop. There are different types of physical barriers: trenches, fences or mulches (straw mulch, paper or plastic sheets or aluminized films) (Vincent *et al.*, 2003). Physical barriers are particularly used inside greenhouses (Aubertot *et al.*, 2005), where vegetables and ornamentals are produced (van Lenteren, 2000). They can also be used on field crops, for example plastic film on potatoes, steel fences around wheat to protect it from grasshoppers, mulch, plastic netting or sheeting against aphids, etc. (Aubertot *et al.*, 2005). Physical barriers have also been developed for fruit production. These include protective nets, grids, trunk protections and mulching (plastic sheeting, woven fabric or mulch plants) (Laget *et al.*, 2015).

Nevertheless, these barriers are mainly made of plastic and largely contribute to plastic wastes from agriculture (Briassoulis *et al.*, 2013). Those agricultural plastic wastes have negative impacts on the environment, human health and the regional economy (Briassoulis *et al.*, 2010; Briassoulis *et al.*, 2013).

Windbreaks (such as trees or hedges) also act as physical barriers, by modifying air circulation they influence the dispersion of insects in the landscape (Ratnadass *et al.*, 2012).

2.5.3. Temporal management through cropping practices

Cultural practices can be adapted to prevent and limit the outbreaks of animal pests, diseases and weeds (Bajwa and Kogan, 2004). Many of these cultural practices need to be thought over time and concern the temporal management of the cropping system. They include practices that modify agroecosystem conditions to disfavour pests and favour their natural enemies, or physical mechanisms that limit pest development (ibid.). Temporal management through cultural practices includes temporal crop diversification (crop rotation and cover crops), the cropping calendar (sowing and harvesting dates, sowing density, fertilisation and irrigation), management of different covers, management of tree architecture, and soil tillage and weeding.

The temporal diversification of crops includes crop successions or crop rotations, with Bézat *et al.* (2022) describing the latter as "*the organisation of the succession of crops on a given field*", and cover crops that are "*established between the harvest of a main crop and the sowing of the next main crop*" (Sudres *et al.*, 2022).

According to Tibi *et al.* (2022), effect of temporal diversification (increasing length of crop rotations, increasing return time of crop and introduce cover crop) is mostly documented for weeds and nematodes. Scientific literature is scarce on insects and diseases. Increasing rotational diversity has a positive effect on weed regulation, flying insects regulation (at landscape scale), soil insects regulation, nematodes regulation, soil-born pathogen regulation, and it has a positif effect on the regulation of aerial pathogens when the inoculum is local.

2.5.3.1. Crop rotation and succession and cover crops

The FAO terminology portal define crop rotation as follows: "*The practice of alternating the species or families of annual and/or biannual crops grown on a specific field in a planned pattern or sequence so as to break weed, pest and disease cycles and to maintain or improve soil fertility and organic matter content*." This definition clearly shows the importance of crop rotations for pest management.

Crop rotation is seen as one of the most effective levers for managing pests without using chemical pesticides (Barzman *et al.*, 2015). Manipulating the cropping sequence with successions of crops from different families makes it possible to break pest life cycles by determining environmental conditions (biotic or abiotic) that are favourable or unfavourable to them (Barzman *et al.*, 2015). A succession of diversified crops provides robustness by preventing the establishment and development of pest populations best suited to the crop (ibid.).

The English term "cover crop" designate a crop sown between two cash crops, the equivalent of the French term "culture intermédiaire" ("intermediate crop") (Sudres *et al.*, 2022). However, cover crops should not be confused with other terms: the fallow period ("interculture" in French), which designates the period between two main crops, and not the plant cover (Justes and Richard, 2017); and intercropping, the combination of at least two crops in the same plot for a significant period of their growth period (Bedoussac and Journet, 2022) (see 2.5.4.3). Cover crops can also remain permanently in the field, with the main crop then sown under the cover crop. The cover crop exists in tandem with the main crop and is described as a living mulch (Médiène *et al.*, 2011).

Weeds

Crop rotation is one of the most effective levers for managing weeds (Nichols *et al.*, 2015). Each crop type within the succession applies different biotic and abiotic constraints on weed populations, favouring some weeds and being unfavourable to others, varying the selection pressure on weeds with each change in crop (ibid.). Three mechanisms are involved in the variation in selection pressure on the various biological stages of weeds:

- The modification in crop management (crop calendar and desynchronisation of the biological cycles of crops and weeds, soil disturbance, and mechanical damage);
- Variation in competition for resources (variations in access to water, light and nutrients);
- Allelopathy (introduction of crops with allelopathic properties which, for example, block weed germination) (ibid; Liebman et Dyck, 1993). Allelopathy can be defined as "*the set of direct or indirect, positive or negative biochemical interactions of one plant with another*" (Petit and Cordeau, 2020).

Indeed, competition for resources such as light, water and nutrients within the same spatio-temporal niche is a way to manage pests through the use of other plants, especially cover crops (Justes *et al.*, 2013; Petit *et al.*, 2018). Above ground, competition for light comes into play and can regulate weed germination and growth. This competition depends on the phenotypic traits of the plant (height and surface area of the plant, leaf angle) (Petit *et al.*, 2018). In the soil, there is competition for water and nutrients. Competitiveness depends on the ecophysiological traits of the plant, its underground biomass and its root system (ibid.). Other factors, such as the speed of establishment, duration of vegetation and the persistence of biomass either living or dead influence the competitiveness of the crop with weeds (Justes *et al.*, 2013). For cover crop, the more a cover crop grows over a lengthy period, the more biomass it can accumulate and therefore the greater its competition with weeds (Mirsky *et al.*, 2017). The competitive effect of cover cropping reduces weed emergence and biomass (Cordeau *et al.*, 2015). Nevertheless, when it comes to germination there is a great variation in the light sensitivity of weed seeds of different species and some weeds have no difficulty in germinating in the presence of plant cover (ibid.). However, the presence of a cover crop strongly limits their growth (ibid.).

Allelopathic activity can be found among several cultivated species, with allelopathic chemicals exuded when they are alive or from dead tissues (Jabran *et al.*, 2015). These substances can be toxic to other plants (de Albuquerque *et al.*, 2011). Introducing plants with allelopathic properties (*e.g.* certain cereals, brassicas and legumes) in cover crops can help control weed flora (Jabran *et al.*, 2015). However, it is difficult to characterise the effects of the allelopathic processes of a cover crop because it is difficult to distinguish them from the competitive effect (Petit and Cordeau, 2020). Inserting temporary pastures within the crop rotation helps to control certain problematic weeds in field crops, in particular ryegrass (Munier-Jolain *et al.*, 2012; Doole and Pannell, 2008).

Pathogens and diseases

With regard to diseases, a crop rotation incorporating non-host crops can break pathogen biological cycles and thereby avoid outbreaks (Shah *et al.*, 2021). This strategy is particularly effective for soil-borne diseases (Ratnadass *et al.*, 2012).

Similarly, with regard to pests, the succession of different crops breaks their biological and reproductive cycles by modifying the aerial and underground environment, disturbing pests established during the previous crop (Bajwa and Kogan, 2004). Crop succession is particularly effective against pests that hibernate in the soil (ibid.). In addition, burying residue through planting the crop or cover crop encourages the degradation of residues from the previous crop and reduces primary inoculum (Bajwa et Kogan, 2004; Justes *et al.*, 2013).

Some crops can also have allelopathic properties against pathogens (Brassicaceae and Poaceae) (ibid.). For example, biofumigation is a method used against soil-borne diseases, usually involving the planting of Brassicaceae as cover crops (Ait-Kaci Ahmed *et al.*, 2020). It is based on the presence of glucosinolates in the tissues and root exudates of Brassicaceae plants which are transformed into isothiocynatates after crushing and burial. These isothiocynatates are potentially toxic to soil-borne diseases (Justes *et al.*, 2013; Ait-Kaci Ahmed *et al.*, 2020). However, the effectiveness of biofumigation can vary greatly in practice (Morris *et al.*, 2020).

Diversified crop succession, especially those including cover crops improve a soil's organic carbon and nitrogen content and stimulate a soil's microbial life (McDaniel *et al.*, 2014), which is likely to increase plant resistance. The presence of a cover crop can stimulate the presence of beneficials within soil microbiota (Justes *et al.*, 2013).

Animal pests

Similarly, with regard to animal pests, the succession of different crops breaks their biological and reproductive cycles by modifying the aerial and underground environment, disturbing pests established during the previous crop (Bajwa and Kogan, 2004).

Cover crops can also have allelopathic properties for controlling other pests. For example, biofumigation works against insects and nematodes (Justes and Richard, 2017; Ait-Kaci Ahmed *et al.*, 2020). Some cover crops also have repellent, intoxication or trapping properties that contribute to pest management (Justes and Richard, 2017).

Furthermore, establishing long rotation with cover crop encourages the development of beneficial populations, especially natural enemies of pests, by providing them with a favourable environment and food (nectar, pollen and prey) (O'Rourke *et al.*, 2008 ; Singhal *et al.*, 2020).

In addition, a diversified crop rotation contributes to balanced soil fertility and better crop plant nutrition, which then improves crop resistance to pests and diseases (Ratnadass *et al.*, 2012). Finally, the diversification of crop successions promotes biodiversity (additional biodiversity of up to 37% according to Beillouin *et al.* (2021)), soil microbial diversity (Venter *et al.*, 2016) and the presence of beneficials (natural enemies of pests) (Rusch, 2020) which improves conservation biological control.

2.5.3.2. Cropping calendar

Adapting the cropping calendar, the date and density of sowing and the date of harvesting can limit the development of pest populations and their damages on crops (Aubertot *et al.*, 2005).

Sowing date

The sowing date can be adapted to desynchronise pest development and the sensitive period of the crop (Attoumani-Ronceaux *et al.*, 2011).

The sowing date can play on weed competition. Playing on the sowing date, combined with a stale seedbed strategy, is one of the major levers to avoid weed infestations (Munier-Jolain, 2018). Late sowing of autumn crops, after the weed germination period, with a stale seedbed, provides good control of autumn weeds, expect for late-emerging weeds (ibid.). Similarly, a late sowing of spring crops disfavours the development of weeds with low temperature requirements (Aubertot *et al.*, 2005). In contrast, stifling crops (*e.g.* rapeseed) can be sown earlier to be more competitive during the weed development period (Attoumani-Ronceaux *et al.*, 2011). The sowing date also affects the level of damages caused by insect pests and the ability of the plant to compensate for those damages (Rusch *et al.*, 2010). For some plants, early sowing reduces insect and worm damage, *e.g.* maize or rice, while for others, late sowing is preferable, *e.g.* soybean or wheat (Bajwa and Kogan, 2004). Finally, the sowing date can be adjusted to control diseases by desynchronising the period of disease dispersal and the period of crop sensitivity (Aubertot *et al.*, 2005; Bousset, 2020).

Nevertheless, other constraints may determine the sowing date. Late sowing of winter crops limits the growing time, for spring crops it can shift the growth cycle to a period of water stress (Aubertot *et al.*, 2005).

Sowing density

The sowing density and the width of the inter-row influence pest control. High population density combined with high fertilisation and irrigation can create a microclimate that favours the dispersal of fungal and soil-borne diseases (Aubertot *et al.*, 2005). Thus, a decrease in crop density can reduce crop diseases (ibid.). However, a high sowing density can favour weed control (Attoumani-Ronceaux *et al.*, 2011).

At the time of sowing, the width of the inter-row can be considered for future mechanical weeding with suitable tools (hoe, weeder, harrow) (Aubertot *et al.*, 2005).

Harvesting date

Adjusting the harvesting date is a factor to reduce the pest population; in general, an early harvest reduces the damage caused by insects (Bajwal and Kogan, 2004). The harvesting date can also affect the weed seed bank (Aubertot *et al.*, 2005).

Moreover, harvesting produces a brutal perturbation on the environment and affects pest natural enemy population. The harvesting date can coincide with their abundance and activity period (Rusch *et al.*, 2010).

2.5.3.3. Fertilisation and irrigation

For diseases, a high availability of nitrogen and water during the vegetative phase contribute to a microclimate favourable to pathogen development (Attoumani-Ronceaux *et al.*, 2011). Thus, reducing the level of nitrogen and water can decrease the level of crop disease.

For insect pests, two main hypotheses have been put forward on the impact of nitrogen availability on the relationship between insect pest populations and host plants (Rusch *et al.*, 2016a): the plant stress hypothesis (White, 1984) and the plant vigor hypothesis (Price, 1991). The plant stress hypothesis states that stressed plants (including nutrient deficiencies) are more attacked by insect pests and are less resistant. In contrast, the plant vigor hypothesis states that vigorous plants are more attacked by insect pests because they provide better quality food. In the literature, both hypotheses have been validated but in a majority of cases, herbivorous pest insects respond to the plant vigour hypothesis, where a high level of fertilisation favours insect pest attacks (Rusch *et al.*, 2016a).

For weeds, nitrogen supply may favour nitrophilic species, thus depending on the crop species and weed traits, level of nitrogen fertilisation may favor crops or weeds (Munier-Jolain, 2018). For example, Moreau *et al.* (2013) suggest that for oilseed rape which is a highly nitrophilic crop with an increased ability to compete with weeds with increasing nitrogen availability, an optimal level of nitrogen fertilisation provides good crop competition. On the contrary, for wheat, which is a moderately nitrophilic crop, a reduction of nitrogen fertilisation could disadvantage the growth of nitrophilic weeds in favour of wheat growth (ibid.). Irrigation may also favour the development of hygrophilic weeds during summer (Aubertot *et al.*, 2005).

To conclude, the principles of integrated pest management suggest using balanced fertilisation and irrigation to prevent harmful organisms (Barzman *et al.*, 2015). Furthermore, long-term inorganic nitrogen fertilisation alters diversity and composition of the soil microbial community (Beltran-Garcia *et al.*, 2021). This affects microbial symbiotic services for crops such as nutrient assimilation and protection against biotic and abiotic stress (ibid.).

An alternative to mineral fertilisation is the use of organic fertilisation through animal manure or green manure. Animal-waste fertilizers (*i.e.*, livestock manure or vermicomposts) have many advantages to control pest (Rowen *et al.*, 2019). Compare to mineral fertility, manure fertility enhances crop chemical defense, it slows uptake of macronutrients that reduce arthropod pest growth and promotes natural enemies of pests by increasing sol-surface habitats and alternative preys (ibid.). Nevertheless, animal manure can be a source of pollution, especially in regions with geographical livestock concentration (Roguet *et al.*, 2015).

Green manure, *i.e.* "*a crop used primarily as a soil amendment and a nutrient source for subsequent crops*", may also provide pest control (Cherr *et al.*, 2006). Green manure decreases weed population by being in competition with them for resources, it may disrupt nematode life cycle and provide habitats for natural enemies of pests, but some green manure species may exacerbate pest infestations requiring a good green manure management (ibid.).

2.5.3.4. Cover, residue and litter management

Management of different covers (grass cover, cover crop, residue or litter) in field have impacts on pests.

Surface residue disadvantages germination and growth of weeds, especially weeds with small seeds, through lowering soil temperatures, restricting light availability, physical growth barriers and potential allelopathic effects (Nichols *et al.*, 2015). Crop residues can welcome pathogen inoculum (especially telluric diseases) (Aubertot *et al.*, 2005). Burying residues through tillage may decrease spore dispersal to other plots and to the next crops (ibid.). As well, destruction of crop residues by tillage destroys life-cycle stages of soil animal pests and may decrease their populations (such as worms and grubs) (Bajwa and Kogan, 2004).

For perennial crops, the foliar litter can host pathogens inoculum and may be destroy through burying, removal, crushing or use of urea (Laget *et al.*, 2015).

Sowed cover crops between two main crops can play a role for weed competition, especially in conservation agriculture (see 2.5.3.1) (Chauvel *et al.*, 2018).

For perennial crops, grass cover and wild flora may bring services and disservices, especially on pest control (Metay *et al.*, 2018). It promotes beneficial organism populations (including natural enemies of pests), it enhances water infiltration and thus limit fungus development and it provides a control on vigor of vineyard that limits pathogen pressure (Barbier *et al.*, 2011). Nevertheless, weeds and grass cover can be in competition with vineyard or fruit production (especially during early stage of growth) and can hosts pests (Barbier *et al.*, 2011; Laget *et al.*, 2015; Metay *et al.*, 2018). Thus, there is a need to control this cover through mechanical weeding, sowed cover, mulching, thermal weed control or partial destruction by crushing, mowing, rolling or animal pasture (Barbier *et al.*, 2011; Laget *et al.*, 2015; Metay *et al.*, 2018).

2.5.3.5. Management of tree architecture

For perennial crops, tree architecture plays a role on pest control. Managing tree architecture modify the microclimate, pest movements (inter-organ distance) and the plant vigor, which influence pest development (Laget *et al.*, 2015, Barbier *et al.*, 2011). Training pruning that influence tree architecture during early stages of growth may also suppress organs affected by pest attacks (Laget *et al.*, 2015).

Work on vine, such as pruning, trimming, debudding, leaf removal and thinning, provides good air circulation and rapid drying of leafs after rain, both decreasing cryptogrammic disease development (Barbier *et al.*, 2011).

2.5.3.6. Soil tillage and weeding

Soil tillage is defined by the FAO term portal as "*Changing of soil conditions for crop production; the mechanical manipulation of soil for any purpose*." It is widely used for weed controls (Colbach and Vacher, 2013), including decrease of seed bank and "mechanical weeding" is defined by FAO term portal as "*Removal of undesirable vegetation by mechanical means*." Soil tillage has also impact on animal pests and pathogens (Attoumani-Ronceaux *et al.*, 2011).

Ploughing

Ploughing involves a reversal of soil horizons, it destroys emerged plants and bury weed seeds into depth horizons where weed seeds cannot sprout or emerge (Munier-Jolain, 2018). Ploughing is a major lever to manage weed seed stock (ibid.). Nevertheless, ploughing can also bring weed seeds to the surface and promotes some weed species compared to others (Colbach and Vacher, 2014). No-tillage system may favor annual grasses, anemophytes, species with large plants, weeds with small seed, with low dormancy, and not very persistent seeds, but also perennials weeds whose underground survival organs are destroyed by ploughing (ibid.). The ideal is to plough before the crops that is the most favorable to the dominant weed (ibid.). It is not necessary to plough every year, the plough frequency depends on the crop sequence (Munier-Jolain, 2018).

As already mention, ploughing may also favor animal pest control (perturbation and destruction of early life stage) and disease control (residue burying) (Attoumani-Ronceaux *et al.*, 2011). Nevertheless, ploughing have drawback effects on soil health (Carr, 2017).

Stale seedbed to reduce seed bank

Stale seedbed (or false seedbed) is a shallow soil-tillage that promotes weeds germination and destroys them before sowing the cash crop, thus reducing the weed seed stock that could potentially emerge in the field (Labreuche *et al.*, 2020). This operation can be repeated several time, shortly before the sowing (Rodriguez, 2018a). Effectiveness of stale seedbed depends on the soil moisture and weed seed dormancy level (Labreuche *et al.*, 2020). With the good weather conditions (enough moisture for germination but not too much for tillage), this technique can be very efficient (Rodriguez, 2018a).

Mechanical weeding

Mechanical weeding destroys emerged weeds. Different tools can realize mechanical weeding during crop growth: weed harrow and rotary hoe that work in full and finger weeder that work in the inter-row (Rodriguez, 2018b). Effectiveness of mechanical weeding depends on the type of tools, type of soil, weather conditions, weeds species, weed development stages and weed position in relation with the sowed raw (ibid.). Mechanical weeding must be considered from the moment of sowing and different tools can complement each other (ibid.). As already mention, ploughing also act as mechanical weeding by destroying weeds (Munier-Jolain, 2018).

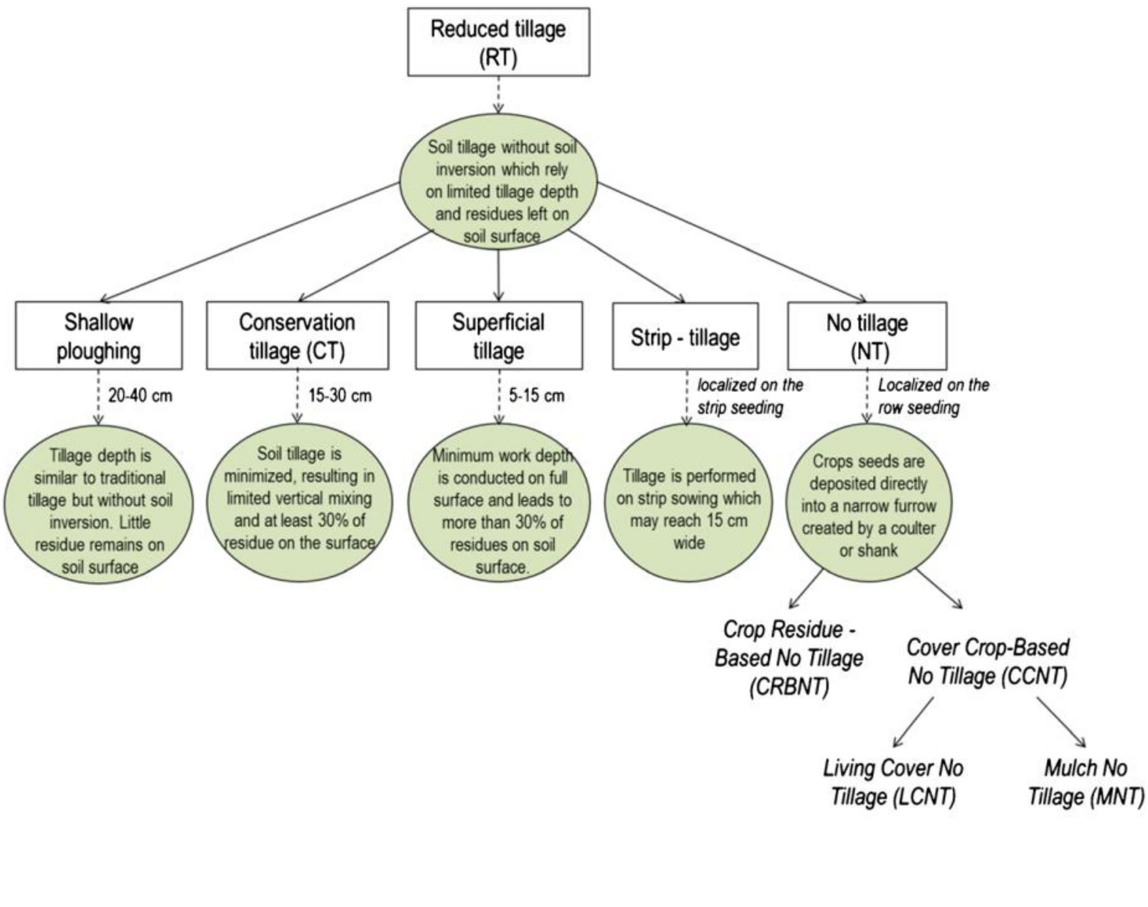
Period of residue burying, of stale seedbed and of mechanical weeding must be well thoughtful, to create a delay between weed growth trigger by stale seedbed and crop growth (Aubertot *et al.*, 2005 et Rodriguez, 2018b).

Reassessment of soil tillage

Soil tillage, especially ploughing, has limits. It demands a large working time and it has a high cost (expensive equipment, fuel) (Aubertot *et al.*, 2005). Moreover, it compromises quality and soil health and increases water and wind erosion (Carr, 2017). Continual soil inversion because of ploughing can lead to a degradation of soil structure and bring to a compaction of the soil and a decrease of soil organic matter (Holland, 2004). Soil tillage disturbs soil fauna, it implies mechanical damage, greater exposure to predation and emigration of arthropods to adjacent habitats (Rusch *et al.*, 2010). It modifies habitat quality, removes microhabitats for reproduction and decreases prey availability, thus it affects natural enemy populations (ibid.). Different methods to diminish ploughing and soil-tillage have been developed from shallow ploughing to no-tillage. There are described in Figure 2-37.

Those techniques have been particularly developed in North and South America (Vincent-Caboud *et al.*, 2019, Laurent, 2015). In contrast, they have not been developed much in Europe (Holland, 2004).

Figure 2-37: Techniques for reducing tillage (Source: Vincent-Caboud *et al.*, 2019)



The conservation agriculture has emerged, it regroups a pool of techniques including decreasing of tillage. According to the FAO, "*conservation agriculture is characterized by three principles: continuous minimum mechanical soil disturbance, permanent organic soil cover and diversification of crop species grown in sequences or associations*" (FAO, 2022). Nevertheless, conservation agriculture systems are criticized because they are frequently dependent on herbicides to control weeds (Vincent-Caboud, 2019). For example, in France, adoption of technique with less soil-tillage in the 1990s led to an increase of herbicide use (Colbach and Vacher, 2014). However, some technical solutions exist to avoid tillage without herbicide use, as the mulch-based no tillage (Vincent-Caboud, 2019). In Europe, the living-cover no tillage, that is less efficient to reduce herbicide dependence, has been more studied than the mulch-based no tillage, contrary to the United-States (ibid.).

Reducing tillage and conservation agriculture have advantages. They provides fuel and labor saving (Silva and Delate, 2017), promote soil biodiversity and increase soil organic matter (Holland, 2004), and enhance natural enemies of pests (Rusch *et al.*, 2016a).

2.5.4. Spatial management of crop diversity within field

2.5.4.1. Introduction and definitions

The spatial diversification of crops can take place at different levels: genes (population), varieties (varietal mixture, population) and species (intercropping, polyculture) (Finckh and Wolfe, 2006). For Tibi *et al.*, (2022), crop diversity within field is widely studied in scientific literature.

At the level of genetic and varietal diversification, diversification can be achieved by cultivating mixtures of pure varieties or by cultivating populations with greater genetic heterogeneity such as older varieties (landraces), composite cross populations and open-pollinated populations (Finckh, 2008; Goldringer *et al.*, 2017).

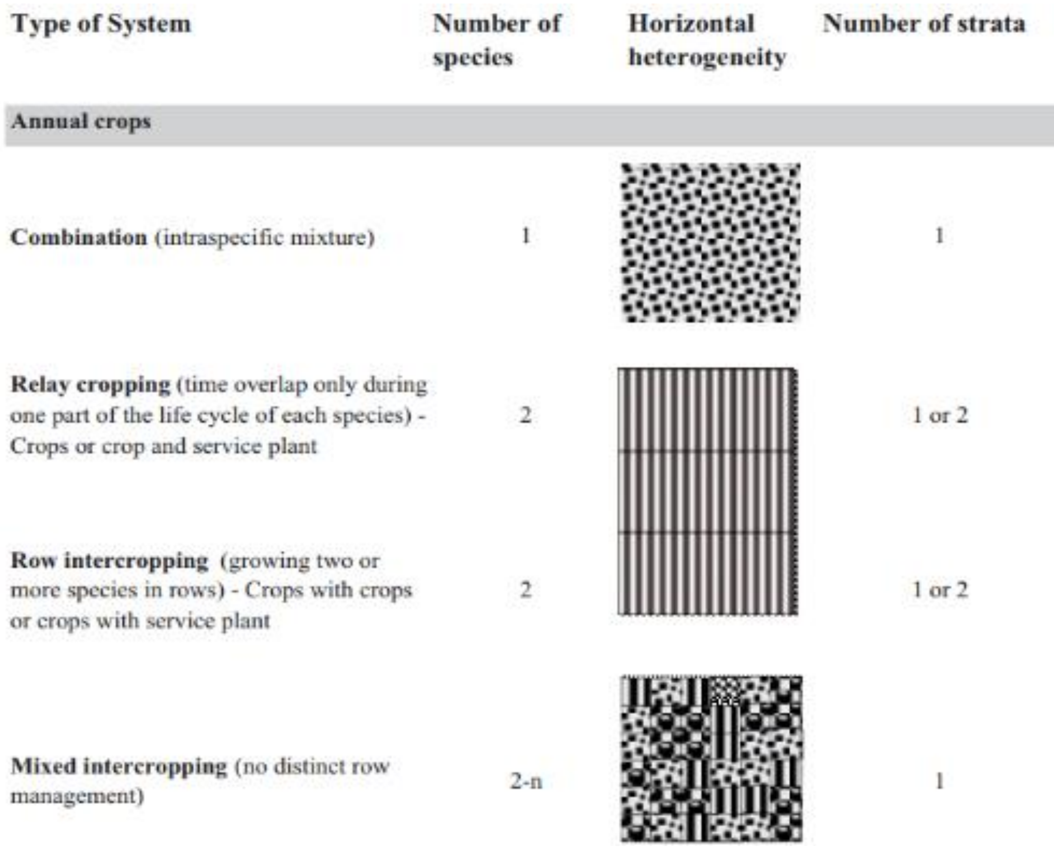
The diversification of species can be achieved by combining annual crops with each other, (intercropping) or by combining annual crops and perennial crops or even perennial crops with each other (agroforestry) (Malézieux *et al.*, 2009).

Varietal mixtures and combined crops can have different distributions in space: either by being grown totally interspersed (row intercropping), making it possible to maximise interactions between species or varieties, or in alternate rows (row intercropping), which reduces interactions, or in fairly wide bands (strip intercropping) for independent management of the crops while allowing for certain interactions, or in blocks/patches with weak interactions (Finckh and Wolfe, 2006). And we should not forget relay cropping, where two or more crops are grown together for only part of their growth cycle (ibid.). In Figure 2-38, Malézieux *et al.* (2009) illustrate some of these spatial distributions.

Below, we explore the advantages of these different types of diversification within field for pest management. First, we examine genetic and varietal diversification (intra-specific diversification) with varietal mixtures and population varieties, and then we consider the mixture of different species (inter-specific diversification) through combined crops and agroforestry.

Tibi *et al.* (2022) conducted a collective scientific expertise study on the effects of diversification on pest regulation. Table 2-7 summarises their results concerning intra-plot diversification. A positive effect means that the mode of action provides pest regulation. An expected effect means that there are theoretical hypotheses on the existence of an effect on pest regulation. A question mark means that there is not enough information in the literature to draw a conclusion.

Figure 2-38: Different forms of crop combinations according to a gradient of complexity (Source: Malézieux *et al.*, 2009)



Type of System	Number of species	Horizontal heterogeneity	Number of strata
Annual crops			
Combination (intraspecific mixture)	1		1
Relay cropping (time overlap only during one part of the life cycle of each species) - Crops or crop and service plant	2		1 or 2
Row intercropping (growing two or more species in rows) - Crops with crops or crops with service plant	2		1 or 2
Mixed intercropping (no distinct row management)	2-n		1

Table 2-7: The effect of modes of intra-plot diversification on the regulation of types of pests, according to the scientific literature (Source: adapted from Tibi *et al.*, 2022)

	Weeds	Flying insects	Soil insects	Vector-borne diseases	Air-borne diseases	Soil-borne diseases	Nematodes
Varietal mixtures	Positive effect expected	Positive effect	?	Weak positive effect	Positive effect but with variable amplitude	Weak effect	?
Combined crops	Positive effect	Strong positive effect	Positive effect	?	Strong positive effect	Positive effect but with variable amplitude	
Agroforestry	Fairly strong positive effect	Positive effect but with variable amplitude	?	?	No consensus in the literature	?	Positive effect

2.5.4.2. Intra-specific diversification through the cultivation of populations and varietal mixtures

Before the 20th century, crops were grown in populations. These were composed of multiple genotypes, multiplied through open pollination in the field and maintained by farmers (Dawson and Goldringer, 2012). These varietal populations evolved and adapted locally to different environmental constraints (ibid.). In the 20th century, through the work of plant breeders, pure, selected and highly homogeneous varieties became dominant in industrialised countries such as those found in Europe (ibid.). This led to a reduction in cultivated biodiversity and, consequently, an increase in the vulnerability of cropping systems (Tooker and Franck, 2012).

There are several agronomic advantages linked to these heterogeneous varieties (Rivière *et al.*, 2013). They make it possible to obtain more stable yields and are more resilient over time when faced with interannual climatic variations (Wolfe *et al.*, 2008) and maintain a diversity of resistance to pathogens (Finckh *et al.*, 2000).

In order to re-establish genetic diversity, in particular to give crops better resistance to pests and diseases, varietal mixtures (variety or cultivar mixtures) which combine different varieties are being developed (Dawson and Goldringer, 2012). The presence of different varieties in a mixture makes it possible to diversify the competitiveness and resistance of the crop to various pests (Grettenberger and Tooker, 2015). We focus here on the use of varietal mixtures for pest management. According to Anchordoquy *et al.* (2022), a varietal mixture can be defined as an agricultural practice that consists of sowing a heterogeneous mixture of varieties of the same species within the same plot.

Action against diseases

Varietal mixtures can greatly reduce pathogen presence and disease development. For example, in their meta-analysis, Huang *et al.* (2012) observed that in 83% of the varietal mixtures studied to combat wheat rust, the average level of disease was lower in varietal mixtures than in pure stands, with a reduction in wheat rust of 30% to 50%.

Similarly, in a large-scale experiment in China, Zhu *et al.* (2000) observed that varietal mixtures in rows of rice greatly reduced blast (the main fungal disease of rice). Also, Enjalbert *et al.*, (2019), observed that the strong heterogeneity of the varietal landscape of rice cultivation on the terraces of YuanYang in China had made it possible to avoid major disease outbreaks for several centuries. Indeed, the mixture of the two sub-varieties of rice with contrasting immune systems (japonica and indica) make it possible to reduce blast inoculum (Enjalbert *et al.*, 2019).

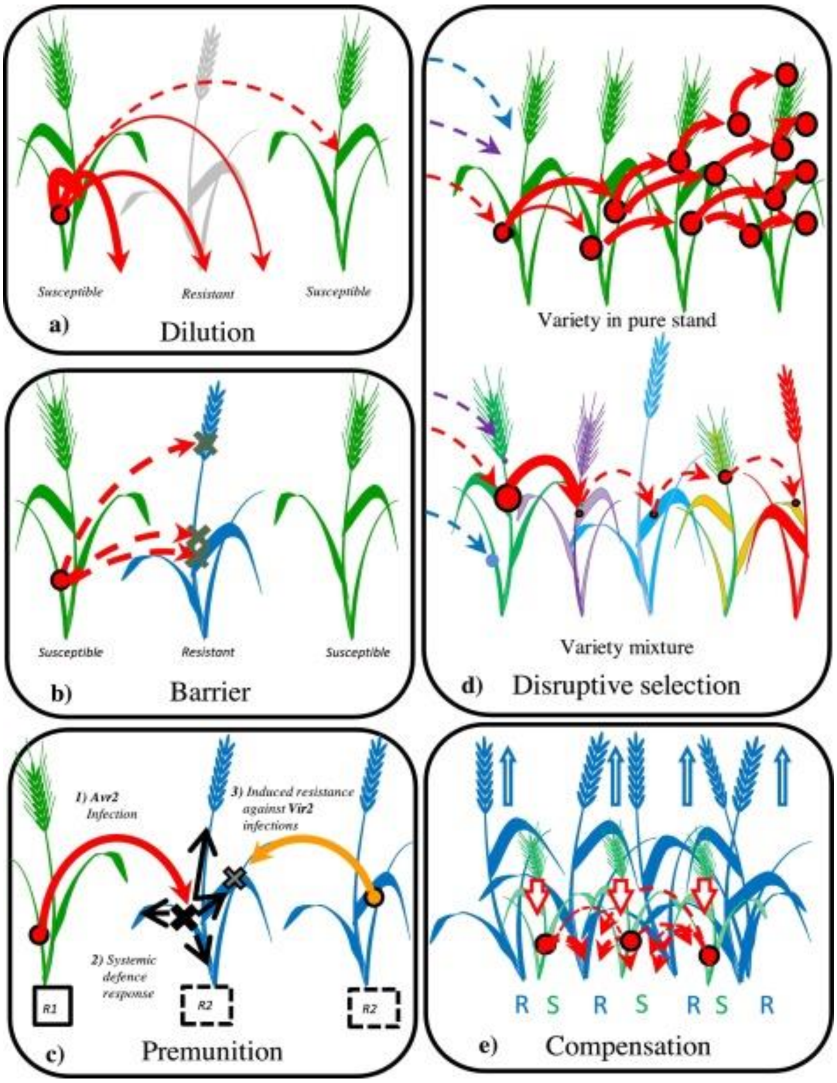
Several mechanisms and effects come into play to reduce the presence and impact of pathogens in varietal mixtures. These have been identified by Litrico and Violle (2015) and Borg *et al.* (2018) and are illustrated in Figure 2-39.

The mechanisms at play are:

- Dilution effect: The reduction in the density of susceptible plants within a mixture reduces disease spread and severity (Reddy, 2017; Litrico and Violle, 2015);
- Barrier effect: The presence of resistant varieties among susceptible ones acts as a physical barrier against the dispersal of spores of virulent pathogens (Finckh *et al.*, 2000; Borg *et al.*, 2018);
- Premunition effect: Within a varietal mixture, a wider diversity of pathogenic strains develop compared to a monovarietal crop. The presence of a non-virulent strain for a variety triggers defence mechanisms that will allow it to be protected from future attacks by virulent strains (Lannou *et al.*, 2005; Litrico and Violle, 2015);

- Selective disruption effect: Within a varietal mixture, pathogens are confronted with different resistances which reduce the speed of adaptation of the pathogen to host plants and its virulence (Litrico and Violle, 2015; Borg *et al.* al., 2018);
- Compensation effect: Within a mixture, susceptible varieties produce a lower yield, leaving room for the growth of resistant varieties that will compensate for the yield loss (ibid.).

Figure 2-39: Illustration of disease reduction mechanisms within varietal mixtures (Source: Borg *et al.*, 2018)



To this can be added the change in microclimate. Varieties that have a different architecture will influence the microclimate and therefore diseases, especially if the plants are grown in alternating strips (Finckh, 2008). For example, Zhu *et al.* (2005) observed that the mixture of rice varieties of different sizes modifies the microclimate, making it less favourable for the dispersal of blast.

Mikaberidze *et al.* (2015) have shown that disease reduction using varietal mixtures is more effective when the pathogens are specialised for a host. If the pathogens are specialised, the severity of disease outbreaks decreases with the increase in the number of varieties composing the mixture.

The scale of diversification also needs to be considered (Finckh, 2008). The increase in surface area of pure variety monocultures leads to an increase in the quantity of inoculum and therefore the regional spread of disease. However, an increase in surface area dedicated to mixtures could make it possible to reduce disease severity and also regional dispersion (ibid.).

Farmers use varietal mixtures to regulate diseases, assembling varieties whose pest resistance or tolerance are complementary, thereby creating a plant cover whose 'average' level of resistance is adapted to the local pathogen complex (Barot *et al.*, 2017; Tibi *et al.*, 2022).

Action against weeds and animal pests

Several mechanisms seem to be involved in the management of animal pests using varietal mixtures: the dilution of resources and effects on the food chain and the presence of natural enemies (Snyder *et al.*, 2020; Koricheva and Hayes, 2018). Indeed, for the dilution of resources, differences in earliness or palatability between varieties can have an effect on insect pests (expert workshop, November 2020).

According to Tibi *et al.* (2022), varietal mixtures have a positive effect in regulating flying insects, but the literature is not consistent enough to conclude on their effect on soil insects. Furthermore, there is a lack of research work based on these hypotheses. This would provide us with a better understanding of the effects of varietal mixtures in cultivated environments (Tooker and Franck, 2012; Snyder *et al.*, 2020).

Varietal mixtures have an expected positive effect on weed regulation, but this effect is still theoretical and literature on the subject is scarce. Planting a mixture would improve the competitiveness of a crop against weeds (Oveisi *et al.*, 2021). Indeed, due to the heterogeneity of plant architecture and phenology, varietal mixtures would increase the interception of light (playing on the differences in plant size), which improves the competitiveness of the crop vis-à-vis weeds and reduces weed biomass (Oveisi *et al.*, 2021; Lammerts van Bueren *et al.*, 2002). So, varieties that offer more or less cover can be grown in a mixture to increase the competitiveness of the crop against weeds (expert workshop, November 2020).

Discussion

The effectiveness of varietal mixtures in managing diseases is quite variable (Mikaberidze *et al.*, 2015). Indeed, the commercial varieties developed so far have been bred for their ability to produce in pure crops, without their behaviour in mixtures having been considered (Dawson and Goldringer 2012; Tibi *et al.*, 2022). The introduction of varietal mixtures from pure varieties and their organisation in terms of space requires consideration, taking into account the desired properties of the varieties and the specificities of the cropping system (Dawson and Goldringen, 2012). Two strategies are considered for the design of mixtures: (1) selecting varieties with the ability to be grown in mixtures to constitute high-performance mixtures (trait-blind); (2) separately selecting a set of varieties on the basis of their functional traits to respond to a set of desired services (trait-based) (Barot *et al.*, 2017). The use of populations would also be an interesting tool and is the subject of participatory breeding programmes (Dawson and Goldringer 2012; Demeulenaere *et al.*, 2017).

2.5.4.3. Inter-specific diversification through intercropping

Intercropping is "*an agricultural practice that consists of planting at least two species in a plot for a significant period of their growth*" (Bedoussac and Journet, 2022). One of the species grown in combination may not be intended for harvesting but provide other services and these are known as companion crops or service crops (Verret *et al.*, 2017). Relay cropping is intercropping for only part of the growth cycle (Finckh and Wolfe, 2006).

Intercropping is a good way to manage pests. Beillouin *et al.* (2022) found in their meta-analysis that intercropping has higher levels of disease and pest control than single cropping (+66%). Verret *et al.* (2017) observed in their meta-analysis that the presence of companion plants in combination with crops decreases weed biomass by 56%. Similarly, Tibi *et al.* (2022) found that according to the scientific literature, intercropping has a positive effect on the regulation of weeds, flying and soil insects and air-borne and soil-borne pathogens, with strong effects on the regulation of flying insects and air-borne pathogens.

Action against weeds

Competition effect

As with intercropping cover crops (see 2.5.3.1), intercropping contributes to weed management through competition for resources (Petit *et al.*, 2018). The increase in plant cover in intercropping increases the competitiveness of cultivated plants (ibid.).

For example, Morison *et al.* (2014) observed that oilseed rape (OSR) combined with legumes can significantly reduce weed coverage and biomass in early autumn. This effect is linked to the biomass produced by the OSR-legume combination. Similarly, a combination of wheat and legumes reduces weed density by 52% compared to wheat alone (Morison *et al.*, 2014). After wheat is harvested, the legume canopy develops enough to provide significant control of weed biomass (ibid.). Conversely, main crop legumes can be grown in combination with grasses to compensate for their low competitiveness (Corre-Hellou *et al.*, 2011). The combination of grasses and legumes provides complementarity between the two species for nitrogen absorption (legumes) and competitiveness with respect to light (grasses) (Munier-Jolain, 2018).

Intercropping can be particularly effective in controlling perennial weeds. For example, red fescue undersown in wheat can reduce quackgrass (couch grass) rhizome biomass by 40% without reducing wheat yields (Bergkvist *et al.*, 2010).

Different relay crops can be planted in combination in order to suppress autumn or spring weeds. The choice of frost-sensitive crops in the relay means they are destroyed by cold conditions in winter without impacting the yield of the main crop (Petit *et al.*, 2018).

Allelopathy

Certain intercropping plants can produce chemical components that will influence the growth of other plants and, in particular, inhibit weed growth (Jabran *et al.*, 2015; Petit *et al.*, 2018).

The role of grass strips on the edge of plots

The outer edges of cultivated plots contribute to supplying weeds to the first few metres of the field (Petit and Cordeau, 2020). Establishing grass strips on the edges of plots limits weed development in cultivated fields (Cordeau *et al.*, 2012), especially if the grass strips are mown and crushed before seed setting (Petit and Cordeau, 2020). Significant coverage of these grass strips makes it possible to compete with weeds and limit the establishment of new species (Cordeau *et al.*, 2012). Grass strips can also be planted as service plants around the plot (Djian-Caporalino *et al.*, 2020).

Grass strips also boost the intensity of ground beetle predation on weed seeds (beetles are big consumers of many weed seeds). Indeed, these strips provide continuity between semi-natural spaces and cultivated plots and are hibernation sites for ground beetles (Petit *et al.*, 2018; Petit and Cordeau, 2020).

Action against insect pests

Dilution effect and spatial dispersion

The combination of different crops makes it more difficult for insect pests to locate crops as it makes the environment more complex (complexity of olfactory and visual stimuli) and creates physical barriers (Vialatte *et al.*, 2023). This hinders the establishment of insect pest populations (ibid.).

Trap crops

Trap crops are plant populations that are, by themselves or through manipulation, deployed to attract, deflect, intercept or retain target insects or the pathogens they carry (Ratnadass, 2010).

Push-pull effect: Trap plants and pest repellent plants

Push-pull is a technique that combines repellent plants (push effect) and trap plants (pull effect) to control pests. Repellent plants repel insects from inside the plot using semiochemicals and trap plants attract them to the edge of the plot (Anton and Jacquin-Joly, 2020). These techniques have been used effectively on small farms in East Africa to protect maize against lepidopterans (Pickett *et al.*, 2014). In Europe, push-pull systems are developing, for example, systems that combine trap plants with volatile organic compounds (Lamy *et al.*, 2018).

Allelopathic effect

Some plants that can be grown in combinations produce components through root exudation that are toxic to nematodes (Ratnadass *et al.*, 2010).

Conservation biological control

Combined crops and flower strips increase the presence of beneficial insects. These natural enemies of insect pests (Letourneau *et al.*, 2011) boost the biological control of crop pests (Rusch, 2020).

Improving nutrition and the biological life of soil

Intercropping with a legume provides complementarity between two species and improves the nutrition of the other crop (Duchene *et al.*, 2017). This combination also increases the biological life of soil (ibid.). These two factors improve plant productivity (ibid.) and plant pest resistance (Ratnadass *et al.*, 2012). This increase in productivity, thanks to the crop combination, is likely to reduce crop damage caused by pests (expert workshop, November 2020).

Action against pathogens

Ratnadass *et al.* (2012) list several effects of intercropping on pathogens:

- The change in microclimate: the fact that crops of species from different botanical families are combined leads to a change in the microclimate, influencing the development of pathogens;
- Allelopathy: some plants release toxic compounds that affect the survival of pathogens;
- The influence of pests: the combination of crops reduces the abundance of insect pests (see above). Since some of these insects are virus vectors, the reduction in their number makes it possible to reduce viruses in cultivated plants;
- Stimulation of antagonists in the soil: a diversified cover allows a diversity of microorganisms to develop in the soil. The more numerous and diversified they are, the more likely it is that antagonists against diseases are present;
- Barrier effect: the presence of intercrops can act as a physical barrier that hinders disease spread;
- Disruption of the spatial cycle: the presence of non-host plants in intercrops reduces disease spread and the quantity of inoculum;
- Improved nutrition: the presence of a combined crop can provide better nutrition of the main crop, strengthening its disease resistance;
- Planting and wind direction: the wind is a dispersal agent for some diseases and can be taken into account in the spatial arrangement when intercropping. For example, Bouws and Finckh (2008) observed that planting rows of potatoes with a combined crop, perpendicular to the wind direction, reduces the epidemic pressure of late blight compared to rows in the same direction as the wind.

Discussion

The effect of intercropping for the regulation of weeds, insect pests and diseases has been widely demonstrated (Tibi *et al.*, 2022). Nevertheless, the knowledge and use of some mechanisms is still subject to research. This includes allelopathy and the development of push-pull systems in Europe (Ratnadass *et al.*, 2012; Petit and Cordeau, 2020; Anton and Jacquin-Joly, 2020). Moreover, diversification requires reflection not only on the choice of the crops to be combined, but also on the development of breeding programmes steered towards inter-specific diversification (Enjalbert *et al.*, 2019; Jacquet *et al.*, 2022).

2.5.4.4. Inter-specific diversification through agroforestry

According to the FAO, agroforestry is "*the collective term for land-use systems and technologies in which woody perennials (e.g. trees, shrubs, palms or bamboos) and agricultural crops or animals are used deliberately on the same parcel of land in some form of spatial and temporal arrangement*".

Agroforestry brings together a wide variety of systems: silvoarable plots (arable crops with poplar or walnut trees), silvopastoral surfaces (meadow orchards, grazed forests), multi-storey crops, agricultural plots bordering lines of trees, hedgerows or riparian forests, bocages, slash-and-burn crops and short rotation coppices (Vigan *et al.*, 2022).

In Europe, the main agroforestry systems are silvopastoral systems and silvoarable systems (or planted plots with trees) (Figure 2-40; Mosquera-Losada *et al.*, 2009).

Figure 2-40: Photos of several European agroforestry systems (Source: Eichhorn *et al.*, 2006)

Plate 1. Olive trees intercropped with wheat. Lazio, Italy.

Plate 2. Cherry trees intercropped with fodder beet. Saxony, Germany.

Plate 3. Walnut trees intercropped with vegetables. The trees are dual purpose, producing nuts and a timber end-product. Campania, Italy.

Plate 4. Poplar trees intercropped with wheat in an experimental plantation operated by the SAFE (Silvoarable Agroforestry For Europe) project. Vézenobres, France.

Several meta-analyses have shown that agroforestry systems make better pest management possible (Pumariño *et al.*, 2015; Beillouin *et al.*, 2021). However, studies on the impact of agroforestry systems in these meta-analyses were mainly carried out in tropical environments (ibid.). Some agroforestry systems are only encountered in tropical areas, such as alley cropping (planting fast-growing shrubs in cultivated fields) or perennial cropping systems under shade (cultivation of shade-tolerant species such as cocoa and coffee under or between shade trees) (Beillouin *et al.*, 2021). It is therefore difficult to distinguish what is specific to European agroforestry systems.

Agroforestry systems provide regulation of weeds, flying insects (with variable range depending on the crop plants and insect life traits), and nematodes. Concerning regulation of air-borne pathogens, effect of agroforestry is ambiguous (Tibi *et al.*, 2022).

The presence of trees in an agricultural plot modifies the microclimate and shade, which influence the development of weeds, animal pests and pathogens (Pumariño *et al.*, 2015; Ratnadass *et al.*, 2012). Agroforestry systems improve crop nutrition and competitiveness against weeds (Pumariño *et al.*, 2015). Trees also act as barriers against the intrusion of pests within the plot (Ratnadass *et al.*, 2012). Finally, trees in agroforestry systems should favour the presence of beneficials by providing them with refuge and nesting spaces (Pumariño *et al.*, 2015; Ratnadass *et al.*, 2012).

2.5.5. Management of landscape

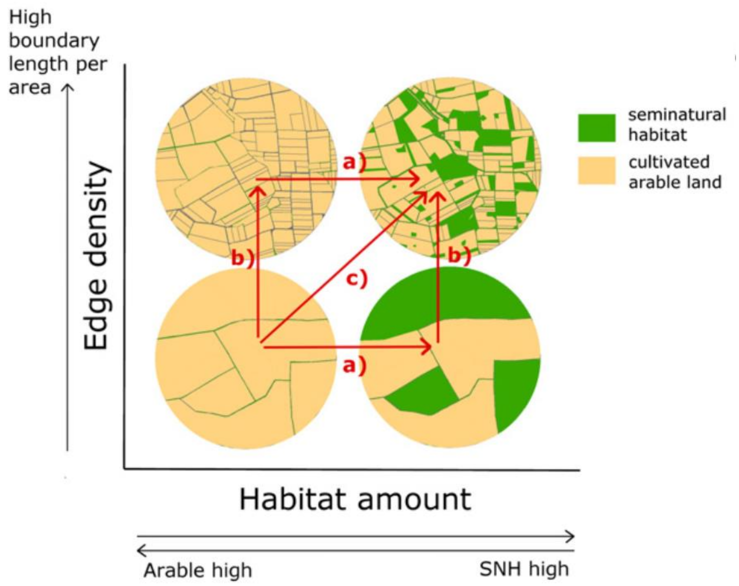
Spatial and temporal management of the landscape is a way of managing pests. We consider a management beyond the field level, including the management of semi-natural habitat (non-crop habitats) and crop mosaic at the landscape level.

Landscape can be described in term of complexity. In landscape ecology literature, landscape complexity is characterized by the composition of habitat types (landscape composition) and the spatial arrangement of those habitats (landscape configuration) (Estrada-Carbona *et al.*, 2022; Dunning *et al.*, 1992). Complex landscapes promote biodiversity; they have strong and significant positive effect on diversity of natural enemies of pests (Estrada-Carbona *et al.*, 2022) and on weed diversity (Boinot *et al.*, 2022). Management of landscape considers landscape composition and landscape configuration and their influence on pest populations.

On Figure 2-41, Martin *et al.* (2019) represent the difference between the management of landscape composition, through increasing of semi-natural habitats (arrow a), and the management of landscape configuration, through decreasing of patch sizes and increasing of patch shape complexity which lead to an increasing of boundary length per area (arrow b), and simultaneous increase (arrow c) combining the two. A patch can be defined as "*contiguous area comprising a single land cover type (e.g., a forest or crop field)*" (Haan *et al.*, 2020).

Landscape context has been widely studied for arthropod pest control, particularly through the enhancement of natural enemies of pests. Thus, the literature shows that diversifying the landscape enhance natural enemies of pests (Vialatte *et al.*, 2023). It is the principle of "conservation biological control" that is "*based on the recognition that pest populations can be kept in check by the action of other living beneficial organisms (in contrast to harmful organisms that damage crops) that are natural enemies to the pest*" (Rusch *et al.*, 2016b). Those natural enemies grow and disperse beyond the field, at landscape level (ibid.). Nevertheless, landscape context also influences weed dispersal, granivores of arable weeds (Petit *et al.*, 2018), and pathogens dispersal (Bousset, 2020).

Figure 2-41: Conceptual representation of the distinction between landscape composition and configuration (Source: Martin *et al.*, 2019)



2.5.5.1. Management through landscape composition

Landscape composition can be defined as the "*amount or diversity of different land-cover types occurring within a landscape*" (Haan *et al.*, 2020). Land-cover types include semi-natural habitats and crops (ibid.). Landscape composition embraces the proportion of semi-natural habitats compare to crops (Médiène *et al.*, 2011), and the diversity or heterogeneity of cover types, including the diversity of semi-natural habitats and the diversity of crops in the landscape (*i.e.* diversity of crop mosaics) (Fahrig *et al.*, 2015). Landscape composition has influence on pest control. Diversified landscape composition promotes natural enemy species (Bianchi *et al.*, 2006, Chaplin-Kramen *et al.*, 2011) and have negative influence on pest abundance in fields (Rusch *et al.*, 2016a).

Landscape composition plays a significant role in pest management through three factors: the semi-natural habitats, diversity of crop mosaic and crop management practices.

Management of semi-natural habitats

Significance of semi-natural habitats for natural enemies of pest and pest control

Diversified landscape with higher proportion of semi-natural habitat show natural enemies abundance and activity (Bianchi *et al.*, 2006, Chaplin-Kramen *et al.*, 2011). Rusch *et al.* (2016a) show that a simplification of the landscape and the disappearance of semi-natural habitats with a relative increase of cultivated land lead to a 46% reduction in the predation of aphid pests. Indeed, the presence of semi-natural habitats brings key resources for natural enemies (Rusch *et al.*, 2016b). Semi-natural habitats comprise woody habitats (forest and hedgerows) and herbaceous habitats (field margins, road verges, fallows and meadows) (Bianchi *et al.*, 2006). There are more stable and relatively undisturbed compare to annual crop, and provide life-support functions for natural enemies, such as sites for overwintering, refuges without disturbance, a more moderate climate than fields, pollen, nectar and alternative hosts and preys (Bianchi *et al.*, 2006, Rusch *et al.*, 2016b). According to Keller and Häni (2000), nine in every ten beneficial organisms need semi-natural habitats during their life cycle, whereas it is the case only for one in two pest species.

However, trophic interactions are complex and response of landscape composition is variable. This underlines that the landscape effects depend on the context, pest and natural enemy species, their traits, crop types, semi-natural habitat types, and farming practices (Tscharntke *et al.*, 2016, Karp *et al.*, 2018).

Quantity of semi-natural habitats: Minimum 20%

A minimum of semi-natural habitats is needed to ensure landscape connectivity and the movement of the different organisms (Mitchell *et al.*, 2013). What about the quantity of semi-natural habitats needed to improve pest control? Even if there is no proof of a minimum of semi-natural habitat percentage to provide pest control, scientific literature can give some clues. In the literature, it is often considered that a complex landscape required at least 20% of semi-natural habitats (Tscharntke *et al.*, 2002; Tscharntke *et al.*, 2005; Batàry *et al.,* 2011; Scheper *et al.*, 2013; Lichtenberg *et al.*, 2017; Garibaldi *et al.*, 2014). Martin *et al.* (2019) also consider that a high edge density corresponds to minimum 20% of semi-natural habitat and they find that high edge density increases natural enemy species abundance and improves pest control. This is why Tscharntke *et al.* (2021) and Garibaldi *et al.* (2020) consider that minimum 20% of semi-natural habitat in the landscape is needed to maintain biodiversity and related ecosystem services, including arthropod pest control (through enhancement of their natural enemies).

Quality of semi-natural habitats: Diversified and aged

Moreover, quality and diversity of semi-natural habitat seems to be important to provide pest control (expert workshop, November 2020). A complex landscape with high diversity of semi-natural habitats may hold most potential for conserving biodiversity and a diversity of natural enemies, because different semi-natural habitat types may support distinct natural enemies (Bianchi *et al.*, 2006). Temporal continuity of semi-natural habitats is also an important factor to support biodiversity (Boetzl *et al.*, 2021).

Semi-natural habitats effects on weeds

Scientific literature is scarcer on weeds, but it suggests that landscape composition has also an impact on weed communities (Petit *et al.*, 2013). Complex landscapes present more diverse habitats associated with more diverse weed communities (ibid.). Moreover, animal granivores of arable weeds, particularly seed-eating carabid beetles, are enhanced by semi-natural habitats (Petit *et al.*, 2018). This is demonstrated for field margins and grass strips, hedgerows, wooded areas and meadows (Vialatte *et al.*, 2023). Birds, that also consume weed seeds, are enhanced by semi-natural habitats (Heikkinnen *et al.*, 2004). This suggests a beneficial effect of semi-natural elements on the regulation of weeds by birds.

Management of crop mosaic diversity

Crop mosaic is the combination of the different patch of crops within the landscape. The composition of the crop mosaic can be defined as the “compositional heterogeneity” of crop mosaic that refers to the diversity of cover type (crop richness and evenness) (Fahrig *et al.*, 2015). It depends on choices from different farmers; those choices depend on environment characteristic, farm resources and logistic constraints (Vasseur *et al.*, 2013). Crop mosaic may change year after year, depending on crop sequences and cropping systems of farmers (ibid.).

Increasing diversification of crop mosaic have a positive effect to control aerial insects and have expected effects to control aerial and vector-born disease (Tibi *et al.*, 2022).

Crop mosaic diversity increase biodiversity and potential biological control

Increasing the compositional heterogeneity of crop mosaic can enhance biodiversity (Sirami *et al.*, 2019). Increasing crop diversity increases the number of different habitat types and supports a higher biodiversity in the landscape that includes a minimal amount of semi-natural habitats (above

11%) (Sirami *et al.*, 2019). Nevertheless, diversified crops can have a negative impact on trophic diversity if the quantity of semi-natural habitat within the landscape is below 4%, because certain beneficial species need a minimum area of permanent semi-natural habitat to live (ibid.). Increasing biodiversity and species diversity increase the chance to have efficient natural enemies of pests (Tscharntke *et al.*, 2005).

For example, Redlich *et al.* (2018) find that the biological control of aphid in landscape with high crop diversity was 8%-33% higher than in landscape with low crop diversity.

Arthropods dynamics within the crop mosaic

Composition of crop mosaic year after year may have effect on arthropod dynamic. For Vasseur *et al.* (2012), two mechanisms are involved: (i) source and sink dynamics and (ii) dilution-concentration effect. In source/sink process, "*productive patches serve as source of emigrants, which disperse to less productive patches called sinks*", population in sink patches cannot be maintain without the immigration from source patches (Dunning *et al.*, 1992). Indeed, arthropods dispersion is link to the surrounding type of crop patches (Grilli, 2010; Santoiemma *et al.*, 2019). Grilli (2010) and Santoiemma *et al.* (2019) find that some arthropods that are vector of disease increase with the presence of surrounding host crop patches. The density of arthropods is also linked the mosaic composition of the previous year. Grilli (2010) observe that the abundance of *Delphacodes kuscheli* (vector of maize disease "Mal de Río Cuarto") is correlated positively with the total area left with stubble, surrounding in the crop mosaic. Bosem Baillod *et al.* (2017) also find that aphids density decreases in crop mosaic with higher crop diversity when the percentage of aphid host crop had decrease from the year before.

About the dilution-concentration effect, the resource concentration in arable monocrop makes the plant crop more visible for insect pests, and thus more vulnerable to pest (Ratnadass *et al.*, 2012). Low level of crop heterogeneity, with one crop (which is the host of a specific pest) being dominant within the landscape, favors the development of this pest. O'Rourke *et al.* (2011) find that decreasing the area of a host crop in the landscape can decrease the density of specialist pests.

Compositional heterogeneity of crop mosaic may also enhance natural enemies of pests (Liu *et al.*, 2018).

Potential effect on disease

Impact of composition of crop mosaic on disease are still theoretical (Tibi *et al.*, 2022). Halliday and Rohr (2019) show that disease dispersal depend on the biodiversity (of animals and plants) at local scale and not at large scale. Disease dispersal increase with the loose of biodiversity at local scale (ibid.).

Finally, the few studies on weeds show no link between the composition of the cultivated part of the landscape and the abundance of weeds or their natural enemies (Vialatte *et al.*, 2023).

Crop management practices at landscape level

Crop practices associated to a cropping system may have impact on arthropods population (particularly pests and natural enemy populations). At landscape level, those practices have an even greater effect on population dynamics.

Pest and natural enemy populations depend on resources of arable fields, especially when the proportion of semi-natural habitats in the landscape is low (Rusch *et al.*, 2010). Then, crop management practices within field (*i.e.* crop diversification, crop rotation, use of nitrogen fertilisation, tillage, cropping calendar and pesticide use) have an impact on pests and natural enemies (ibid.). These practices may have effects at a landscape level.

Temporal variations in the landscape also affect population dynamics (Fahrig *et al.*, 2015). Temporal variability of habitat (habitat life span) may affect landscape connectivity and thus dispersal and survival of arthropods populations (Kindlmann and Burel, 2008).

Organic farming

The presence of fields cultivated in organic farming in the landscape has positive effects on biodiversity compared to conventional farming, but this effect depends on the landscape context (Tuck *et al.*, 2014). Carabids have an important role in weed seed predation. The presence of organic farms in the landscape enhances their activity (Diekötter *et al.*, 2016). Organic farming has more impact on biodiversity in simplified landscape with a large amount of arable field (Tuck *et al.*, 2014). It suggests that where complex landscapes already support a high level of biodiversity, local crop management practices have less impact on biodiversity (Rusch *et al.*, 2016b). Therefore, spatial and temporal diversification of crop practices and restoration of complex landscape seems to have higher impact on biodiversity than a simple conversion of arable fields cultivated in conventional farming to organic farming (Tscharntke *et al.*, 2021).

2.5.5.2. Management through landscape configuration

The landscape configuration refers to the spatial arrangement, the size and the shape of the different habitats in the landscape (Rusch *et al.*, 2016b; Haan *et al.*, 2020). Landscape configuration affects biodiversity, natural enemy population and pest control (Haan *et al.*, 2020), but also weed control (Petit *et al.*, 2018) and disease control (Bousset, 2020).

Landscape configuration influences pests and natural enemies' dynamics, their development and their ability to colonies crop habitats and provide biological control. Some ecological processes that depends on configuration of different habitat types (crops and semi-natural habitats) affect arthropod population dynamics between these different types of habitat (Dunning *et al.*, 1992).

Those ecological processes are: landscape complementation, landscape supplementation, source/sink relationships and neighborhood effects (ibid.). Landscape complementation refers to a situation where a specie needs two different resources localized in two different habitat types in the landscape, involving species dispersal between those habitat types. In landscape supplementation process, the population of a patch increase if close patch brings the same resources and function. In source/sink process, "*productive patches serve as source of emigrants, which disperse to less productive patches called sinks*" (ibid.), population in sink patches cannot be maintain without the immigration from source patches. Finally, in neighborhood effect process, population in a patch is more affected by the characteristics of the contiguous patches than by those located further away.

Different factors influence those ecological processes at landscape level: (i) spatial arrangement between semi-natural habitats and crops and landscape connectivity, and (ii) landscape grain size and edge density (two correlated variables).

Management of the spatial arrangement between semi-natural habitats and crops within the landscape

Spatial arrangement of semi-natural habitats and crops: Increasing semi-natural habitats in landscape

For many natural enemies, their presence within fields depends on colonization of individuals from semi-natural habitats of field edges, for other natural enemies the movement is bi-directional, they move between crop habitats and semi-natural habitats (Tscharntke *et al.*, 2007). These two processes can result in "spillover effects" that enhance pest control: semi-natural habitats provide resources to sustain natural enemies population, which spillover into another habitat type (crops) to exploit another resource (crop pests) (ibid.). Spillover depends on the distance between the two habitats types (ibid.). Diversity and density of natural enemy population decline with the increase of distance with semi-natural habitats (Bianchi *et al.*, 2006). Moreover, natural enemies can colonize field interiors earlier with expanded interface between crop and semi-natural habitats (Bianchi *et al.*, 2006). Thus, semi-natural habitats should be regularly distributed with minimum 20% of semi-natural area per square km (Garibaldi *et al.*, 2020).

Landscape connectivity

Landscape connectivity corresponds to "*the degree of which a landscape facilitates the movement of organisms and matters*" (Mitchell *et al.*, 2013). Thus, landscape connectivity enhances the organism movements, particularly of natural enemies, which is directly link to pest control (ibid.). The connectivity concerns both that of the cultivated vegetation of the landscape, and that of the semi-natural vegetation. Landscape connectivity can be measure in several ways, "*such as distances between or among patches, or characteristics of the landscape between patches that influence how easily organisms can disperse*" (Haan *et al.*, 2020). Landscape connectivity is altered by change in habitat type and habitat fragmentation (Mitchell *et al.*, 2013). Habitat fragmentation includes habitat loss, increasing number of patches with smaller size, and increasing patch isolation (Fahrig, 2003). Habitat fragmentation has negative impact on biodiversity (ibid.). Improving connectivity across landscapes is considered essential for maintaining effective natural regulations in agroecosystems (Ong *et al.*, 2018).

The effect of habitat connectivity in the landscape on animal pests is a little more studied. It seems that the isolation between cultures of the same nature is rather favorable to arthropod regulation (see for example Grilli, 2010).

Hedges and semi-natural habitats as physical barriers

On the borders of the field, tall and dense woody plantations such as hedges, boundary plantations and windbreakers, act as physical barriers that can interfere insect pest movement (Ratnadass *et al.*, 2012). Therefore, depending on situation, woody vegetation (in agroforestry or hedgerow systems) can limits pest entry and keep natural enemies inside fields (ibid.).

The positioning of semi-natural habitats within the landscape can have an impact on plant diseases. Hedges or woody plantations may act as physical barrier on pathogen spores and reduce disease dispersal (expert workshop, November 2020). Non-host plants sown as barrier crops can also act as physical barrier to reduce dispersal of a pathogen inoculum (Ratnadass *et al.*, 2012).

For weeds, management of field margins, as establishment of wildflower mixes sown strips and sown grass strips can decrease weed occurrence into the fields (Ratnadass *et al.*, 2012; Cordeau *et al.*, 2012).

Management of landscape grain size and edge density for increasing landscape complexity

Edge density and landscape grain size are related to the spatial complexity of the cover types, *i.e.* field size and length of field edges (Fahrig *et al.*, 2015).

Increasing edge density for increasing control of animal pest

Landscape configuration can be measured "*as the density of edges between crop fields and their surrounding*", surrounding includes neighboring crops and semi-natural habitats (Martin *et al.*, 2019). Field edge can be field-field ecotones (without permanent vegetation), grass strips, hedgerows, walls, ditches or combinations, or permanent hedges that provides refuges for many species (Clough *et al.*, 2020). Martin *et al.* (2019) find that pest control by natural enemies of pests is highest in landscape with low arable land (< 40%) and high edge density. In comparison, pest control is lower with low edge density regardless of the amount of semi-natural habitats.

Edge density has different impacts according to arthropods traits: natural enemies of pests that overwinter outside crops benefits from high edge density, which is not the case for natural enemies that overwinter in crops. Moreover, pest benefits from low edge density landscape. Thus, Martin *et al.* (2019) suggest having between 0.2 and 0.4 km/ha of hedgerow to promote biological control of animal pest.

Landscape grain size and shape complexity

The grain size is "*the average size (diameter or area) of habitat patches on a landscape*" (Haan *et al.*, 2020). Grain size can be measure by edge density (fine grain landscape has higher edge density) and the field size. The Figure 2-42 bellow shows the difference between fine-grain (small patch) and coarse-grain (large patch) landscape.

Fine-grains landscapes can enhance natural enemies and facilitate the movement of natural enemies between field edges and field interiors, which should provide better pest control for crops (ibid.). Irregular or convoluted shapes of fields can also facilitate colonization of natural enemies in field interiors and enhancing pest suppression (ibid.).

Figure 2-42: Photography of different landscape grains, from fine-grain to coarse-grain landscape (Source: Hann *et al.*, 2020)

Field size and biological control

Increasing the heterogeneity of the crop mosaic, particularly reducing field size, enhance biodiversity (Sirami *et al.*, 2019). Reducing field size from 5 ha to 2.8 ha has the same impact on raising biodiversity than increasing semi-natural habitat cover from 0.5 to 11% (ibid.). Sirami *et al.* (2019) observe that the effect of reducing field size is not only due to the increasing of semi-natural habitats between fields. Decreasing field size has more impact on biodiversity than diversifying crop mosaic (ibid.).

As well, Clough *et al.* (2020) find that increasing field size from one ha to six ha has the same negative effect on biodiversity than decreasing semi-natural habitat cover from 35% to 0%. Different mechanisms are implied in the reduction of biodiversity with the increase of field size: decreasing of field edge, and decreasing of crop diversity at small and large scale (Clough *et al.*, 2020).

A recent review of scientific literature conducted by Vialatte *et al.* (2023) shows that aerial insect pests are disadvantaged in landscapes where crops are poorly connected and fields are smaller.

Landscape configuration (size and shape of fields and distribution of semi-natural habitats) can also affect weed diversity and distribution (Petit *et al.*, 2013). Weed dispersal occur at large spatial and temporal scale, especially through agricultural equipment and animals, thus, weed dispersal depends on landscape pattern and crop heterogeneity (pointing out importance of the networks of transportation and field margins) (ibid.). In a recent study, Boinot *et al.* (2022) found that found that dense and complex hedgerows landscapes increased both species and functional diversity of weed communities, reduced the dominance of competitive weeds, and did not increase weed cover in field cores. Thus, landscapes with dense hedgerows could actually enhance ecosystem services provided by weed communities and reduce weed-crop competition (ibid.).

Configurational crop heterogeneity should also have effects on plant disease dispersion. If the fields are close together with a high density of the host species, with each generation of the pathogen, the epidemic spreads from field to field. Reducing the field size or the proportion of a crop within the landscape allows limiting spatial connectivity of pathogen (Bousset, 2020). By limiting crop host density and avoiding contiguity between spore sources and host fields, increasing crop heterogeneity should reduce the dispersal of pathogen inoculum (ibid.).

Spatial arrangement of field elements

Configuration of annual crops

The arrangement of crops within field may influence pest control. Different forms of intercropping or varietal mixtures are possible: mixed intercropping, row intercropping, strip intercropping or plot intercropping (Finckh and Wolfe, 2006). It gives different proprieties to the relationship between two varieties within mixtures or two species in intercropping, that can enhance control of animal pest, disease and weed (*e.g.* barrier effects, microclimate change, interaction between species, push-pull effect, resource complementation, etc.) (Finckh and Wolfe, 2006 ; Malézieux *et al.*, 2009 ; Zhu *et al.*, 2005 ; Ratnadass *et al.*, 2012 ; Petit *et al.*, 2018).

Other elements could be taken into account for crops configuration. For example, wind is a dispersal factor for pathogens and seeding row-intercropping perpendicular to wind direction may help to control disease (Bouws and Finckh, 2008).

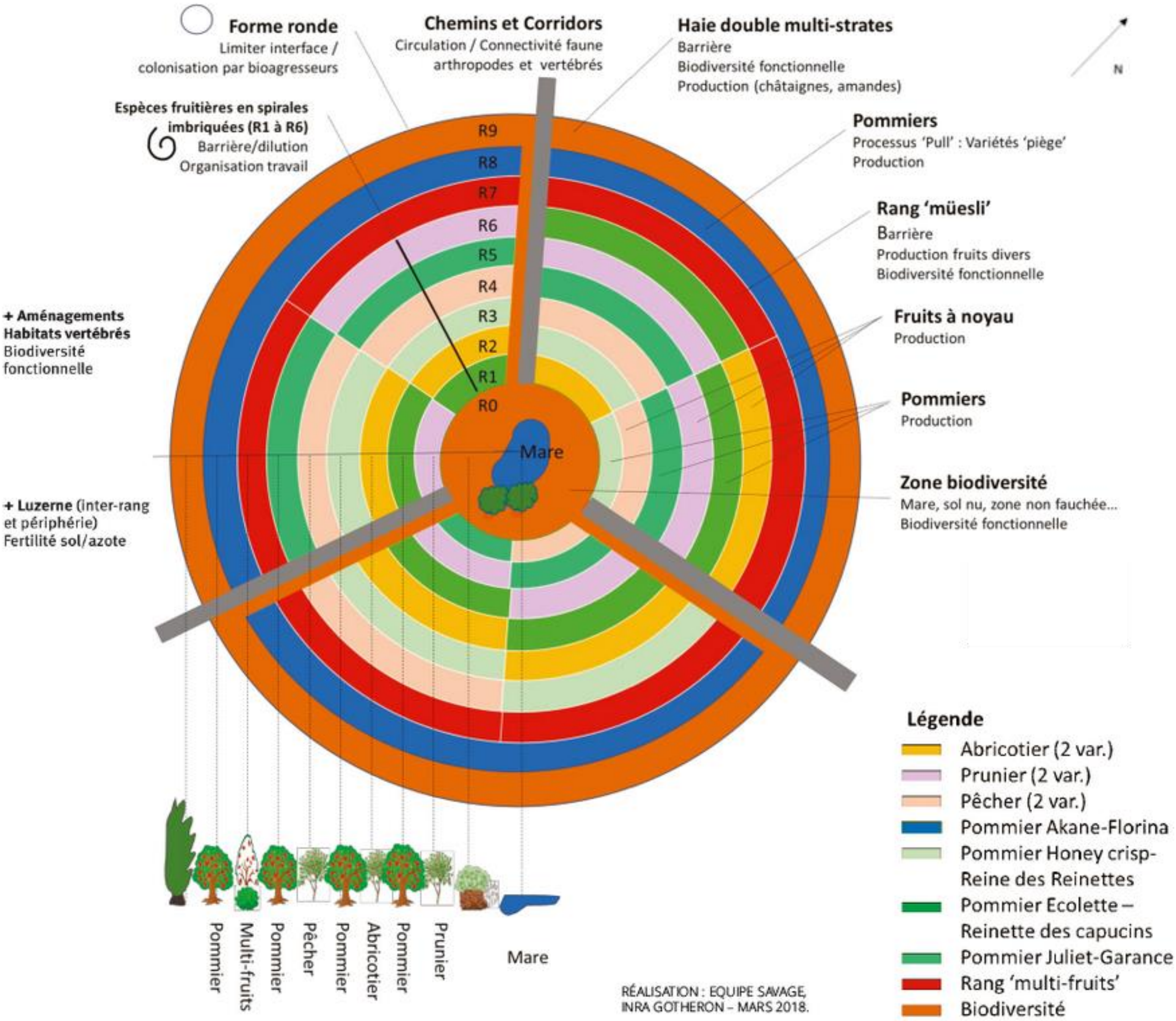
Configuration of perennial crops

Perennial crops arrangement could be a lever to enhance pest control. The density and the shape of the plantation may influence pest and natural enemies' movement (Laget *et al.*, 2015; Simon, 2019).

The French INRAE experimentation Unit in Gotheron has experimented how the shape of an orchard and the spatial arrangement of trees may influence biological regulation. Researchers have designed and implemented a circle orchard, which take landscape context and biological regulations into account (Figure 2-43).

The orchard is planted in concentric circles because its shape is minimizing perimeter/surface ratio, limiting the bordure effect and pest entry (Simon, 2019). External circle of high trees plays the role of barrier and windbreaker and provide diverse resources for natural enemies (ibid.). The spatial arrangement of the others woody circle is thinking according different functions: primary and secondary production, physical and chemical barriers, dilution effect, pull pest, enhance biodiversity. Others infrastructures are implemented to enhance biodiversity and beneficial organisms, as a central pond, nesting boxes, raptor perches, screes and alfalfa inter-rows (ibid.).

Figure 2-43: Gotheron orchard, fruit production space based on biological regulations.
(Source: INRA Gotheron, 2018)



2.5.6. Plant breeding

2.5.6.1. Introduction: How plant breeding can improve pest management

The genetic make-up of a crop gives it many properties, in particular the ability to be less sensitive to pests (resistance to pathogens and pests) or to reduce their impact/presence (*e.g.* competitiveness against weeds). Varietal improvement is therefore essential for agriculture without chemical pesticides, as the varieties currently available have not been selected for this type of management. It must also take into account climate change, which will impose abiotic stresses that are likely to influence pest and weed communities, and even the emergence of new communities. The research to be carried out in genetics will have to define and integrate new selection criteria to achieve the objective of agriculture without chemical pesticides and to involve all the actors in the seed sector and, more widely, all the agricultural actors (production, collection, transformation, valorisation; expert workshop, December 2020), including the farmers who implement cropping practices on the varieties (Laperche *et al.*, 2022). In this sense, varietal improvement will also have to mobilise selection strategies integrating participatory approaches[19], which are complementary to classical selection approaches.

The main objective of classical breeding for several decades has been to create highly productive varieties (with high yield potential) when grown under optimal conditions, with the result that the genetic diversity of cultivated species has been drastically reduced, due in particular to the development, concentration and standardisation of the seed market. Another objective of breeding crop species was to facilitate their use in processing by food companies. In contrast, pest resistance was not a breeding objective, as pest control was achieved through the use of chemical pesticides. The varieties selected were therefore very sensitive to pests. Furthermore, these varieties were not adapted to certain cropping practices (*e.g.* diversification) used to manage pests. Resistance (and tolerance) to pests, especially diseases, is now part of the selection and registration for the majority of cultivated species (Jacquet and Jouan, 2022).

In order to produce crops without chemical pesticides, it is now necessary to define new selection objectives integrating new criteria and new plant breeding strategies oriented towards prophylaxis and crop diversification. The response of plants to stresses (biotic such as pests, and abiotic such as climate change) alone or in combination is an important issue for breeding (Laperche *et al.*, 2022). However, the definition of new selection objectives remains difficult because of the uncertainties related to ongoing global changes (expert workshop, December 2020).

2.5.6.2. Classical selection on the basis of durable resistance criteria

The durability of resistance genes (*i.e.* the length of time during which this resistance provides satisfactory epidemiological control in an environment favourable to the disease) and the search for a greater diversity of molecular resistance mechanisms currently constitute a major challenge in plant breeding (Laperche *et al.*, 2022). The knowledge acquired over the last decades on the molecular basis of resistance mechanisms and on the interactions between plants and pests has contributed to the development of breeding strategies aimed at improving the resistance of crops to pests. Current breeding schemes are mainly based on varietal types with little genetic heterogeneity (pure lines, F1 hybrids, clones; Laperche *et al.*, 2022). Breeders have long relied on the use of single-gene control resistances (major and qualitative effect R-genes) because of their strong effects and ease of use in breeding. These *R* genes generally code for immune receptors that directly or indirectly recognise pest molecules (*e.g.* recognition of elicitors) and trigger strong and rapid defence responses in the plant (*e.g.* production of volatile organic compounds), but these defences are short-lived and rapidly bypassed by the pest thanks to its strong evolutionary capabilities (*i.e.* modification of the molecular mechanisms determining the aggressiveness and infectivity of the pest towards the plant). In contrast, resistance controlled by QTLs (quantitative trait loci, with a minor and quantitative effect) is considered more durable and is generally not strain-specific (Laperche *et al.*, 2022). Given their weak effect, it is necessary to accumulate several QTLs within a single genotype or to combine them with single-gene resistances controlled by R genes (*e.g.* by gene pyramiding) to achieve a high level of resistance, with complementary resistance spectra or modes of action. Breeding is now oriented towards the search for sustainable tolerance to pests, rather than towards the search for resistance (which can be bypassed by pests and the development of pest resistance). Other avenues of research are also being explored, such as identifying resistance genes that 'balance' the trade-off between resistance and production (Deng *et al.*, 2017; Wang *et al.*, 2018), or that limit the negative effect of defence proteins on plant growth (Xu *et al.*, 2017).

[19] A breeding approach in which farmers and researchers create species based on the needs expressed by farmers that have not been satisfied by conventionally produced seeds (Laperche *et al.*, 2022).

In addition to the selection of tolerant varieties, breeding challenges will also have to focus on other traits such as the response of the crop to biocontrol, plant defence stimulators, biostimulants, microbiota, local soil and climate conditions, the set-up of aerial and root architectures that are unfavourable to pests, or the co-evolutionary processes between the crop and the pest (expert workshop, April 2021).

The identification of the genes controlling the traits of interest requires suitable phenotyping tools to target the traits of interest and suitable genetic analysis methods. In this sense, the new genome editing techniques make it possible to envisage other avenues for plant breeding, and their potential implications should be examined. However, genome editing cannot be carried out without excellent characterisation of the gene(s) controlling the trait of interest and the genome of the species. Finally, while the use of this biotechnology may be interesting for traits under oligo or monogenic control, it seems more difficult to implement it for complex traits under polygenic control (Laperche *et al.*, 2022).

Whether the approach is based on the use of genetic control or direct stimulation of the crop immune system, the mechanisms of action are the same and follow the same pathways (expert workshop, April 2021).

2.5.6.3. Selection on new crop diversification criteria

A greater diversity of species and varieties in cultivated plots favours the resistance of the vegetation to pests likely to infest the plot (Jeuffroy *et al.*, 2022). The growing of varietal mixtures, chosen for their complementary resistances, also makes it possible to maintain or even slightly increase yield (Borg *et al.*, 2018; de Vallavieille-Pope *et al.*, 2006). The association of different species in plots is also an effective means of controlling pests (Stomph *et al.*, 2020). This association allows diluting the host density (for diseases and insects), modifying the microclimate in the vegetation or creating a barrier effect. Such a barrier slows down the physical dispersion of the pathogen or increases the temporal and spatial competitiveness of the crop plants against weeds. In field crops, mixtures of species including legumes or even trees or shrubs (agroforestry) are still rare (Jeuffroy *et al.*, 2022) but such mixtures could contribute to pest control.

Breeding programmes aimed at creating varieties adapted to mixtures, 'population varieties' or species adapted to associations and to local contexts, are still underdeveloped (Enjalbert *et al.*, 2019; Laperche *et al.*, 2022). The challenge for breeders lies in the ability to evaluate and select future varieties for their own value and also for their capacity to be mixed and to optimise (positive) interactions between neighbouring plants within the cultivated plot (Annicchiarico *et al.*, 2019). Building mixture adapted to local environmental conditions therefore leads to targeting the main traits for the targeted production system, and then identifying components (varieties or species) with different and complementary traits (*e.g.* by playing on disease resistance mechanisms, earliness, rooting depth, aerial architecture, nutrient absorption capacity; Laperche *et al.*, 2022), thus making the crops more competitive against pests.

In addition to diversifying rotations and spatial associations of varieties and species within plots and landscapes, other practices can be used to manage pests and diseases for chemical pesticide-free agriculture. These include, for example, the introduction of service plants (*e.g.* intermediate crops, plants with pest-repulsive properties) and agroecological infrastructures (*e.g.* hedges), the adaptation of sowing dates, nitrogen fertilisation strategies, pruning or leaf-thinning methods, tillage and non-tillage methods, or the coupling of crop and animal production (Jeuffroy *et al.*, 2022). These authors also indicate that the frequency and spatial organisation of resistance genes in the landscape, as well as cropping practices that have an effect on the genetic evolution capacities of pests, must be reasoned out so as not to favour resistance bypasses and to maintain sustainable resistance (Aubertot *et al.*, 2006; Delière *et al.*, 2017; Papaïx *et al.*, 2013). In general, breeding schemes should favour genetic heterogeneity in plots and landscapes (Litrico and Violle, 2015).

Species associations and varietal mixtures are increasingly used in field crops but are still almost non-existent in other cropping systems (viticulture, arboriculture, vegetable gardening). However, we can cite the example of biodynamic vineyards (Cravero, 2019; Doring *et al.*, 2019) or the example of the Gotheron experimental orchard (Simon *et al.*, 2017; Penvern *et al.*, 2018), whose spatial and temporal organisation of species and varieties grown, as well as the circular shape of the semi-natural habitats, aim to 'break' the genetic monotony of the plot (Jeuffroy *et al.*, 2022). There is also the emergence of orchards-vegetables (mixing fruit and vegetable species), which still raise questions about work and profitability in the short and long term (Paut *et al.*, 2021).

2.5.6.4. Selection on new criteria integrating soil and microorganisms

The diversification of cropping systems, aiming at increasing different ecosystem services (*e.g.* pest resistance, induction of positive feedback loops between plants and soil, valorisation of some species in push-pull strategies, interest of perennial species for agroforestry systems), will probably lead to an increase in the number of species cultivated. Taking into account services other than production requires the integration of ecological concepts of interaction between plants and their environment modulated by microorganisms (Gopal and Gupta, 2016).

Promising findings highlighted that the soil microbiome diversity can improve plant tolerance and resistance to several pests, and crop yields (Trivedi *et al.*, 2017). Soil microbiome diversity and composition can have a profound effect on stress tolerance (Bernardo *et al.*, 2017), plant health (Mendes *et al.*, 2011), and pest control (Bartoli *et al.*, 2018; Lachaise *et al.*, 2017). But little research has been conducted so far on the durable effects of plant heritability through complex feedbacks between plant and soil (Jacquet *et al.*, 2022). Future breeding programmes should focus on the ability of plants to interact with the soil microbiome to recruit microorganisms that enable plants to better defend themselves against pests and limit their development in the soil (see DEEP IMPACT project: Mougel *et al.,* 2019). Selection should aim to strengthen interactions between plants and soil microorganisms, to produce seeds with a microbial population adapted to the local environment (in the plot) and to cropping practices, or to improve plant nutrition thanks to microorganisms (Hunter *et al.*, 2014). The functioning of the rhizosphere, corresponding to the soil zone subjected to root activity, is a major interface between the plant and its environment (Carof *et al.*, 2018) and the ability of plants to recruit and maintain themselves in this environment is crucial for chemical pesticide-free agriculture (Simon *et al.*, 2019).

2.5.6.5. Participatory selection to develop 'population varieties'

Genetic diversity is also enhanced by farmers who are involved in participatory breeding for seed exchange and the implementation of varietal crosses and mixtures and species associations (Jacquet *et al.*, 2022). Participatory breeding helps to preserve genetic resources *in situ* in the face of climate change and innovative practices and is complementary to *ex situ* approaches (Hawtin *et al.*, 1996). However, *in situ* management of genetic resources is difficult to implement because it requires the long-term maintenance of the agroecosystems in which the species under study evolve. The underlying scientific hypothesis is that maintaining evolutionary pressure on these genetic resources makes it possible to maintain interesting adaptation genes. In wheat, for example, this concept of dynamic *in situ* management of genetic resources has been developed within the framework of participatory breeding programmes, where evolving varieties have proved to be more stable over time (*i.e.* between climatic seasons) and between environments than commercial varieties (Goldringer *et al.*, 2020; van Frank *et al.*, 2020).

Several examples show the successful mobilisation of this type of participatory approach to transform agricultural systems (Bakker *et al.*, 2021; Moraine *et al.*, 2016; Pelzer *et al.*, 2020; Périnelle *et al.*, 2021, Jeuffroy *et al.*, 2022) despite the lock-in of sociotechnical systems (Meynard *et al.*, 2018) and seed markets. Such dynamic management of genetic diversity thus makes it possible both to conserve adaptive genes in the population and to maintain genetic diversity in the fields in connection with the production of ecosystem services (Laperche *et al.*, 2022). The 'population varieties' thus obtained through participatory breeding are characterised by their high adaptability to local biotic and abiotic conditions. Their genetic diversity gives them durable resistance to pests and greater tolerance to abiotic stresses. On the other hand, these ‘population varieties’ are generally characterised by lower productivity.

It is becoming increasingly clear that the breeding programmes to be developed will have to combine classical breeder approaches with farmer participatory approaches in order to create new varieties adapted to the local soil and climate environment and to local cropping practices (Dawson and Goldberger, 2008). All these approaches must be mobilised to meet the challenge of chemical pesticide-free agriculture. However, the impacts of new participatory breeding schemes on the seed multiplication phase should not be underestimated. Indeed, the local adaptation of varieties and their potential heterogeneity, as well as the maintenance of a high level of genetic diversity, will have repercussions on the conditions for multiplication, intellectual protection of innovation and the associated economic model (Laperche *et al.*, 2022).

2.5.6.6. The particular case of perennial plants and the rootstock-graft association

The selection of resistant varieties is essential for perennial crops (viticulture, arboriculture, vegetable gardening) for which the means of controlling pests, apart from chemical control, remain limited. The varieties and rootstocks of different species of vineyards, orchards or vegetables may have varying degrees of sensitivity to diseases or pests, or even total resistance to some strains of disease (*e.g.* scab-resistant varieties in apple, Sharka resistant varieties in apricot, fire blight resistant varieties in apple and pear, fire blight resistant rootstocks in apple and pear) (Laget *et al.*, 2015).

Grafting, or overgrafting, of varieties adapted to rootstocks makes it possible to rapidly modify the behaviour of the whole plant or tree (*e.g.* conferring resistance traits on the grafts) without modifying the genetic resource of the grafted variety. It can also increase the spatial diversity of plants or trees in order to strengthen the agroecological immunity of the crop, particularly in the event of changes in local phytosanitary and/or pedoclimatic conditions (expert workshop, February 2021). Grafting height can also modify plant sensitivity to pests, for example a reduction in bacterial blight symptoms in apricot by increasing the grafting height (Laget *et al.*, 2015).

The majority of studies so far have focused on grafts and very few on rootstocks (Warschefsky *et al.*, 2016). However, the choice of rootstock is decisive because it conditions the behaviour of the crop and its production for several decades. For example, rootstocks will have be more tolerant to inoculums that can last for several years, even if the search for such tolerance results in a loss of production. The choice of rootstock will also have to favour positive interactions between the rootstock root system and soil microorganisms. In this sense, selection should focus on mycorrhization processes that stimulate the graft defences, or on the rootstock ability to recruit microorganisms that induce resistance in the graft without having to change the graft variety (expert workshops, December 2020, February 2021 and April 2021).

There is also a lack of knowledge about the potential of the rootstock-graft association to improve plant or tree resistance. It remains fragmentary and empirical, based on observations. For example, on apple, the response to plant defence stimulators may vary according to the choice of the rootstock-graft association. On apricot, the rootstock-graft association may be resistant to a given pest, whereas the rootstock and the graft, when taken separately, are sensitive to that pest. Rootstock selection programmes should be set up to improve the varietal resistance of perennial species (expert workshop, February 2021).

2.5.7. Epidemiological surveillance

In the context of crop protection, epidemiosurveillance consists in "*monitoring the development of pests in order to take preventive or curative action in good time*" (Reboud *et al.*, 2022). It is not a mode of action in itself, since it does not act directly on pests, but it is a tool that can be used to modulate the implementation of different modes of action.

2.5.7.1. Epidemiosurveillance already well established in Europe

At European Union level, Member States are encouraged to set up pest surveillance systems. Indeed, all European Union countries are members of the International Plant Protection Convention (IPPC), which calls for the establishment of an official national plant protection organisation (NPPO), one of whose tasks is to monitor standing plants, including crops and wild flora (IPPC, 1997).

Several robust epidemiosurveillance networks already exist in several European countries. In Denmark, for example, a national surveillance network linked to agricultural advisers enables the development of numerous crop pests and diseases to be monitored online, with the data collected also feeding into a "Crop protection Online" decision-support tool recommending optimised curative actions to farmers (Sonderskov *et al.*, 2014). In Germany, an online prevention platform that integrates meteorological data into epidemic models provides decision-support tools at regional level (Racca *et al.*, 2011). In Switzerland, an online decision support platform provides local recommendations on control measures against fruit tree pests (Samietz *et al.*, 2011). Finally, in France, an epidemiosurveillance network has been in place since the 1940s. The data collected in the field are analysed and disseminated in the form of weekly Plant Health Bulletins classified by region and crop type (MAAF, 2015).

There is also European monitoring for certain pests. For example, UK, Dutch and Danish researchers have worked together to monitor the spread of potato late blight (Barzman *et al.*, 2015). In addition, the EuroBlight platform collects data from pesticide companies, advisors and farmers in order to map the distribution of dominant pathogens and their dynamics over several years and in several European countries (ibid.).

However, weeds are not monitored in epidemiological surveillance systems. Weeds resemble crops at the young stage, a period during which treatment decisions need to be made, which makes observing them complicated (Barzman *et al.*, 2015). However, it would be possible to monitor weeds by making observations at the end of the growing season or on a small untreated area; this would make it possible to map weeds (ibid.).

2.5.7.2. What epidemiosurveillance makes possible

Epidemiosurveillance networks collect meteorological and field data on the development stage and progress of diseases and insect pests (Sonderskov *et al*., 2014; Racca *et al.*, 2011; Samietz *et al.*, 2011). Based on this data, models can be used to predict the development of pests and diseases (ibid.). Using these data, decision-support tools can be used to optimise treatments against pests; they provide information on whether or not it is necessary to treat, and make it possible to optimise the doses applied and the treatment period. Decision-support tools also incorporate treatment or damage thresholds, according to which information on intervention is given or not (Barzman *et al.*, 2015; Sonderskov *et al*., 2014).

Epidemiosurveillance networks enable a whole network of stakeholders (farmers, advisors, etc.) to gain a better understanding of health risks and to maintain expertise in plant pathology (ibid.). The collection of long-term field data provides access to new data as well as historical data, which is used to improve disease and pest forecasting models (Reboud *et al.*, 2017; Sonderskov *et al*., 2014).

The acquisition of epidemiosurveillance data can be improved thanks to the development of increasingly powerful and accurate digital tools and sensors (Reboud *et al.*, 2022). Epidemiosurveillance should make it possible to reduce the use of plant protection products by targeting them according to plant protection needs (Reboud *et al.*, 2017), which is not always the case.

2.5.7.3. The limits of current epidemiological surveillance

The effectiveness of epidemiosurveillance in reducing pesticide use is currently limited. In fact, epidemiosurveillance is mainly focused on curative rather than preventive actions.

The notion of damage and treatment thresholds can be called into question. Thresholds are not necessarily suitable for managing weeds and polycyclic diseases, or when resistant crops are used (Barzman *et al.*, 2015). An alert that a threshold has been exceeded almost automatically triggers a treatment, whereas the aim of epidemiological monitoring is to modulate these treatments (expert workshop, November 2020). Thresholds provide narrow information on the presence of a pest on a given crop at a given time, equivalent to “whether or not to treat“, but they do not take into account the deployment of other approaches and other parameters for managing pests (Barzman *et al.*, 2015).

By giving an alert message about a risk, epidemiosurveillance can lead to insurance-type behaviour: treatment: a chemical pesticide is triggered to protect against the risk of a pest developing, rather than to fight against a pest that is already present (expert workshop, November 2020).

In addition, the recommendations of the decision support tools do not take into account the practices and prophylactic measures put in place by the farmer (Reboud *et al.*, 2017). Thus, the messages are not modulated according to what has already been put in place at the level of the cropping system to reduce risks.

Finally, monitoring is generally carried out on a regional scale, whereas recommendations should be adapted to very local conditions, since decisions are taken at plot level (expert workshop, November 2020).

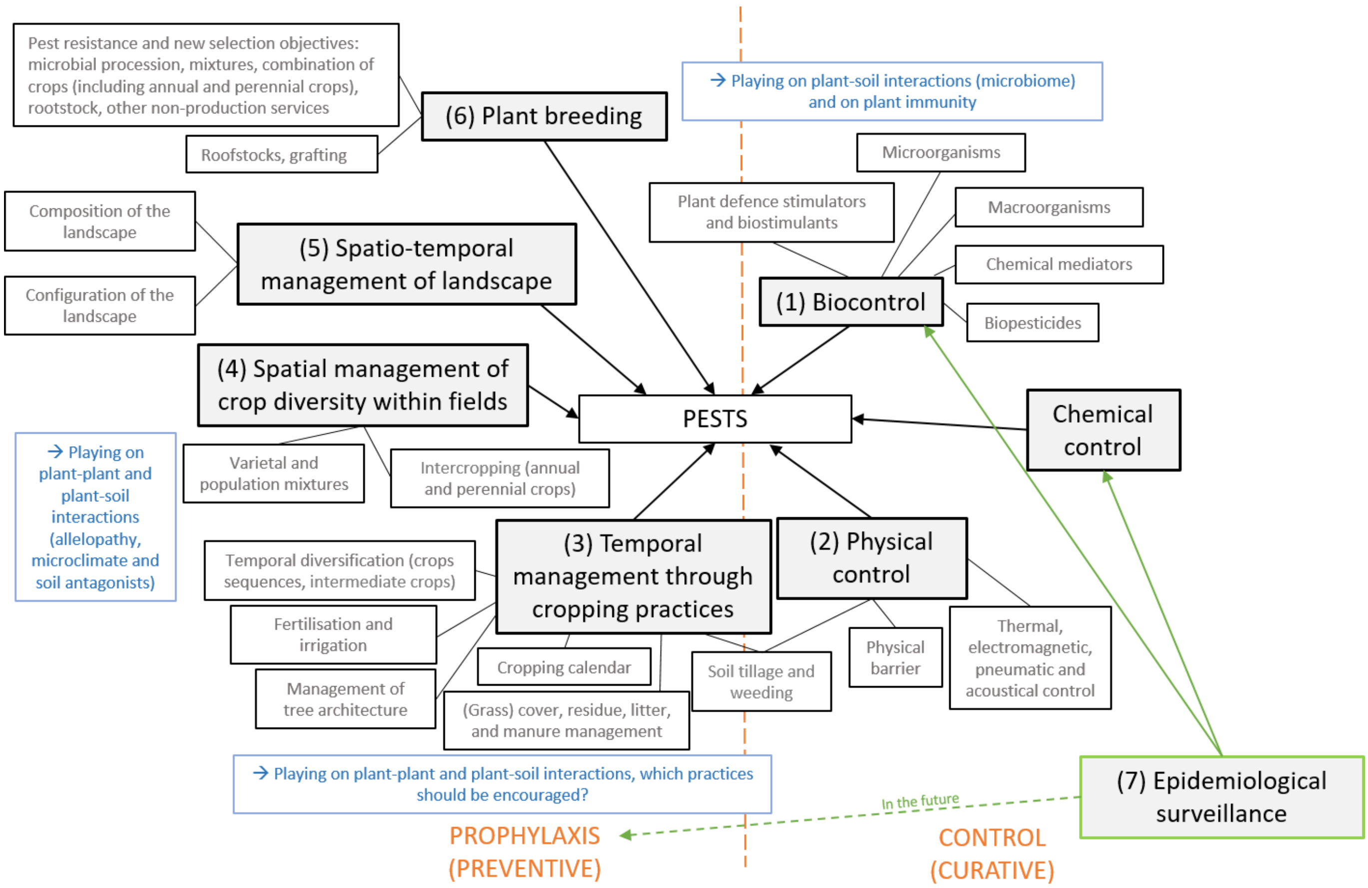
Other monitoring systems focusing on prophylaxis could be developed. Such monitoring would be on a larger scale and over the longer term, targeting objects other than pests, using new digital tools to anticipate the development of pests before they appear (Morris *et al.*, 2021). We elaborate this point in Section 2.6 on future monitoring for preventive action on pests.

Conclusion

To conclude, Figure 2-44 below summarises the six modes of action for acting on pests (in the centre of the Figure) and the role of epidemiological surveillance in crop protection. The modes of action are shown in black squares and the levers of action in grey squares. These modes of action have been divided into two categories: control (or curative) modes of action, on the right, and prophylactic (or preventive) modes of action, on the left.

Some levers of action are both curative and preventive levers. For example, tillage can be used to manage weeds, either preventively by reducing the weed seed bank, or curatively to eliminate weeds that are already present. The plant/plant or plant/soil interactions linked to certain action levers are represented by the blue squares around the action modes and levers in Figure 2-44. Certain biocontrol products (microorganisms, biostimulants and plant defence products) affect plant/soil interactions and plant immunity. Intra-plot diversification and temporal diversification affect plant/plant and plant/soil interactions. Cultural practices affect plant/plant and plant/soil interactions, which raises the question of which practices should be used to favour positive interactions. Finally, epidemiological monitoring, shown in green in the Figure, is currently used for curative action, chemical control or the use of biocontrol products. We assume that epidemiosurveillance will subsequently be used for preventive actions (see Section 2.6).

Figure 2-44: Crop protection diagram – the six modes of action



2.6. Building pesticide-free crop protection and cropping systems in Europe in 2050

Authors: Olivier Mora, Jeanne-Alix Berne, Jean-Louis Drouet, Chantal Le Mouël, Victor Kieffer, Lise Paresys

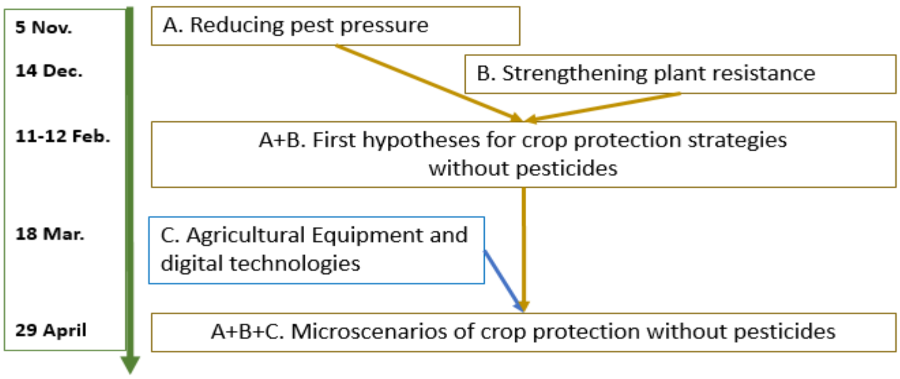
This Section is based on the work of the Experts listed in the Table A2 of the Appendix of the report. It has been reviewed by Jean-Noël Aubertot (INRAE, AGIR), Bruno Chauvel (INRAE, Agroécologie), Jérôme Enjalbert (INRAE, GQE Le Moulon), Bernadette Julier (INRAE, URP3F), Melen Leclerc (INRAE, IGEPP), Agnès Ricroch (AgroParisTech), Emmanuelle Vaudour (AgroParisTech).

Table of contents

2.6.1. The organisation of workshops to elaborate pesticide-free cropping systems

'Cropping systems' thematic groups have been settled in the context of the foresight study on chemical pesticide-free agriculture in Europe in 2050. Three thematic groups that were defined from the start of the project met on November 5, December 14, 2020, and March 18, 2021, respectively: (1) Group A focused on 'Reducing pest pressure'; (2) Group B focused on 'Strengthening plant resistance'; (3) Group C focused on 'Agricultural equipment and digital technologies' (Figure 2-45) (see Table A2 in the Appendix of the report).

Figure 2-45: Organisation of the thematic groups in 2020-2021



In order to develop hypotheses of change of crop protection strategies and cropping systems in 2050, these different groups were brought together in two successive meetings to combine their different approaches (Figure 2-45). A first 'Cropping systems' meeting, aiming to develop the first hypotheses for crop protection strategies without pesticides (pest management strategies without pesticides and rupture hypotheses) brought together experts from the A and B groups on February 11th and 12th, 2021. A second 'Cropping systems' meeting took place on April 29th, 2021, bringing together experts from the first two thematic groups with those from the C group. At this meeting, the experts were asked to complete and validate the previously developed hypotheses and then to build microscenarios of crop protection without pesticides in 2050 based on these hypotheses (see 2.6.5). This Section covers the outcomes of these meetings.

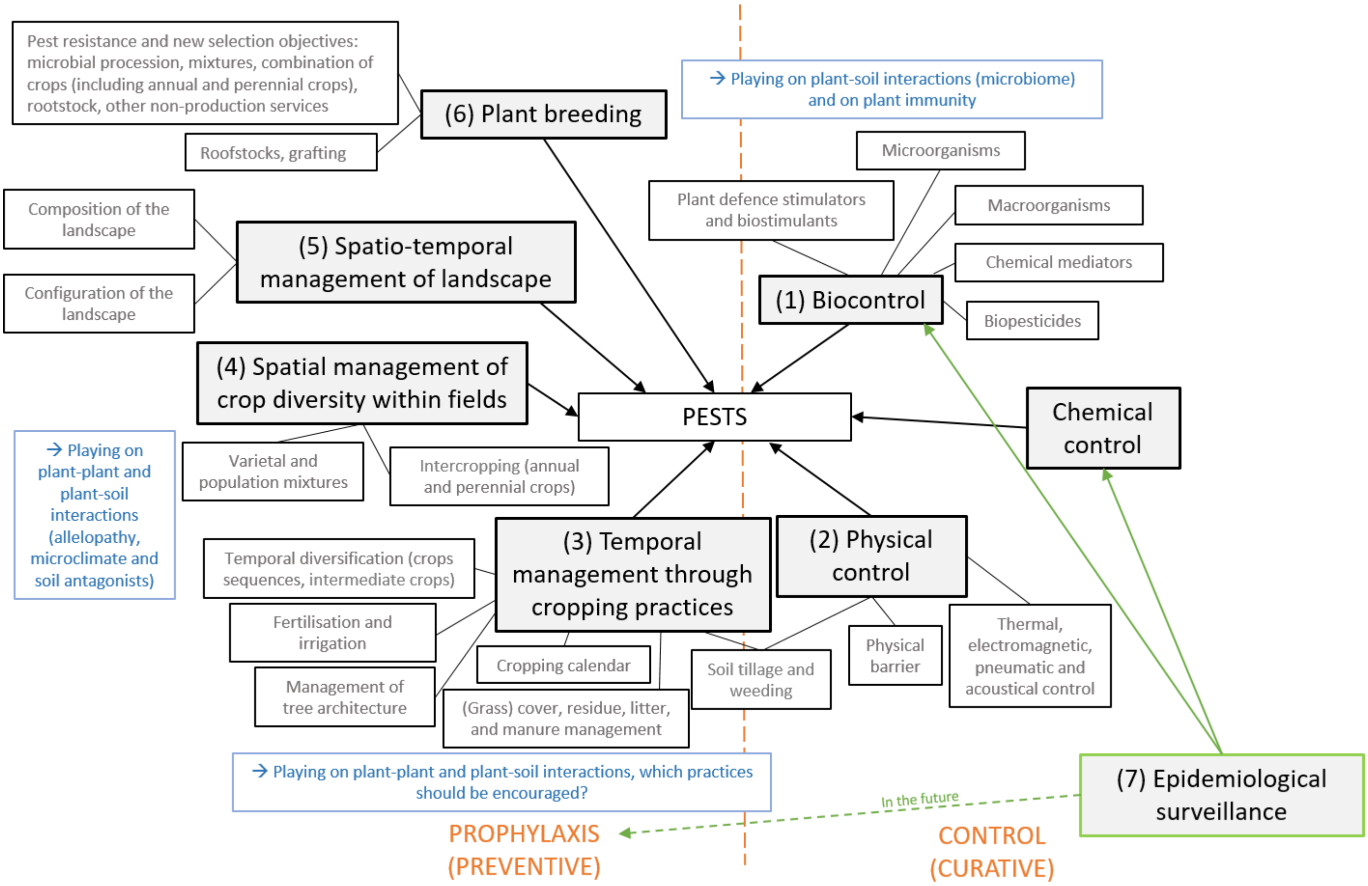
2.6.2. Redesigning plant protection and identifying possible ruptures

2.6.2.1. Summary diagram of crop protection

Crop protection as discussed by groups A and B and synthesized by the project team can be summarized through Figure 2-46. For the purpose of reducing pest pressure without chemical pesticides, group A identified five modes of action (grey boxes in Figure 2-46): 1) biocontrol; 2) physical control; 3) temporal management through cropping practices; 4) spatial management of crop diversity within field; 5) spatio-temporal management of landscape. Group B added a sixth mode of action, plant breeding (6), and completed the other modes of action with additional considerations concerning the plant scale and plant-soil and plant-plant interactions.

Figure 2-46: Summary diagram of crop protection

Black boxes represent different way to act on pests such as animal pests, diseases and weeds; blue boxes represent the plant/plant and plant/soil interaction



Management of pests can be achieved through control and prophylaxis.

For control (on the right side of the diagram, Figure 2-46), apart from chemical pesticides, we can include **Biocontrol (1).** By biocontrol, we mean application of biocontrol products (conservation biological control is integrated into another mode of action) such as biopesticides (or natural substances), chemical mediators, macro-organisms and microorganisms. Plant defence stimulators and bio-stimulants are included in biocontrol products in this analysis. **Physical control (2)** is also a means of control, for example soil tillage (which is also prophylactic) and mechanical weeding, physical barriers such as nets and thermal, electromagnetic, pneumatic and acoustical control.

Regarding **prophylaxis** (on the left side of the diagram, Figure 2-46), first, there is **temporal management through cropping practices (3)** that concerns soil tillage, grass cover, cover, residue, litter and manure management, the cropping calendar (density of sowing, sowing date and harvest date), fertilisation and irrigation, management of tree architecture and temporal diversification, which includes crop sequences and intermediate crops.

The second prophylactic mode of action is **spatial management of crop diversity within field (4)**. This consists of using varietal and population mixtures and combinations of crops (intercropping), which include a combination of annual and perennial crops (agroforestry).

The mode of action **spatio-temporal management of landscape (5)** aims to promote natural enemies of pests (**conservation biological control)** and disfavour pests through the management of semi-natural habitats (SNH) and crops (annual and perennial). There are two aspect of the management at landscape scale: the composition and the configuration of the landscape. The composition of the landscape is the quantity of the different semi-natural habitats and the different crops in the mosaic of crops. The configuration of the landscape corresponds to the spatial arrangement of plant assemblage, it includes the spatial arrangement of SNH and crops (field shape, field size, etc.).

Finally, **plant breeding (6)** includes several challenges in addition to breeding for direct pest resistance (disease resistance, pest resistance or escape, weed control through allelopathy and competition) or tolerance. It includes new breeding objectives such as (i) selecting a seed with a microbial procession, (ii) breeding mixtures (varieties and populations) and not varieties only selected for pure stand performance, and combination of different species (including combination of annual and perennial crops), (iii) selecting rootstock and (iv) selecting for non-production services. There are two main types of breeding efforts, the one conducted by private breeding companies (and also in public institutes) and the one performed through participatory plant breeding, usually by farmers. The latter is particularly interesting for identifying seeds adapted to the local cropping system and plot (particularly soil conditions and soil microbiome). For perennial crops, the grafting is also a way to manage genetic resources (rapid variety change, resistance bringing through rootstock).

Among these modes of action, some have specific effects on **plant-plant** and **plant-soil interactions** (blue squares on the outer edges of the diagram, Figure 2-46). Indeed, introducing biocontrol products influences plant-soil interactions and plant immunity. Intra-plot and temporal diversification affect plant-plant and plant-soil interactions (through allelopathic plants, changes in the microclimate and the promotion of soil antagonists). Cultural practices also affect these interactions and raise the question of how to promote positive plant-plant and plant-soil interactions.

Finally, **epidemiological surveillance (7)** is not a mode of action in itself because it does not allow for direct action on pests. For the moment, epidemiological surveillance is mainly used for chemical control (crossing the threshold of a risk indicator and so triggering treatment) and biocontrol, but the foresight approach aims to reflect on ways of using epidemiological surveillance for prophylaxis.

2.6.2.2. A foresight method based on innovation through withdrawal

During the first ‘Cropping systems’ workshop, experts were asked to reflect on crop protection strategies in cropping systems without chemical pesticides in 2050.

For this, it was suggested using, in a reverse mode, a simplified version of the theory of ‘innovation through withdrawal’ (Goulet and Vinck, 2012). This theory was developed to describe the innovation of no-till techniques. According to Goulet and Vinck (2012) the innovation through withdrawal consist in three stages:

1. Creating what the authors call ‘centrifugal associations’ that is to define the problem with the entity that has to be withdrawn. As an example, ploughing is a technical act that decreases the soil’s biological life and encourages erosion. In case of chemical pesticides, multiple negative impacts on the environment and health because of the use of these products are well known;
2. Making visible other entities: when we remove the entity (eg. ploughing), are there any pre-existing but non-visible entities that are made visible? When removing ploughing, new concerns about the soil and the soil’s biological life are made visible when developing no-till techniques;
3. Mobilising new entities in the sociotechnical network. The deletion of the entity is possible thanks to the introduction of new technical objects. Considering removing ploughing, specific seeding machinery and herbicides are part of no-till innovation.

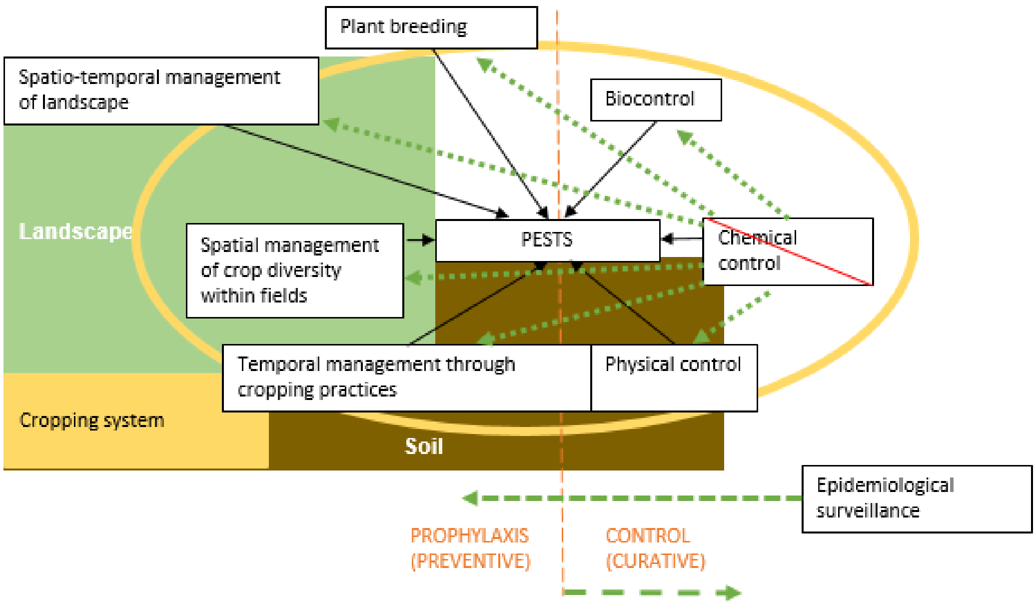
This type of innovation 'through withdrawal' redefines the entities (biological entities, human actors, technical acts) involved and their interactions. It introduces a blurring of the boundaries of the socio-technical network under consideration (on what is, or is not, part of it) and on the categories of the actors considered.

The reasoning adopted for the foresight work consists in investigating two questions: What happens when an entity is removed from a system (in this case when removing chemical pesticides)? And how the socio-technical network could be reconstructed around the deletion of this technical act?

Inspired by the innovation through withdrawal approach, the following question was presented to experts with the aim of imagining crop protection without chemical pesticides: 'When we remove chemical control, what happens to crop protection?' The reflection was displayed through a diagram built by the project team (Figure 2-47), being a simplified representation of the previous diagram (Figure 2-46).

Different paths were foreseen when taking away chemical control. Firstly, the withdrawal of chemical control can possibly lead to changes in all the other modes of action (green arrows), being either simple substitutions (one to one) or the replacement of chemical control with several modes of action acting jointly. Secondly, new entities that are used to regulate pests such as soil and landscape became visible and integrated to crop protection. Further, the elimination of chemical control also raises the question of what is meant by a pest, a point that we will address later in the Chapter (paragraph 2.6.2.3).

Figure 2-47: Mobilizing the approach of innovation through withdrawal for crop protection without chemical pesticides



From this first thinking, three generic issues emerged for crop protection:

- For the general crop protection strategy: switching from **a curative strategy to a prophylactic strategy**;
- For cropping systems: the **replacement** of chemical pesticides with other products and/or other practices (level "Substitution" of the "ESR" concept, from Hill et McRae, 1995) **or, indeed, a redesign** of crop protection and cropping systems (level "Redesign" of the "ESR" concept, from Hill et McRae, 1995);
- For interacting entities: the visibility of **specific entities** that relate to **biological processes** mobilised for the regulation of pests such as **landscapes, soils and biodiversity**.

2.6.2.3. Method for identifying rupture hypotheses

Identifying rupture hypotheses

For the purpose of identifying rupture hypotheses in crop protection, we went back to the previous work on the challenges of eliminating chemical control, which was designed to imagine cropping systems without pesticides in 2050.

Emerging from the previous exercise and by the use in a reverse mode of the theory of innovation through withdrawal (Goulet and Vinck, 2012), two compartments become more visible in the future of crop protection, when chemical control is removed, these being the landscape and the soil.

However, in foresight work, as we consider the possible futures of a system, we often have to modify its boundaries. The challenge of foresight is therefore to reconsider what is internal and what is external, to shift the dividing line that distinguishes the system and its context.

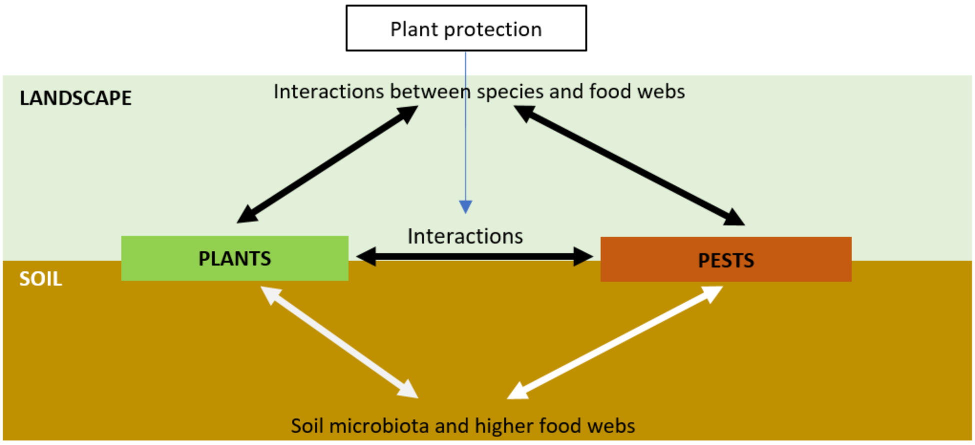
Studies on the sociology of innovation and socio-technical networks underline the fact that innovation constitutes a moment of uncertainty, and that the transformations of a socio-technical network generate a blurring of the boundaries of the network and set in motion the categories of actors and agents (humans and non-humans) (Callon, 1986; Latour, 2014). So, the nature of the interacting entities within the socio-technical network can be modified by the removal of an element. The innovation process sets categories in motion: between nature and technical, between material and intangible, between scientific and empirical, etc.

From the diagram of the modes of action (Figure 2-46), we conducted a work which first focused on the notion of pests and which led to two preliminary remarks:

- The classic crop protection schemes, such as the one developed in the summary diagram (Figure 2-46), present pests at their centre and describe the different levers for acting against these pests. This is where we offer a first conceptual shift. Instead of considering that crop protection aims to act against a pest, we suggest considering that crop protection aims to act on plants, pests and the **interactions between plants and pests**;
- A second remark relates to the very notion of pest. We know that the same species can at a given moment, be considered as a pest from the point of view of the cropping system and of a given crop, and no longer be considered as a pest at another time (see for an example on pathogens, Méthot and Alizon, 2014; for an example on weeds, Bretagnolle and Gaba, 2015). This species is always an element of the ecosystem and the biodiversity with no specific direct interaction with the crop plant. So, the notion of ‘pest’ is related to a **role assigned to a biological entity** in relation to cultivated species.

From these reflections, we have built the conceptual diagram (Figure 2-48) that places the interaction between the cultivated plant and pests within larger networks of interactions within landscape and soil. In this diagram, the first conceptual shift refers to the aim of crop protection, which is to act on the interactions between cultivated plants and pests. The second displacement refers to plants and pests that are integrated into relationships within a landscape and soil.

Figure 2-48: Redefinition of pests and their interactions with plants and the environment [for convenience, climate and cropping practices are not represented]



Deepening rupture hypotheses

To look ahead to 2050 and to test and explore the rupture hypothesis, we asked experts several questions in the form of 'what if?'

1. What if, in 2050, we could completely remodel landscapes and territories, how could we rationalise crop protection? What does it mean to manage pest pressure through the redesign of landscapes? How can we control pest pressure through spatial organisation?
2. What if, in 2050, we could act on soil microbial communities and on the holobiont, how would crop protection be redefined? What could holobiont-based crop protection be?
3. What if, in 2050, we could act on and strengthen plant immunity, what would crop protection based on plant immunity be? What is crop protection based on plant immunity? Can we think of the collective immunity of cultivated plant populations?
4. What if, in 2050, we had predictive epidemiological surveillance tools, how would crop protection be transformed? What could prophylactic epidemiological surveillance be? Can we base crop protection (time) on a new form of epidemiological surveillance and how can we link it with other modes of action?

It should be noted that the fourth hypothesis on epidemiological surveillance and monitoring was explored separately by the project team, in the paragraph 2.6.5.

The exploration of the rupture hypotheses was broken down into three points:

1. Imagining the rupture hypothesis, the knowledge acquired in 2050 in this particular area and its possible applications, giving substance to the hypothesis;
2. How to fully mobilise the effects of this hypothesis for the management of pests? What possible consequences could there be of this rupture hypothesis on other modes of action?
3. How can this hypothesis be combined with other modes of action and cropping systems to build effective crop protection?

2.6.2.4. Exploring rupture hypotheses in 2050

In this paragraph, we present the results of the various workshops carried out with thematic groups on rupture hypotheses in crop protection.

First hypothesis: Designing diversified landscapes adapted to local contexts and their evolution

In the rupture hypothesis n°1 'Designing diversified landscapes adapted to local contexts and their evolution', organisms harmful to crops are managed through interactions beyond the field level, and over space and time. Biodiversity and agrobiodiversity are mobilised to influence biological regulations. The hypothesis is not limited to crop protection purposes. It uses the principle of sub-optimality and must allow for the conservation of living organisms that are neither useful nor harmful to crops (Darnhofer *et al.*, 2008; Grumbach and Hamant, 2020). It involves different pest management strategies, from the landscape to the field level, including the cropping system level. It involves considering landscapes as interfaces between agro-ecosystems and actors who shape them.

This rupture hypothesis relies on landscape and crop diversification. Diversified landscape and cropping systems are designed (i) to be adapted to local contexts and their evolution; and (ii) to create, in terms of habitats and resources, discontinuities for harmful organisms and continuities for beneficials and other (neither useful nor harmful) living organisms. In this hypothesis, landscapes are composed of a stable matrix of natural and semi-natural habitats and a mosaic of crops that can be shaped in its composition and configuration, following the below criteria:

- 20% of land are covered by **natural and semi-natural habitats (Garibaldi *et al.*, 2020; Tscharntke *et al.*, 2021)**. These are distributed regularly throughout landscapes. They include wooded and herbaceous areas (permanent pastures). They must remain natural and semi-natural. Their diversity and age have an effect on their role on biological regulations;
- **Cropping systems** are diversified over space and time. They involve growing a diversity of crops in successive years in the same field (long rotations), and/or growing more than one crop in sequence over a year in the same field (multiple cropping, including cover cropping), and/or growing several crop species in close proximity within the same field (intercropping), and/or mixing varieties or populations (in standard pureline varieties, plants are almost identical while in populations, all plants are genetically distinct) within the same field, and/or growing perennial and annual crop species within the same field (agroforestry systems). Crop management practices are chosen to manage harmful organisms (*e.g.*, use of push-pull intercrops, barrier crops, weed-competing crops, diversity of crop cycles and resistance to limit risks, turnover in varieties, etc.) and inocula (resource dilution, crop frequency in the rotation, etc.), while preserving beneficials and other living organisms;
- **Crop fields** are small and bordered by interfaces with natural and semi-natural habitats.

In this hypothesis, **tools to monitor biological regulations** are in place to inform crop protection decisions over time, and to allow for the **early change of the mosaic of crops**, including the design adaptation of cropping systems. These tools take into account the relationships between (i) indicators on the dynamics of potentially harmful organisms; (ii) the composition, configuration and crop management practices within the mosaic of crops in previous years and during the on-going year; and (iii) the climatic context. From this point of view, learning is necessary on interactions and transformations operating within landscapes. New 'damage' thresholds that are deemed acceptable are also defined.

Finally, in this rupture hypothesis, **actors' practices are coordinated at the landscape level**. Actors involved in the governance of diversified landscapes and cropping systems can change over time depending on the spatial scale at which harmful organisms are to be managed. Supporting this hypothesis requires a collective recognition of the multi-functionality of agriculture and ecosystem services.

Second hypothesis: Managing the holobiont by strengthening host-microbiota interactions

The rupture hypothesis **'Managing the holobiont by strengthening host-microbiota interactions'** mobilise **host-microbiota interactions** in order to bolster the protection of cultivated plants against pests in 2050. This hypothesis relies on controlling or directing (depending on the versions of the hypothesis) the holobiont. Holobiont is defined as an assemblage of species including cultivated plants and their associated microbes in soil and rhizosphere, phyllosphere, and endosphere; plant and plant-associated microbes form a single evolutionary unit (Simon *et al.*, 2019). The host-microbiota interaction works as follows. To meet its needs in its environment, the **plant recruits microorganisms from a reservoir of microbial diversity** (virus, bacteria, archea, protists, fungi; found mainly in the soil) with which it builds stable relationships being, for example, symbiosis as in the case of mycorrhizae (as described in Section 2.3 related to plant interactions). Crop protection based on the holobiont looks for strengthening the **functions of the microbiota**, so as to enhance the protection of the plant and its resistance to pests, as well as to **strengthen the adaptability of the holobiont** (its ability to recruit microorganisms) in the face of disturbances (biotic or abiotic). To do this, the development of very localised and contextualised action on the microbiota is needed, as well as a full articulation with the cropping system.

To this end, **diagnostic tools for microbiota** (in particular soil microbiota) should be developed by 2050 based on indicators that characterise the state of the microbiota and its relationship to the plant (Mocali *et al.*, 2008). From this point of view, knowledge on the microorganisms constituting the microbiota needs to be refined by 2050 to have a better understanding of microbial diversity reservoirs (soil, air, water and weeds, animal pests) and to specify the ways of controlling or modulating these reservoirs.

Several levers that can be used to manage soil microbiota, some of which are already in use, could be systematised. For instance, **varietal selection** adapted to strengthen plant-microbiota interactions (extended phenotype) and the **inoculation of key microorganisms** to modulate the microbiota (for instance, developing certain protective ecosystem services of a plant). Varietal selection should also **consider the characteristics of low-input cropping systems** since high levels of chemical fertilisation are unfavourable to strengthening plant-microbiota interactions (Wallenstein, 2017).

Other levers for modulating microbiota concern **cropping practices**. These include tillage, organic amendments and residue management, but the choice of crops and cover crops also makes it possible to modulate the microbiota by playing on the contributions of microorganisms (manure) and on the composition of soil microorganisms (selection by cultivated plants or weeds, by the presence or absence of residues, etc.). Due to the sensitivity of soil microorganisms to chemical fertilisation and the particularly important link between high fertilisation levels and high pest presence, a **reduction in chemical fertilisation** makes it possible to reinforce the recruitment capacities of cultivated plants and to reduce pest virulence.

The management of soil microbiota should be considered in relation to the **local context** (local microbiota, etc.) **of the cropping system** (tillage, amendments, etc.) in order to avoid incompatibilities regarding the targeted objectives. This management requires **continuous monitoring of the soil microbiota at the field scale** to measure both the effects of the cropping system on microbiota over time and the consequences of targeted interventions aimed at modulating the microbiota. From this point of view, certain practices developed on an empirical basis designed to strengthen soil capacities (suppressive soils (Schlatter *et al.*, 2017), plant growth-promoting rhizobacteria, for example) could be developed.

In this hypothesis, it is also necessary to consider the multi-services produced by the microbiota (plant nutrition, mycorrhization, resistance to stress and phenotypic plasticity) which is mobilised in the cropping system.

Finally, all of the holobionts present in the field play a role in crop protection. For example, by controlling pests through the promotion of parasitic bacteria in the microbiota of insect pests.

Third hypothesis: Strengthening the immunity of cultivated plants directly and indirectly

This rupture hypothesis for crop protection without pesticides is based on **directly or indirectly** strengthening the **immunity of plants**.

Direct strengthening of plant immunity can occur through two pathways:

- Through stimulating the immune **system**: either via the **exogenous supply of plant defence stimulators (PDS)** or via the **introduction of plant species that produce plant defence stimulators**. The exogenous supply of PDS can be **combined with the exogenous supply of bio-stimulants** in order to achieve an optimal balance between defence and growth processes, seeking synergistic effects. PDS can also be applied preventively, which can be likened to the plant defense priming (Desmedt *et al*., 2021). The negative effects of these substances on plants, on their biotic (flora and fauna) and abiotic environment and on humans must be studied. This lever is complementary to the genetic lever that delivers totally or partially resistant varieties. It relaxes the pressure on resistance genes and potentially delays resistance overcoming;
- **Through genetic control**: firstly by **selecting genotypes resistant to pests** (major and minor resistance genes conferring total or partial resistance) and **rootstocks** for perennial plants. This lever shows greater durability over time than direct stimulation of the immune system. Secondly, until now, selection has been mainly achieved through 'classical' breeding using phenotypic screening assisted by molecular tools (to trace resistance genes or to apply genomic selection) based on natural variation. Genetic engineering (gene introduction through transgenesis or more recently genome editing) is a way to introduce or modify genes to mimic the immunity developed by related or unrelated (especially wild) species.

Indirect strengthening of plant immunity is about not losing, or at least maintaining, their genetic or acquired immunity. It can be achieved by promoting:

- **Positive interactions between plants and their immediate environment**: in particular, by promoting **biological interactions that strengthen plant resistance** and by combining prophylaxis with the quality of the various microbiota (endogenous to the plant, rhizosphere and phyllosphere) and by building on the understanding and use of the **plant's response to multiple stresses**;
- **Positive interactions between plants and their environment at larger spatial and temporal scales (production system, landscape and regional):**
    - In a system **capable of constantly evolving and adjusting to emerging threats**, which means anticipating and imagining in advance new (prophylactic) solutions to impact plant immunity. This anticipation requires defining immunity indicators and thresholds and quantifying them (level of protection of the plant against pest attack, molecular and optical indicators, etc.) using in particular epidemiological surveillance devices (satellite sensors, digital technologies, data assimilation models, etc.);
    - Through the **diversification** of cultivated crops, carrying different resistance genes, introducing species and **varietal mixtures** or pyramiding genes within a variety;
    - Through **rethinking the geographical location of crops** and the specialisation of cropping areas, by selecting **varieties adapted to agro-pedoclimatic conditions** (crop management, local soil and climate characteristics) and to changes in the climate;
    - **Through the introduction of service plants** into crop successions and landscapes: either as permanent ground cover preventing weed development; or in **competition with weeds** to limit their access to resources and hindering their development; or by playing a role as **sentinel plants** by diffusing 'odours' in the landscape through **allelochemistry**; or acting as a **physical barrier** by planting service plants on plot edges and so protecting crops in the centre of the plot, promoting positive plant-insect or plant-plant interactions;

- Through **careful reasoning** about cultivated species and varieties (especially to increase the durability of resistance through varietal deployment) and service plants in **plots and landscapes, and rethinking plot and landscape design**.

2.6.3. Pest management strategies for different pests, in systems without chemical pesticides in 2050

2.6.3.1. Method for designing pest management strategies in systems without chemical pesticides in 2050

Experts worked during the first ‘Cropping systems’ meeting (February 11, 2021) separately on each type of pest (weeds, animal pests and diseases) from the crop protection diagram (Figure 2-47). They were asked to answer four questions for each type of pest:

1. If we withdraw pesticides for controlling this category of pest, what other modes of action can replace them?
2. Are there material entities (soil, species/varieties, landscape) which acquire new importance in the crop protection strategy?
3. To what extent can we shift the strategy of crop protection towards increased prophylaxis?
4. What could be the new place of epidemiological surveillance in this strategy?

From this first workshop, the DEPE project team defined several management principles to manage in 2050 the different types of pests found in crop systems without pesticides. The aim was to obtain several hypotheses for the possible change of these crop protection strategies without chemical pesticides by 2050.

These hypotheses were then reworked and deepened during the second ‘Cropping systems’ meeting (April 29, 2021). The results of these two workshops are presented below.

2.6.3.2. Management strategies for different categories of pests in systems without chemical pesticides in 2050

Weed management strategies

Weeds are **in majority native** to cultivated plots and are an integral part of the **biodiversity** of agroecosystems. The **three main stages of weed development** are **seeds in the soil**, **germinated and emerged plants**, and **seeds produced** and disseminated either naturally (*e.g.*, wind, runoff or animal) or anthropogenically (*e.g.*, agricultural equipment, seed lots or manure). Hypotheses (Table 2-8) have been proposed to act on these three stages of development in order to reduce the presence of weeds in cultivated plots and their transfer to landscapes.

Based on these hypothesis, **three main strategies** have been defined to act on the main stages of development (Table 2-8):

- **Eliminating weeds** (with control).
- **Limiting weed development** by improving the competitiveness of cultivated plants for access to resources or by strengthening natural processes.
- **Exploiting the ecosystem services of weeds** (*e.g.*, as fodder biomass).

For weeds, it is **very difficult to distinguish control actions and prophylactic actions**. For example, the suppression of a weed plant (control) results in the absence of weed seed production (prophylaxis). Furthermore, unlike other types of pests such as animal pests and diseases, it is currently **very difficult to assess yield losses due to the presence of weeds** and to define **thresholds for weed damage**, but weeds can have an impact on yield, which is well known in organic farming. The general principle of weed control/prophylaxis is to make sure that cultivated plants **maintain a development lead** over weeds.

The **alternative modes of action** to chemical control are mainly:

- **Physical control**: tillage and mechanical weeding (*e.g.*, RTK precision harrowing, intelligent robots), straw and chaff management, use of weed 'shorteners' (*e.g.*, trimmers);
- **Plant breeding**: selection of cultivated plants based on functional **competitive traits**, including **chemical** (allelopathy and allelochemistry), **morphological** (*e.g.*, reduced root architecture and developed aerial architecture with a spread leaf shape facilitating access to light resources, early growth vigour) and **physiological** (*e.g.*, efficient use of captured resources);
- **Temporal management** and **cropping practices** are also levers to be used to reduce weed development and seed production (reduction of the seedbank in the soil): optimal sowing dates, increased sowing densities of cultivated plants, choice of types of cultivated plants, choice of rotations and crop successions, establishment of **annual or perennial covers** (*e.g.* living-mulch) which may even be **weed covers**;
- **Biological control**: use of insects or diseases that develop on weeds.

Soil management is a major lever because the soil is the reservoir of weed seeds. The improvement of the knowledge on the microbiota of weed seeds could strengthen the potential impact of soil management. Some tillage techniques could **reduce the seedbank in soil** but could also cause problems (*e.g.*, cost and soil degradation). It is also important to increase the **purity of cultivated seed lots** in order to not import new weeds.

The lever of **landscape management** does not seem to be readily available because weeds are predominantly native, mostly endocyclic, *i.e.* strongly impacted by the history of cultivated plots, unlike some animal pests and (mobile) plant pathogens. Nevertheless, there are some avenues to explore:

- **Managing the size of cultivated plots** in order to reduce the intra-plot diversity of weed populations and thus increase the effectiveness of other control methods.
- **Planting strips of different crops** in order to reduce the spread of weeds.
- **Building landscape structures** that **host birds and insects** which feed on weed seeds or seedlings, thus providing a form of biological control. However, weed and weed seeds suppression could lead to the loss of some birds and insects, thus altering the cycles of other biological communities. In this case, weed suppression could become a negative action for the agroecosystem management.

Epidemiological surveillance could also contribute to weed control, for example:

- **Better knowledge (quantity and location) of the weed seedbanks in soils and of the flora in place** could help to reduce the seedbank in place and **identify the crops to be avoided** for several years because they favour the development of certain weed seeds. This would require the development of **agricultural equipment** (*e.g.*, cameras and robots) and **digital technologies** (for example, information processing) to sample the stocks and the composition of weed seeds in soils (*i.e.* a form of bio-vigilance), to sequence their DNA, detect the presence or absence and quantity of weed seed species harmful to cultivated plants and then target their destruction.
- To help set up **collective strategies to limit the transport of weed seeds** via agricultural equipment (including equipment washing) or trade (including phytosanitary passport at national level and certificate at international level, based on inspection of seed lots and seed production in the field), and to eradicate or limit the risks of development of new **toxic and allergenic invasive species** (for example, datura (jimsonweed) and common ragweed).

Table 2-8: Weed management strategies for crop protection without chemical pesticides in 2050

Evolution hypotheses (in blue) for a weed management strategy without pesticides crossed with three major weed management strategies (in columns) with the three major stages of weed development (in rows). The underlying modes of action are in brown italic characters and the entities used are in green italic characters.

Strategies *Acting on*:	**Eliminating weeds (control)**	**Limiting the development of weeds (control + prophylaxis)**	**Mobilising weed services (control + prophylaxis)**
Seed stock in the soil	*- Identifying the seedbank using digital technologies. Prophylaxis/ epidemiological surveillance/digital technologies.* *Soil* *- Then destroy the seedbank. Prophylaxis/physical control/ crop control/ agricultural equipment. Plant*	*Conservation biological control* *- Encouraging insects and birds predators.* *Landscape* *- Modulating the microbial balances of soil to limit seed germination.* *Soil/plant* *- Anticipating the arrival of certain weeds.* *Epidemiological surveillance* *- Establishing annual or perennial cover crops/service plants. Prophylaxis/ crop control/ temporal management* *- Optimising the dates and densities of sowing of cultivated plants, crop successions.* *Plant / Landscape*	Trophic chains to increase community diversity (belowground and above ground)
Germinated / emerged plant	*- Mechanical or manual weeding* *Physical control/agricultural equipment* *Plant/soil* *- Use of biocontrol products (biopesticides)* *Biocontrol* *- Selection of allelopathic traits* *Genetic control* *Plant*	*- Selecting competitive traits: chemical (hormonal/allelopathic), phenotypic (aerial/root architecture), functional (e.g. nitrogen use efficiency)* *Genetic control* *- Weeding, topping, using towed equipment and robots* *Physical control/crop control/ digital technologies* *Plant/soil*	*- Living with weeds, accepting specific, intra-plot and temporal diversity, accepting loss of yield and quality* *- Exploiting two plant covers (crop and weed), the role of weeds in biodiversity. Crop control/temporal management* *-Use of weeds to limit soil erosion (vineyards).* *Attraction of pests to limit damages on crops*
Seed produced	*- Limiting agricultural interventions* *- Washing agricultural equipment* *- Limiting human and animal movements in fields* *Agricultural equipment* *Landscape*	*Reducing the external input of weed seeds (increasing the purity of cultivated seed batches)* *- Reducing seed dispersal through landscape design (creating hedges) and management of agricultural equipment* *Agricultural equipment* *Landscape*	*Exploiting the role of weed seeds for biodiversity (e.g. feeding insects and birds)* *- Establishing hedges serving as a refuge for insects and birds* *Crop control/temporal management* *Landscape*

Pest management strategies

Three alternative hypotheses for chemical pesticide-free management of pests (insects, mites, nematodes, molluscs, birds and mammals) have been identified (Table 2-9). They are:

- **Eliminating pests** by **substituting chemical control with biocontrol**. In addition, when it is possible, crop resistance is improved (genetic control) and when necessary, physical barriers to pests (*e.g.*, nets) are used (physical control). This hypothesis does not involve major changes in current cropping systems;
- **Isolating crops from pests by growing them under controlled environment conditions in appropriate facilities**. This hypothesis involves controlling inflows and outflows of cropping systems. The viability of such cropping systems for large areas in 2050 is uncertain (economic and energy costs, material availability);
- **Influencing the dynamics of pest populations through biological regulations by increasing biodiversity and agrobiodiversity from the landscape to the field level**. This hypothesis relies on diversified landscapes and cropping systems. These are designed (i) to create, in terms of habitats and resources, discontinuities for pests and continuities for beneficials and other living organisms (not considered as pests); and (ii) to be adapted to local contexts and their evolution. In this hypothesis:
    - **Landscapes** are composed of a **stable matrix of natural and semi-natural habitats**, and a mosaic of crops that can be changed in its composition and configuration. Field size is reduced.
    - **Cropping systems are diversified over space and time** (agroforestry systems, intercrops, variety and population mixtures, multiple crops and long rotations). Their **management** (*e.g.*, grinding, burial or grazing of residues) **is adapted to better manage inocula**, while preserving beneficials and other living organisms not considered as pests. Varieties and populations are selected for the purpose of crop diversification (*e.g.*, to promote plant-plant interactions) and the implementation of other preventive crop protection practices.
    - The use of **physical barriers** to pests (*e.g.*, nets) may be necessary, especially for perennial crops. As a last resort or transiently, when prophylaxis fails, **biocontrol** can be used to reduce pest populations. Pests can also be removed manually or mechanically and valued as food.

Better knowledge and monitoring of pest life cycles and food webs at the landscape level is needed to inform strategic and tactical decisions for influencing biological regulations. Damage thresholds must be redefined and crop losses in terms of both quantity and quality must be accepted.

Table 2-9: Alternative strategies for chemical pesticide-free pest management in 2050

Strategy	Eliminating pests (control)	Isolating crops from pests (control)	Influencing the dynamics of pest populations (prophylaxis)
Main lever of action	Eliminating pests by substituting chemical control with biocontrol	Isolating crops from pests by growing them under controlled environment conditions in appropriate facilities	Influencing the dynamics of pest populations through biological regulations by increasing biodiversity and agrobiodiversity from the landscape to the field level (landscape and crop diversification) - Stable matrix of natural and semi-natural habitats +mosaic of small crop fields that can be changed in its composition and configuration - Cropping systems diversified in space and time
Complementary lever(s) of action	- Genetic control (crop resistance) - Physical control (*e.g.*, nets)		- Crop management practices to better manage inocula (*e.g.*, grinding, burial or grazing of residues) - Genetic control (varieties and populations selected for landscape and crop diversification and the implementation of other preventive practices) - Physical control (*e.g.*, nets for perennial crops) - As a last resort, biocontrol (especially for perennial crops)
Other levers	No major changes in current cropping systems	- Controlled inflows and outflows of cropping systems - Affordable economic and energy costs, available materials	- Better knowledge and monitoring of pest life cycles and food webs at the landscape level to inform strategic and tactical decisions for influencing biological regulations - Redefined damage thresholds and crop losses accepted in terms of both quantity and quality

Disease management strategies

Four disease management strategies that do not use chemical pesticides were identified to manage diseases (Table 2-10).

The **'No control measures'** management strategy is based entirely on **prophylaxis**. This management strategy is reinforced by the selection of **less sensitive varieties and rootstocks**, adapted to the agronomic context of the plot, **seeds** or plants with a **protective microbiota** and the choice of the plot. Emphasis is also placed on the **choice of variety mixtures, intercropping** and **plant covers** that are unfavourable to pathogens, taking into account the arthropod community, which depends on the chosen variety, increasing **soil biodiversity** and the **inoculation of a protective microbiota**. **The acceptance of products with defects** by consumers helps to consolidate this management strategy.

In the **'Isolate from the environment'** management strategy, **the growing medium is isolated from the natural environment** and plants are grown in greenhouses. This management strategy is reinforced by the selection of varieties and rootstocks suitable for greenhouse cultivation. The emphasis is on seeds and plants, which must be **healthy initially** in order to avoid the introduction of inoculum into the medium, and on **inoculation with a protective microbiota**. The management strategy also involves **controlling the elements introduced into the closed system**, **monitoring the spread of inoculum** via irrigation water, machines and people**. Careful monitoring of the physiological state** of plants and soil throughout the crop cycle makes it possible to consolidate this management strategy. Fine tuned microclimate (temperature and humidity) is also a powerful lever of this strategy.

The **'Controlling the disease cycle'** management strategy relies on levers such as the selection of **less susceptible varieties and rootstocks** and seeds or plants with a **protective microbiota**. Emphasis is also placed on the choice of **mixtures of species and varieties, intercrops** and **plant covers** that are unfavourable to pathogens and vectors of pathogens, **sowing density** to create abiotic conditions unfavourable to pathogens, **fertilisation management**, rethinking **rotations** and establishing **suppressive landscapes** (landscape less favourable to the development of epidemics). The management strategy is reinforced by **monitoring the spread of inoculum** via irrigation water, the **aggressiveness of pathogens** and their dispersion. **Careful monitoring of the physiological state** of plants and soil throughout the crop cycle and a systemic approach to plant immunity make it possible to consolidate this management strategy.

At last, the **'Strengthening the immunity of plants against diseases'** management strategy relies on levers such as the selection of **less sensitive varieties and rootstocks** and **for new uses** (response to plant defence stimulators, architecture unfavourable to pathogens, service plants, etc.), as well as the selection of seeds or plants with a **protective microbiota**. Emphasis is placed on the **use of plant defence stimulators** and the **inoculation of pathogen antagonists**. This management strategy also involves choosing **mixtures of varieties** and **sowing densities** favourable to plant defences. **Careful monitoring of the physiological state of plants and soil** throughout the crop cycle makes it possible to consolidate this management strategy.

Table 2-10: Disease management strategies for crop protection without chemical pesticides in 2050

Management strategy	No control measures (prophylaxis)	Isolate from the environment	Controlling the disease cycle	Strengthening the immunity of plants against diseases
Breeding (varietal selection)	Less susceptible and more tolerant varieties/rootstocks, seeds/plants with combinations of resistance genes, breeding for mixtures, protective indigenous microbiota Agroecological immunity	Varieties/rootstocks selected for greenhouse cultivation	Less susceptible and more tolerant varieties/rootstocks, seeds/plants with a protective indigenous microbiota	Less susceptible and more tolerant varieties/rootstocks and for new uses, seeds/plants with more resistance factors and favouring a protective indigenous microbiota
Cultural control	Varietal/species mixtures and intercrops Plant covers Selected or inoculated indigenous microbiota Role of arthropods		Varietal/species mixtures and intercrops Plant covers Seed density Fertilisation and rotations Suppressive landscapes	Plant defences at leaf and soil level: Seed density Varietal mixtures
Seeds and plants / soil / microbiota	Soil biodiversity in the broad sense (virtuous circle of food webs, more stable over time, more biomass)	Pathogen-antagonist 'core' microbiota taxa Healthy seeds and plants, protective microbiota	Pathogen-antagonist 'core' microbiota taxa Healthy seeds and plants, inoculated with a protective microbiota Microbial soil biocontrol	Promoting soil biodiversity to strengthen plant defences Increasing the biological diversity of soil microbiota
Control actions			Specific phages Antagonistic microbial taxa Biocontrol Entomovection	Plant defence stimulators *Ad-hoc* inoculation of antagonists
Other	Ensure consumers accept products with defects Choice of cultivation site	Control the elements introduced Close monitoring of plants and soil Monitoring for the presence of inoculum (irrigation water, machines and people)	Intervention thresholds Close monitoring of plants and soil Monitoring for the presence of inoculum (irrigation water), pathogen aggressiveness and dispersion Systematic approach	Balance between growth, yields and defence against pests Close monitoring of the physiological state of plants and soil throughout the crop cycle

2.6.4. Micro-scenarios of cropping systems without chemical pesticides in 2050

2.6.4.1. Method for constructing micro-scenarios of cropping systems without pesticides in 2050

The construction of the cropping system microscenarios is based on a morphological table (Table 2-11) which groups together hypotheses for the evolution of dimensions in the system.

The construction of cropping systems in 2050 accounts for various dimensions related to crop protection such as animal pest, pathogen and weed management strategies, which participate in the implementation of these strategies. Furthermore, other contextual dimensions that determine the cropping system, such as agricultural equipment and digital technologies or collective action have been addressed separately.

The morphological table is constructed by applying, for each dimension of the system, the previously constructed hypotheses of change in 2050. On each line there are *a priori* alternative hypotheses describing the different possible evolutions of a given dimension by 2050.

The table has been supplemented by a first line with the three rupture hypotheses for crop protection on which we worked. As a working hypothesis, we considered that each rupture hypothesis was capable of generating a crop system micro-scenario in 2050.

The instructions given to the experts for the construction of cropping system micro-scenarios were as follows. From a chosen rupture hypothesis (line 1), the hypotheses of management strategy for animal pests, weeds and diseases most consistent with this rupture hypothesis is selected and is completed with additional assumptions on agricultural equipment and digital technologies.

Following these instructions, three micro-scenarios were constructed based on three rupture hypotheses.

Table 2-11: Morphological table for cropping systems

	Hypotheses of change in 2050			
Crop protection based on…	Diversification of landscapes	Management of the holobiont	Strengthening plant immunity	
Management strategy for animal pests	Eliminating pests (control)	Isolating crops from pests (control)	Influencing the dynamics of pest populations (prophylaxis + control)	
Management strategy for weeds	Limiting weeds (control)	Limiting weed development (prophylaxis + control)	Mobilising weed services (prophylaxis + services)	
Management strategy for diseases	No control (prophylaxis)	Isolating crops from the environment (control)	Managing disease cycles (prophylaxis + control)	Strengthening plant immunity against diseases (prophylaxis + control)

2.6.4.2. The three micro-scenarios for cropping systems in 2050

Micro-scenario based on the diversification of landscapes

This micro-scenario is based on the rupture hypothesis ‘Designing diversified landscapes adapted to local contexts and their evolution’.

In this rupture hypothesis, crop protection is based on prophylaxis. Biodiversity and agrobiodiversity from the landscape to the field level is used to influence biological regulations and manage organisms harmful to crops. In this rupture hypothesis, control methods are used only as a last resort or transiently.

The hypotheses ‘Eliminating pests’ and ‘Isolating crops from pests’, for animal pests (insects, mites, nematodes, molluscs, birds and mammals), ‘Limiting weeds’ for weeds and ‘Isolating crops from the environment’ for diseases thus appeared inconsistent with the rupture hypothesis (Table 2-12). The presence of pests is necessary to maintain beneficial populations. The conservation of weeds that are neither useful nor harmful to crops must be permitted in order to maintain biodiversity.

Table 2-12: Morphological table for the micro-scenario based on landscape diversification

	Hypotheses of change in 2050			
Crop protection based on…	Diversification of landscapes	Management of the holobiont	Strengthening plant immunity	
Management strategy for animal pests	Eliminating pests (control)	Isolating crops from pests (control)	Influencing the dynamics of pest populations (prophylaxis + control)	
Management strategy for weeds	Limiting weeds (control)	Limiting weed development (prophylaxis + control)	Mobilising weed services (prophylaxis + services)	
Management strategy for diseases	No control (prophylaxis)	Isolating crops from the environment (control)	Managing disease cycles (prophylaxis + control)	Strengthening plant immunity against diseases (prophylaxis + control)

Management strategies for animal pests, weeds and diseases

The management strategies involving ’Influencing the dynamics of pest populations’ and ‘No control’ of diseases, which are based on prophylaxis, appeared to be consistent with a landscape diversification approach (Table 2-12). These hypotheses involve redefining ‘damage’ thresholds and spreading risks of damage. They also involve acquiring new knowledge about pest and disease cycles and biological regulations in order to support decisions on prophylaxis.

The weed management strategy was further discussed. The hypothesis on ‘Mobilising weed services’ was interpreted as modifying the nature of weeds, which would become service crops. The hypothesis on ‘Limiting weed development’ was interpreted as not considering the conservation of weeds useful for biological regulations (or for the provision of other services) and the conservation of weeds that are neither useful nor harmful although these are an integral part of biodiversity. In this micro-scenario, weed development must be managed to find a compromise between crop losses and services provided at the landscape level, while accepting the presence of weeds that do not affect crop production without providing services.

Other elements contributing to the micro-scenario

In this micro-scenario, the pooling of equipment could be mobilised for crop protection at the landscape level. It was however specified that not all equipment, sensors and data are pooled, that some equipment are modular, and that automation and robots could be part of the equipment and digital technology that can be used at a landscape level. In this micro-scenario, three forms of pooling were distinguished: pooling to share investments, pooling to coordinate observations, and pooling to coordinate actions on biological regulations.

The micro-scenario based on landscape diversification relies on landscape and crop diversification adapted to local conditions (relocation of crops and livestock, economy of scope *versus* economy of scale). It requires actors of agri-food systems to be strongly coordinated so as to discuss the sharing of risks and benefits at the landscape scale. Supporting this micro-scenario requires a collective recognition of the multifunctionality of agriculture and ecosystem services. It raises questions of governance: who participates in the design of the mosaic of crops and landscapes? Should land property rights (*usus, fructus, abusus*) be redefined? This microscenario should be linked to a specific hypothesis on farm structure, allowing an action at the landscape level.

Micro-scenario based on the management of the holobiont

This micro-scenario of crop protection is based on the rupture hypothesis '**management of the holobiont**' (Table 2-13).

By 2050, the management of holobiont and microbiota is considered to be a driving force that radically transforms crop protection without using chemical pesticides.

Table 2-13: Morphological table for the micro-scenario based on managing the holobiont

	Hypotheses of change in 2050			
Crop protection based on…	Diversification of landscapes	Management of the holobiont	Strengthening plant immunity	
Management strategy for animal pests	Eliminating pests (control)	Isolating crops from pests (control)	Influencing the dynamics of pest populations (prophylaxis + control)	
Management strategy for weeds	Limiting weeds (control)	Limiting weed development (prophylaxis + control)	Mobilising weed services (prophylaxis + services)	
Management strategy for diseases	No control (prophylaxis)	Isolating crops from the environment (control)	Managing disease cycles (prophylaxis + control)	Strengthening plant immunity against diseases (prophylaxis + control)

Two possible and divergent micro-scenarios were identified during the workshop, which vary according to the degree of control of the holobiont and according to the relationship with microbial biodiversity. It was chosen to work on managing the holobiont by modulating the biodiversity of the existing microbiome in a systemic, integrative and historical strategy (management of soil diversity based on indicators). Another management strategy consisting in managing (in the sense of designing) the holobiont by reconfiguring the microbiome with inoculations of microorganisms (commercial inputs and inoculum) and by modifying the host could have been considered but it was seen as too close to the approach of the third microscenario.

The animal pest management strategy comprises of "Influencing the dynamics of pest populations" through the modification of pest microbiota (in particular by inoculation of microorganisms to act on the holobiont of pests such as pathogens or microorganisms disrupting reproduction or nutrition, or through agricultural practices favouring these microorganisms) and also by using microorganisms synthesising volatile organic compounds that can disrupt pest perception or recognition (confusion strategies).

In this micro-scenario, the weed management strategy combines strategies to "Limiting weed development" and "Mobilising weed services". In the first case, we seek to strengthen the microbiota of a cultivated plant (by promoting the plant's establishment, germination and acquisition of nutrients) in order to make it more competitive with weeds. Furthermore, we can also exploit the effects of allelopathy linked to soil microorganisms. In the second case, through weed plant cover we can promote the strengthening of a reservoir of microbial biodiversity which is beneficial for the cultivated plant, especially in the face of biotic or abiotic disturbances. In particular, the biodiversity and ecosystem services of the microbiome are managed through crop rotations.

Finally, the disease management strategy directly employs the capacities of the holobiont and the microbiome to manage pathogens, corresponding to the hypothesis on "Managing disease cycles". It exploits the competition within the microbiome between pathogens and other microorganisms that share the same microbiome niches in order to protect the plant by preventing diseases from taking hold. In addition, plant-microorganism interactions can change plant defence levels and, by strengthening interactions with microorganisms (direct or seed inoculation, selection of seed/microbiota combinations, plant defence stimulators) can provide a better response to disease attacks.

The crop protection strategy in this micro-scenario could mobilise (i) agricultural equipment to control weeds and pests via the cropping system to manage the holobiont, and (ii) agricultural equipment (robots and sprayers) for targeted inoculation with microorganisms. This strategy requires the availability of **diagnostic tools for the microbiome** of the field (and microbiomes in general) such as shared **proxy detection instruments** in order to detect the presence of symptoms on plants but also to anticipate disease development at the microbial level by monitoring the soil's microbial diversity. These tools for diagnosing microorganisms present in the soil microbiome involve a more systemic rationale for cropping systems. This involves anticipating the presence of microorganisms which are favourable or unfavourable to the crop successions that we can envisage, based on knowledge of the state and history of the soil microbiome, the cropping system and soil fertility. By learning to master these new tools within groups of farmers, they collectively constitute knowledge to interpret the data and design *in situ* management strategies for the holobiont.

Micro-scenario based on strengthening plant immunity

This paragraph presents the principles of a micro-scenario based on strengthening the immunity of cropped plants both directly and indirectly, which is titled **'Dynamic management of the immunity of cropped plants assisted by digital technologies and robotics'**. The principles and hypotheses are summarised in Table 2-14.

In this micro-scenario, it seems *a priori* impossible to "eliminate all animal **pests"** or to "isolate crops from pests" to strengthen plant immunity. The strategy involving "**acting on pest dynamics"** was chosen as a priority, raising the question of thresholds for plant immunity and the number of pests when they become established. Indeed, if the initial number of pests is too high, plants can lose their immunity if the immunity threshold is exceeded or if pests bypass plant resistance. To better manage, treat or strengthen plant immunity, it is essential to be able to **control the initial size of the pest population through prophylactic actions**, in particular agroecological crop protection strategies, or use of **biocontrol** or **allelochemistry** (*e.g.*, the emission of volatile organic compounds (VOCs) which can even create olfactory landscapes for which the scale will be specified) whose processes are still poorly understood. Plant immunity could also be **strengthened indirectly** by seeking to create a barrier against pests and isolate crops from pests, for example, by **controlling their population dynamics** or by **creating landscapes that are unfavourable to pest establishment**.

Table 2-14: Morphological table for the micro-scenario based on strengthening plant immunity

	Hypotheses of change in 2050			
Crop protection based on…	Diversification of landscapes	Management of the holobiont	Strengthening plant immunity	
Management strategy for animal pests	Eliminating pests (control)	Isolating crops from pests (control)	Influencing the dynamics of pest populations (prophylaxis + control)	
Management strategy for weeds	Limiting weeds (control)	Limiting weed development (prophylaxis + control)	Mobilising weed services (prophylaxis + services)	
Management strategy for diseases	No control (prophylaxis)	Isolating crops from the environment (control)	Managing disease cycles (prophylaxis + control)	Strengthening plant immunity against diseases (prophylaxis + control)

As with pests, the strategy of "**eliminating weeds"** does not seem feasible for the strengthening of plant immunity. The strategy of "**mobilising weed services"** was selected as a priority, in particular (i) by setting up cropping systems including multi-species cover crops, (ii) using weed cover crops as **intermediate covers**, for the production of **fodder** or **as refuges for beneficial insects**, (iii) using weed seeds as **food for insects and birds**, (iv) by **promoting positive interactions between cropped plants and weeds**, in particular through allelopathy or even (v) by **introducing microbial antagonists on weeds** to serve as the primary inoculum and **combat pathogens** (a process that is still poorly understood). The strategy of "**limiting weed development**" was also chosen. Its implementation would consist of (i) promoting the negative interactions (still poorly understood) of cropped plants on weeds through **allelopathy** and **allelochemistry** (for example, the production of root exudates containing molecules toxic to weeds, similar to the effects of VOC emissions on insect pests, see above) and (ii) to **preserve the competitive advantage of cropped plants** for their access to resources (for example, light and nutrients). The latter two principles, with different purposes (mobilisation versus limitation), require a paradigm shift and an **acceptance that we live with weeds** that are endogenous to cultivated fields.

The four strategies suggested for **disease management** seem compatible with strengthening plant immunity, with a slight preference for "**strengthening the capacity of plants to combat diseases"**, in particular by seeking to avoid the presence of inocula in crops, achieved by **preventing the sexual reproduction of pathogens** (on which knowledge is still scarce compared to that which has been acquired on the asexual phases of the cycle). Strengthening the immune capacities of plants to combat diseases (and also against insect pests and weeds) could be carried out by (i) **classical breeding** both on phenotypes or marker assisted selection (genomic selection) to integrate new resistance sources in new varieties, (ii) **genetic editing of cropped plants** which would allow them to produce toxins from one or more of their genes using the whole range of genetic techniques (*e.g.*, Crispr and crosses), (iii) **external stimulation** (plant defence stimulators and bio-stimulants) or **stimulating varietal resistance** using classical breeding varietal improvement techniques.

Agricultural equipment and digital technologies, without having a direct link with plant immunity, contribute to strengthening it directly, for example, by providing plant defence stimulators or biocontrol products, or indirectly, by acting on the biotic and abiotic environment of cropped plants. Precision agricultural equipment and digital technologies will be needed to (i) **monitor and diagnose the presence of pests and the immunity status of plants**, using various sensors (on board or on the ground) accurately collecting a large number of heterogeneous data (for example, the physiological status of plants, soil characteristics and meteorological conditions) and (ii) act quickly and locally, for example with targeted inputs of plant defence stimulators using swarms of small robots that can move continuously in micro-plots (instead of using a limited number of large agricultural equipment). Beyond their **positive aspects**, these three trends in agricultural equipment can also have **negative impacts** on plant health, the environment and on animal and human health, which remain to be assessed (*e.g.*, the emission of **nanoparticles which are toxic** for cropped plants, energy consumption linked to the acquisition of large quantities of data and an unfavourable carbon balance).

2.6.5. Surveillance for chemical pesticide-free crop protection strategies in 2050

As we have seen earlier (paragraph 2.5.7), the epidemiological surveillance systems currently used in Europe are essentially focused on curative actions, relying in particular on the use of chemical pesticides. However, establishing pesticide-free agricultural systems requires the redesign of agricultural systems, developing prophylactic actions which anticipate the potential development of pests and take advantage of natural regulations.

In order to meet the challenges of future pesticide-free agricultural systems, it is therefore essential to redesign epidemiological surveillance systems, ensuring they are focused on prophylaxis (Jacquet *et al.*, 2022). This requires decentring pest epidemiological surveillance systems, directing them towards anticipating the risks linked to pests through the integration of a more global analysis of agroecosystems (workshop, April 2021). This involves broadening the framework of epidemiological surveillance through the monitoring of new subjects, expanding surveillance spatio-temporal scales and using new tools, particularly digital ones (Jacquet *et al.*, 2022; Morris *et al.*, 2021). The term ‘epidemiological surveillance’ would therefore no longer be appropriate. Rather, the system established would be a follow-up, surveillance and supervision system (monitoring) (workshop, April 2021; Reboud *et al.*, 2022).

Following the conclusion of the workshops we held, here we examine what could characterise such a monitoring and surveillance system. Then we will present the first hypothesis of a rupture which has been developed. Finally, we will present the monitoring and surveillance issues for three crop protection strategies in 2050. These strategies are in line with our finalised crop protection strategies.

2.6.5.1. Characteristics of a new monitoring system for pesticide-free agriculture

Surveillance of new subjects

Expanding observations to take into account pest life cycles

Current epidemiological surveillance is based on the observation of pests already present in agricultural plots (Jacquet *et al.*, 2022). However, pesticide-free agriculture requires the anticipation of risks and the future occurrence of pests in order to implement prophylactic measures. Once pests are present, it is too late to apply solutions other than curative actions (workshop, April 2021). The monitoring actions that need to be implemented vary depending on the type of pest (pathogens, pests or weeds), and require a broadening of observation efforts in order to take into account the history of pest life cycles.

During their life cycles, pests develop and move in different environments and at different scales beyond cultivated plots (Morris *et al.*, 2021; Deguine *et al.*, 2023). These can be semi-natural habitats, soil, air or water (Morris *et al.*, 2021; Petit *et al.*, 2012; workshop, February 2021).

Indeed, insect pests and their natural enemies develop and move beyond cultivated plots, with non-agricultural habitats (in other words semi-natural habitats) providing them with the resources necessary for their survival (Rusch *et al.*, 2016). A large number of crop plant pathogens are present and thrive in non-agricultural habitats and cultivated soils (Morris *et al.*, 2009). Non-agricultural habitats also exert selection pressure on pathogens which will therefore develop more or less virulent traits (Morris *et al.*, 2009). Finally, weed seeds are located in the soil and are dispersed between plots and between cultivated plots and semi-natural habitats (Petit *et al.*, 2012).

In order to anticipate the risks linked to pests and their possible development within agricultural plots, it therefore seems necessary to consider all the environments (including vectors) involved in pest life cycles. This means monitoring beyond cultivated plots, *i.e.* non-agricultural reservoirs, semi-natural habitats, soil, air and water (Morris *et al.*, 2009; Morris *et al.*, 2021; Jacquet *et al.*, 2022).

New indicators to indirectly anticipate pests

Using indirect observations, new indicators can provide for the early anticipation of pests. These observable elements are correlated with pest presence. Their detection would make it possible to better anticipate risks (interview with Morris and Soubeyran, 2021). For example, the fine-tuned detection of pheromones would make it possible to detect insect pests early (see the PheroSensor research project, PPR CPA – 2020/2026).

Expanding surveillance's spatio-temporal scales

Currently, epidemiological surveillance is conducted across limited spatial and temporal scales. It focuses on the scale of the cultivated plot and anticipates in the short-term (Jacquet *et al.*, 2022). However, pest movements take place over large scales and in the long term, depending in particular on each pest's life cycle (Morris *et al.*, 2021; Petit *et al.*, 2012). Plant pathogens and insects spread over long distances via natural processes such as the flow of surface water and the circulation of air masses (Morris *et al.*, 2021). Weeds also spread over large scales and in the long term (Petit *et al.*, 2012), for example via roads and motor vehicles (von der Lippe and Kowarik, 2007) and water courses (workshop, February 2021).

Observing the spread of pathogens over long distances through water or air can help anticipate when and where an invasion will occur in a new region (Morris *et al.*, 2021). For example, a model evaluating the spread of soybean rust made it possible to predict the movement of the disease from South America to North America (Isard *et al.*, 2005).

Organising the long-term monitoring of pests at large spatial scales would therefore make it possible to better anticipate the invasion risk of these pests. Data from surveillance could be linked to other environmental variables, such as land use, in order to create scenarios for the spread of pests over long distances and to implement anticipatory actions (Morris *et al.*, 2021).

This monitoring would require the collection, management and interpretation of a significant amount of data, which may be possible through the use of digital tools and modelling (Morris *et al.*, 2021; Reboud *et al.*, 2022).

Tools for expanded surveillance

Digital tools to increase data acquisition

Digital tools make it possible to increase data acquisition and monitor many different subjects in order to characterise the state of a plant and its environment (Reboud *et al.*, 2022). For example, there are many different sensors that can detect highly diverse information (pH, temperature, plant wilting, optical sensors, etc.) (Bellon-Maurel and Huyghe, 2017). These sensors can be fixed, used alone or in a network, or be mobile, attached to an animal or embedded in agricultural machines and aerial vehicles (drones, planes and satellites) (ibid.). These sensors connect wirelessly and the development of the Internet of Things, low-frequency and cellular network infrastructure allows sensors to be connected in a network (Reboud *et al.*, 2022). These sensor networks can result in mapped information (Fuentes-Peñailillo *et al.*, 2021).

New technologies could be further developed for agricultural surveillance. The use of satellites and text mining would enable large-scale observation for the early detection of information; drones and robots with sensors would increase proximity observations tenfold (interview with Morris and Soubeyran, 2021).

Human observation remains necessary to acquire field data. Digital tools can then facilitate data collection. For example, farmers can us smartphones to collect observations and share them within an observation network using crowdsourcing approaches (Bellon-Maurel and Huyghe, 2017). So, digital tools can also be central to data collection through participatory, citizen or collaborative science approaches (Reboud *et al.*, 2022).

Tools for managing mass data

The data acquired requires significant management in order to be analysed and interpreted.

First, if these data are to be useful, they must be shared and easily accessible in order to anticipate risks over a large scale (interview with Morris and Soubeyran, 2021; Bellon-Maurel and Huyghe, 2017). This raises the question of the interoperability of mass data arriving from different sources and of different natures (Bournigal, 2014). The integration of heterogeneous data can be achieved thanks to the scientific discipline of ontology (Bournigal, 2014; Morris *et al.*, 2021). Access to data can be provided through a web portal presenting a catalogue of data and services, with standard information (Morris *et al.*, 2021).

Agricultural databases and portals accessible to farmers already exist in Europe. For example, in Denmark the LandbrugsInfo database linked to the 'landmand.dk' portal is used to develop decision support tools and to inform farmers. This is also the case for the Data Hub DKE data exchange platform in Germany (Bournigal, 2016).

The creation of data platforms requires prior reflection on data ownership and governance (Bellon-Maurel and Huyghe, 2017).

Models for interpreting data

Models make it possible to analyse and interpret data and then issue recommendations (Bournigal, 2016). Several model types exist:

- Mechanistic models which provide a qualitative understanding of the system being studied but require detailed knowledge of the processes (Reboud *et al.*, 2022);
- Statistical approaches that can process mass data, such as deep learning and machine learning, though these still have limits (Reboud *et al.*, 2022).

It would be interesting to develop hybrid models, mixing mass data and qualitative knowledge (interview with Morris and Soubeyran, 2021). Such models have already been used to identify risk factors for the spread of pathogens (Martinetti and Soubeyrand, 2019).

Co-modelling is also an interesting tool for understanding complex systems (Morris *et al.*, 2021). Co-modelling brings together technical and scientific experts with stakeholders (consumers, citizens, producers, etc.). This method improves the sharing and integration of knowledge from different actors and makes it possible to produce knowledge on stakeholder behaviours, perceptions and reactions (ibid.).

The agricultural practices introduced, prophylactic measures, rotation, varietal choice, etc. must be considered in models in order to weight the recommendations issued according to practices (Reboud *et al.*, 2017).

Decision support tools

Decision support tools will provide indications based on all the information provided by data and models in order to make decisions on the ground.

As surveillance for chemical pesticide-free agriculture extends beyond agricultural systems, decision support tools must be aimed at local stakeholders in addition to farmers (Reboud *et al.*, 2022).

Decision support tools must involve decision makers and adapt to each situation (interview with Morris and Soubeyran, 2021).

2.6.5.2. A tentative hypothesis for all-encompassing surveillance: Supervision of environmental health and its regulations, on a large scale and over the long term, as a component of prophylaxis

A hypothesis for a rupture in surveillance was constructed following an interview with two experts (Cindy Morris and Samuel Soubeyrand) and during subsequent work in a thematic expert group in April 2021, but was not subsequently retained.

Supervision of environmental health and its regulations

The title of this hypothesis is: **Supervision of environmental health and its regulations, on a large scale and over the long term, as a component of prophylaxis**.

To broaden epidemiological surveillance, the very term epidemiological surveillance has been called into question, and discarded in favour of the expression ‘Supervision of environmental health and its regulations’. This supervision would provide an analysis of the operational state of the agroecosystem and its multiple functions. This supervision checks both the general quality of the system’s regulations (so that these regulations are those expected to bring the system to the desired state) and, more specifically, the regulations which could fail and lead to a crisis situation. The goal is to have a robust and resilient system.

For this, several things seem necessary:

- A maximisation of levers for observation, using a combination of large-scale general tools (remote sensing, satellites and text mining) and local observations (human or technological);
- An expansion of observations which are as much interested in plant health (indirect observations) as in all ecosystem services and their quality (observation of pests and beneficials, cultivated and non-cultivated hosts, the abiotic environment, biological regulations or regulatory potential, and even the capacity of the system to absorb an epidemic);
- Observation of actors’ practices (in a broad sense) and their impacts;
- Pooling and sharing of data;
- Appropriation of data by farmers and other local stakeholders (land managers);
- Modelling of biological mechanisms making anticipation possible at different time horizons (different types of possible and complementary models);
- Collective organisation of actions (at a territorial scale);
- Management of collective influences (in particular social networks) with dissemination and regulation of modelling results;

- Environmental health seen as a common good and financed as such;
- A clear linkage of prophylactic actions and environmental health supervision;
- The development of a new employment sector making it possible to establish the link between this supervision and the prophylactic practices implemented.

The limits of this hypothesis

This hypothesis amounts to having to monitor everything all of the time, and to be interested in all ecosystem services and regulations. Such hypotheses require the collection and processing of a very large quantity of data and risks having a significant energy cost and environmental impact. It also requires the acquisition of a significant level of knowledge and understanding on the development of pests making it possible for this information to be processed. This hypothesis seems difficult to achieve by 2050. In addition, the link to specific prophylactic measures remains difficult to establish in the absence of a hypothesis on the cropping system.

It therefore seemed preferable to us to start from the crop protection systems already developed and to address the issue of monitoring and surveillance in the three crop protection strategies for pesticide-free agriculture in 2050.

2.6.5.3. Monitoring and surveillance in the three crop protection strategies in 2050

For each crop protection strategy micro-scenario in 2050, the project team and expert groups constructed a specific monitoring and surveillance hypothesis (see Table 2-15). Monitoring is necessary to implement effective crop protection; it makes it possible to anticipate the development of pests through appropriate prophylactic actions.

Monitoring is focused on specific subjects that need to be observed and understood in order to anticipate the development of pests and maintain the proper functioning of the crop protection strategy. Each monitoring effort is conducted according to specific methods which concern the subject being monitored, monitoring scale, monitoring indicators, monitoring and data processing methods and, finally, the use of monitoring results for crop protection.

This means the subjects to be monitored vary depending on the crop protection strategy. These specific subjects are the state of microbial diversity (particularly soil and air) and the health of the holobiont in the first case, the state of biological regulations at the landscape scale in the second case, and the health state of the plant and its environment in the third case.

Table 2-15: The monitoring hypotheses in the three crop protection micro-scenarios

Crop protection micro-scenario	*Managing the holobiont of cultivated plants*	*Designing complex and diverse landscapes*	*Strengthening the immunity of cultivated plants*
Monitoring and surveillance hypothesis	**Monitoring of the holobiont, microbial biodiversity and microbiota**	**Monitoring of biological regulations and biodiversity at the landscape scale and anticipating their effects on crops**	**Monitoring the health of the plant (immune and physiological state) and its environment**
Purpose of monitoring	*Microorganisms and their relationships with the cultivated plant (microbiota including soil)* - Characterising reservoirs of microbial diversity and their dynamics over time - Characterising the functions of the microbiota ('core' microbiota) - Characterising the adaptability of the holobiont (ability to recruit microorganisms)	*Biological regulations and their effects on crops and biodiversity at the landscape scale* - Evaluating and explaining the effects of interactions between pest population dynamics, biodiversity, practices and climatic context on crops	*Immune and physiological state of cultivated plants and their biotic and abiotic environment* - Characterising the immune and physiological state of cultivated plants - Characterising the state of the biotic and abiotic environments of cultivated plants
Scale	**Plot**	**Landscape**/Plot	**Plant**/Plot/Landscape
Monitoring indicators	- Indicators of the **functions** carried out by microbiota, to identify situations where there is an absence of microorganisms from the 'core' microbiota crucial for plant defences - Markers characterising **healthy or sick plants** (dysbiosis situations) - Markers for **pathogen presence** (bacteria and fungi)	- Indicators of **effects on crop yields** (damage and/or crop losses with redefined damage thresholds) and on **biodiversity** (other living organisms not harmful to crops) - Indicators explaining these effects: • Indicators relating to pest population dynamics • Indicators relating to biodiversity (beneficials and agrobiodiversity) • Indicators relating to agricultural practices, composition and configuration of the crop mosaic • Indicators relating to the climatic context	- **Molecular** indicators of the immune and physiological state of cultivated plants (concentration of certain pigments or metabolites, etc.) - **Optical** indicators: **biological** indicators (characterisation of seed, aerial and soil microbiota; growth and senescence of cultivated plants; presence of pests, pathogens or weeds) and **agronomic** indicators (crop successions and cropping practices, weed state, varieties, rootstock) - **Physico-chemical** indicators of the state of the **aerial** and **soil abiotic environment** of cultivated plants (weather conditions, soil characteristics, VOC contents, etc.)

Table 2-15 (continued): The monitoring hypotheses in the three crop protection micro-scenarios

Crop protection micro-scenario	*Managing the holobiont of cultivated plants*	*Designing complex and diverse landscapes*	*Strengthening the immunity of cultivated plants*
Monitoring and surveillance hypothesis	**Monitoring of the holobiont, microbial biodiversity and microbiota**	**Monitoring of biological regulations and biodiversity at the landscape scale and anticipating their effects on crops**	**Monitoring the health of the plant (immune and physiological state) and its environment**
Monitoring and information processing methods	*Soil microbiota diagnostic tools:* - **Metagenomic** tools through **sequencing of microorganisms** to identify the diversity of pathogens and commensal or mutualistic microorganisms - **Automated analysis** based on **interpretation algorithms** to characterise the functions of microorganisms within the microbiota - Tools to characterise the **presence of mycorrhizae** in soils - **Shared proximity detection** tools to detect the presence of symptoms in plants *Monitoring actors:* - **Participatory monitoring** by farmers' groups	*Diagnostic tools for biological regulations and their effects:* - **Automated monitoring with sensors** (high temporal and spatial resolution) **combined with rapid monitoring** (less precise, more qualitative observations) - **Inter- and intra-annual** monitoring of relationships between indicators - Models for **mapping the spatio-temporal diffusion** of pests *Monitoring actors:* - **Participatory monitoring** by landscape stakeholders (citizens, agricultural supply chain stakeholders, non-agricultural stakeholders); action funders	*Diagnostic tools for the immune and physiological state of cultivated plants:* - **Genomic and molecular analyses** (destructive methods) of cultivated plants to quantify molecular indicators - **Electronic noses** under development to quantify olfactory indicators - **Sentinel plants** (trap plants) established in the plot or landscape - **Proxidetection** (*e.g.* ground sensors, drones, etc.) at the local scale (plant and its immediate environment) or remote sensing (*e.g.* drones, satellites, etc.) at large spatial scales to quantify optical indicators *Monitoring actors:* **Collective organisation and management** of observation tools, digital information processing technologies, data and results produced by monitoring
Mobilisation of monitoring for crop protection	- **Systemic and historical** approach: thinking about crop successions based on knowledge of (1) the state and history of the soil microbiome, (2) the cropping system and (3) indicators of soil fertility in order to select microorganisms favourable to crops (*e.g.* symbioses) - **Collective learning approaches** for new tools within groups of farmers to build knowledge for the interpretation of data and design of *in situ* holobiont management strategies	- **Systemic and adaptive** approach: learning about the interactions and transformations operating within landscapes, **capitalising year on year** to transform experience into decision rules - **Sharing of risks** and benefits at the landscape scale; accountability of landscape stakeholders for the effects of their actions - **Network for the exchange** of experiences and knowledge within and between landscapes	- Thinking about successions and cropping practices based on past and present data on the immune and physiological state of cultivated plants, pest presence and the state of the biotic and abiotic environment of cultivated plants - **Training and collective learning systems for farmers and other agriculture-linked territorial stakeholders** for the acquisition/processing/use of data and results, so as to **enable them to share** advice, data and agricultural equipment to assess the immune status of plants and intervene preventively rather than curatively

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Section 2.1

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Section 2.5

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European Chemical Pesticide-Free Agriculture in 2050

Chapter 3

Changes in the other dimensions of the food system in 2050

Table of contents

Introduction

Achieving chemical pesticide-free agriculture by 2050 implies transforming the various components of food systems, beyond cropping systems. This is why as part of this foresight study, in addition to building micro-scenarios of cropping systems without chemical pesticides, we also looked at other components of the food system, and studied how their changes could shape chemical pesticide-free agriculture in 2050. We studied European farm structures, food value chains, public policies, diets, agricultural equipment and digital technologies, as well as Agricultural Knowledge and Innovation Systems (AKIS).

For each of these components, a retrospective analysis was conducted, identifying major trends, weak signals and potential ruptures through literature reviews and interviews. Based on these analyses, several expert groups developed alternative hypotheses describing the possible changes of these components by 2050.

This chapter present the outcomes of this work, on farm structures (Section 3.1), food value chains (Section 3.2), public policies (Section 3.3), and diets, agricultural equipment and digital technologies, and education and AKIS (Section 3.4).

3.1. Farm structures in Europe: Past trends and future changes in 2050

Authors: Jeanne-Alix Berne, Olivier Mora

Table of contents

Introduction

The structure of farms in Europe is one of the components of the system addressed by the ‘Chemical Pesticide-free Agriculture in Europe in 2050’ foresight study. Indeed, the type of farm structures, their organisation and the way in which they fit into value chains are elements that will determine European agriculture in 2050.

The work described in this Section is based on several sources: analyses of Eurostat data (from surveys on the structures of agricultural holdings conducted by each European Union Member State), interviews with experts (Laurent Piet, INRAE-SMART, and Alfons Balmann, Leibniz Institute of Agricultural Development in Transition Economies (IAMO)), a literature review, and workshops with the European expert committee and the foresight project team.

According to experts, no link can be established easily between farm structures and pesticide use. This is why it was decided that we would explore the range of possible futures of farm structures in 2050 in Europe in general. These farm structures will have to achieve the transition towards pesticide-free agriculture by 2050. During the phase of scenario building (see Section 4.1), we will explore through consistent narratives how these farm structures will accomplish a transition towards pesticide-free agriculture in 2050 (financial capacity for investment and organisational innovation, key actors, service and advisory structures, etc.).

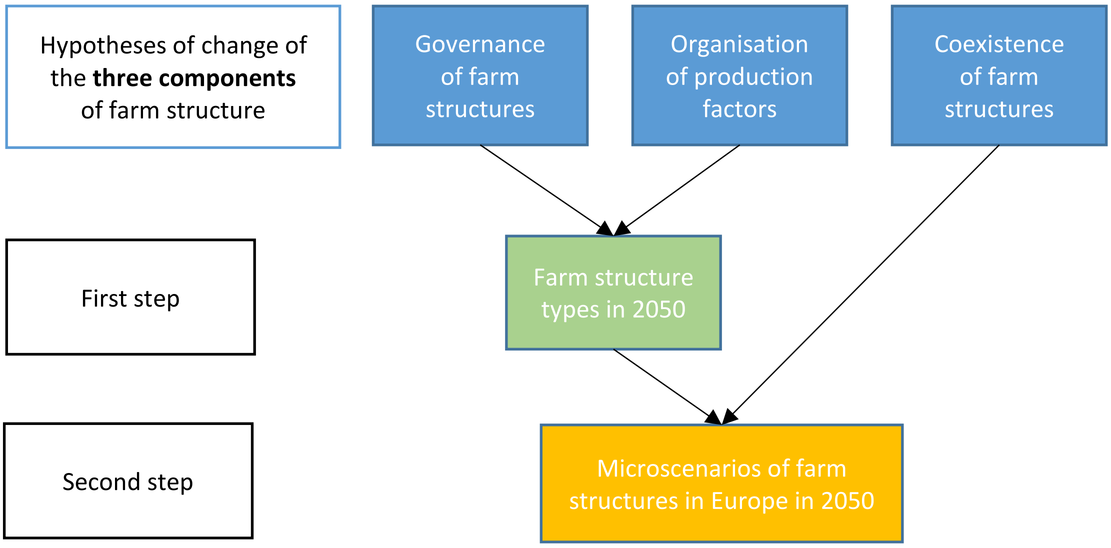
To build micro-scenarios on farm structures in 2050 in Europe, our framework was inspired by the methodological framework of Chapter 10 of the Agrimonde-Terra foresight entitled ‘Farm Structures: Current Shaping and Future Farms’ (Donnars *et al.*, 2018).

According to Eurostat (2018) "*an agricultural holding or holding or farm is a single unit, both technically and economically, operating under a single management and which undertakes economic activities in agriculture […] either as its primary or secondary activity*". Donnars *et al.* (2018) characterise farm structures by the combination of production factors (labour, land and capital) and their integration into social and economic dynamics. This is why we defined the governance of agricultural structures and the organisation of production factors (labour, land and capital) as components for imagining types of structures in 2050. Because farm structures are highly diverse in Europe (Eurostat, 2021a), we considered a third component relating to the coexistence of differentiated structures in order to describe the landscape of agricultural structures in Europe in 2050.

We have therefore explored three components that define farm structures: the coexistence of different structures in Europe, the governance of structures and the organisation of production factors. For each of these components, we conducted a retrospective analysis of major trends, weak signals and possible ruptures. Based on this, various hypotheses of change in 2050 were developed. The construction of microscenarios in 2050 was conducted in two stages (see Figure 3-1).

The combination of the governance of structures and organisation of production factors made it possible to create first hypotheses on the types of farm structures that would exist in 2050. In a second step, by building assumptions on the coexistence of different structures, we have defined the way in which these different types of agricultural structures would coexist in Europe in 2050. Doing so, the hypotheses in 2050 of the first two components, governance of structures and organisation of production factors, were connected to the hypotheses of coexistence of structures in 2050, in order to elaborate microscenarios describing farm structures in Europe in 2050.

Figure 3-1: Steps for building microscenarios for farm structures in Europe in 2050



3.1.1. Retrospective analysis and hypotheses of change for the coexistence of different farm structures, the governance of farm structures and the organization of production factors

3.1.1.1. The coexistence of farm structures in Europe

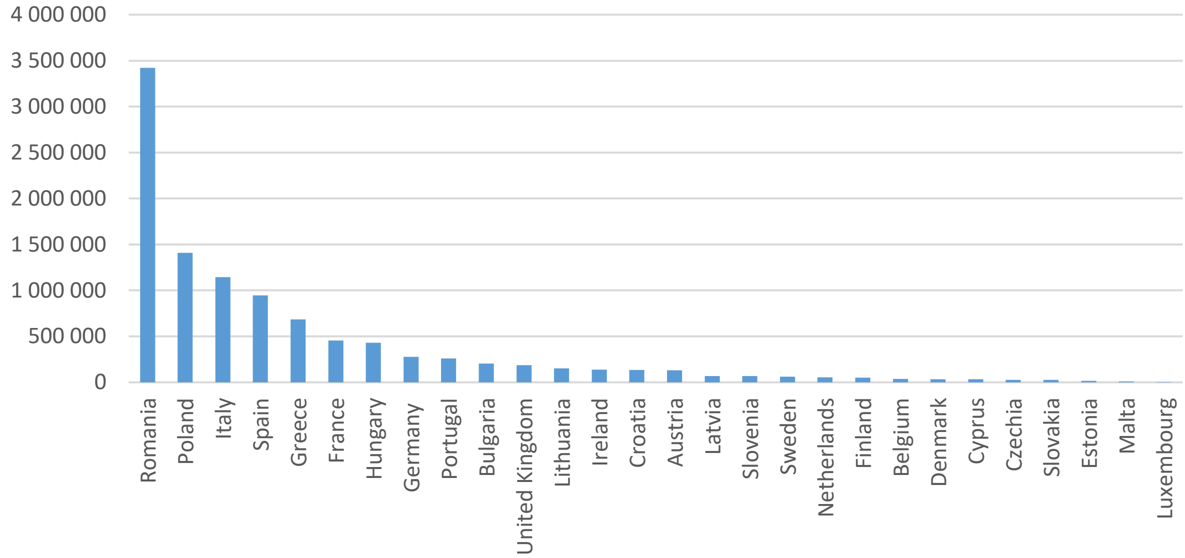
Three factors characterise recent changes in farm structures in Europe: a reduction in the number of farms, an increase in the size of farms and an increased specialisation (Neuenfeldt *et al.*, 2019). These dynamics led to a situation with increasingly dual and specialised farms despite a diversity of farms in Europe.

Retrospective analysis: Dynamics and diversity of European farm structures, a reduction in the number of European farms and an increase in their size

A highly variable number of farms between European Member States

In 2016, there were 10.5 million farms in the European Union, with one third located in Romania (Eurostat, 2021a). Romania therefore has a significant influence on European averages. Figure 3-2 shows the number of farms by Member State. Romania, Poland, Italy, Spain and Greece are the Member States with the largest number of farms.

Figure 3-2: Number of farms per country in Europe, 2016 (Source: Eurostat, processed by authors)



Farm numbers in sharp decline

On a European scale, the number of farms has been falling sharply for several decades (Figures 3-3 and 3-4). In Figure 3-3, we can see that the fall in the number of farms has accelerated sharply since the 2000s, particularly with the entry of new Member States from Central and Eastern Europe into the European Union (EU).

Indeed, Piet (2018) points out that these strong structural changes are greater in Central and Eastern Europe Member States than in Western European countries. Over the 2006-2016 period, the number of farms in Europe has decreased from nearly 14.5 million to less than 10.5 million (i.e., almost a 29% decrease). Daniłowska (2018) confirmed this trend using data from 2008 to 2016, with an average 24% decrease in the number of farms in Europe (Figure 3-5).

Figure 3-3: Evolution in the number of farms in the European Union since 1950 (Source: Hansen, 2020, Eurostat data)

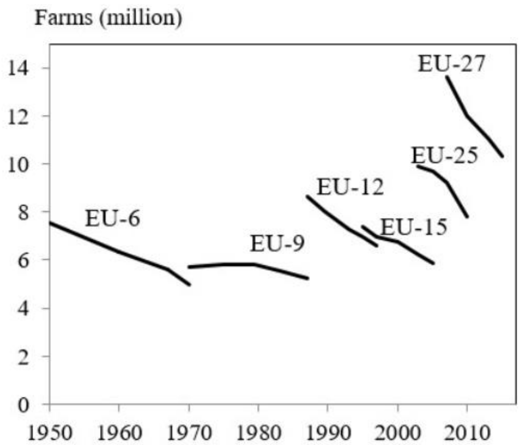


Figure 3-4: Evolution in the number of farms in the European Union (except Croatia) between 2005 and 2016 (Source: Eurostat, processed by authors)

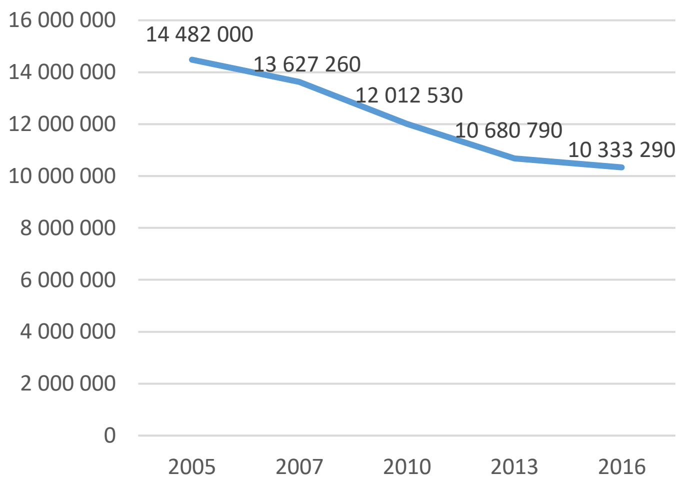
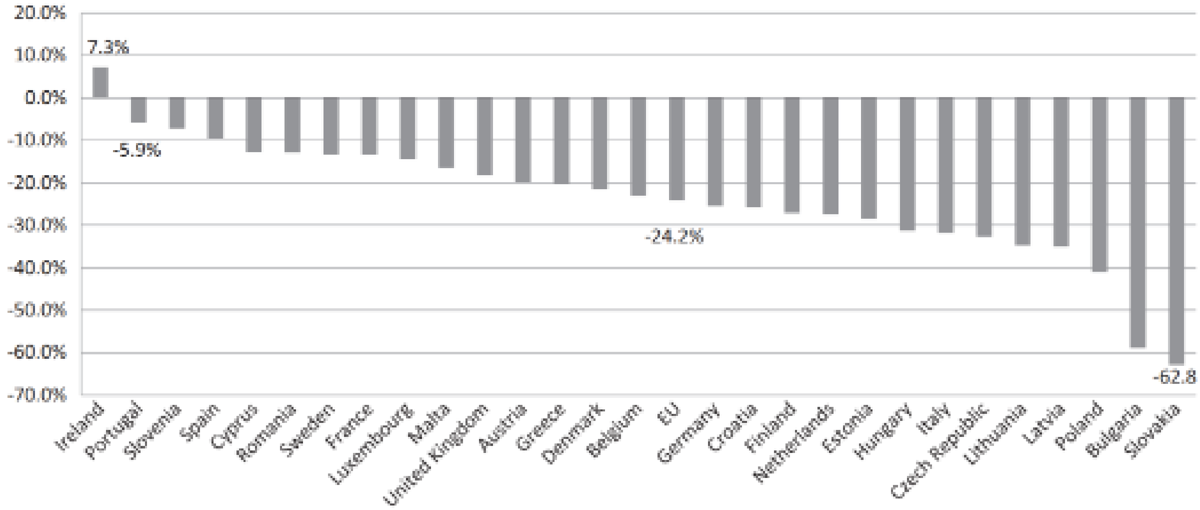


Figure 3-5: Change in the number of farms (in %) in Member States between 2008 and 2016 (Source: Daniłowska, 2018)



As shown by Daniłowska (2018), the reduction in the number of farm concerns all Member States (with the exception of Ireland) but occurs at very different rates in each country, ranging from a reduction of 6% in Portugal to a reduction of 63% in Slovakia between 2008 and 2016. The greatest falls in the number of farms over the period principally concerns countries in Central and Eastern Europe, with a reduction of more than 30% in Slovakia, Bulgaria, Poland, Latvia, Lithuania, Czech Republic and Hungary. Some Western and Northern European countries have also seen a reduction in their farm numbers that is higher than the European average, including Italy, Germany, Finland and the Netherlands.

Increasingly large farms, reflecting a concentration of land

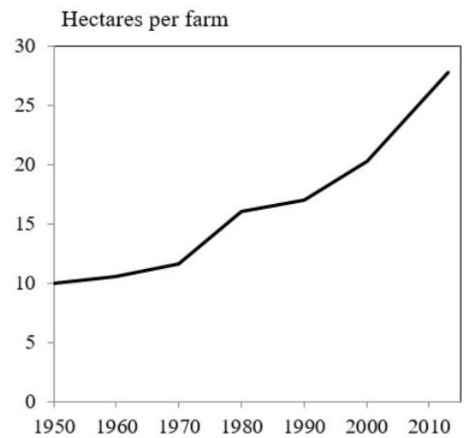
• Is size an appropriate indicator for describing farm structures?

Size, indicating the area used by a farm, can be a criterion for defining farms (Dufumier and Bergeret, 2002; Piet, 2018). Nevertheless, the area used by farms is a controversial indicator. Indeed, the surface area of a farm also depends on the type of farming involved, the farm's economic situation and the pedoclimatic zone in which it is located (European Commission, 2013a; Neuenfeldt *et al.*, 2019; Donnars *et al.*, 2018). In this retrospective analysis, changes in farm size makes can highlight major trends in agricultural structures, such as the enlargement of farms and the concentration of land as well as the strong duality of farms in European Member States.

• Increasingly large farms

Figure 3-6 shows a sharp increase in the average farm size in Europe since the 1950s.

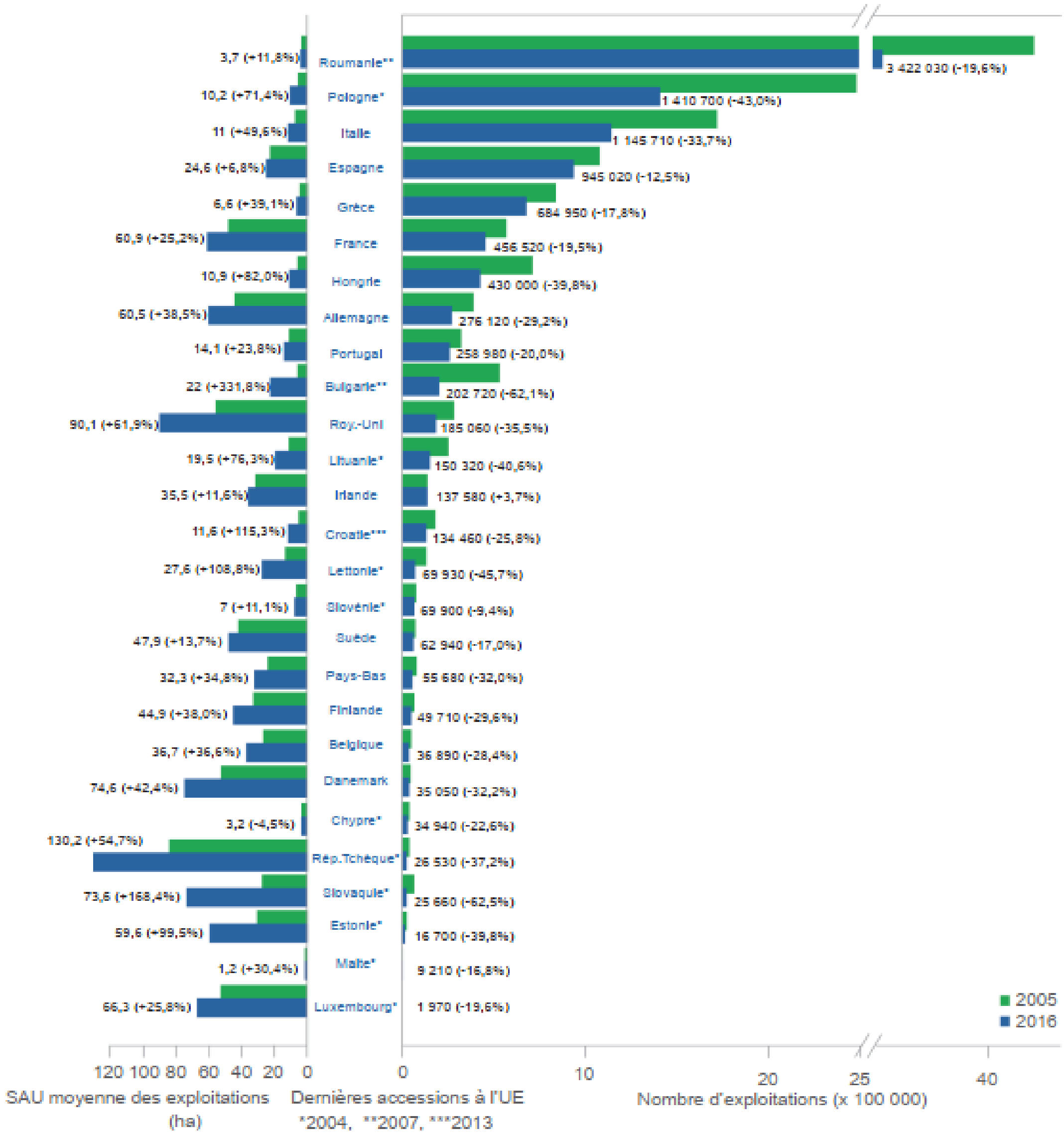
Figure 3-6: Increase in the average size of farms in Europe (Source: Hansen, 2020; FAO data 2013 and 2016)



Indeed, in all Member States the reduction in the number of farms correspond to an increase in the average area cultivated per farm (Figure 3-7). On a EU average, between 2005 and 2010, the number of farms fell by 3.7% per year, while the average farm size grew by 3.8% (Neuenfeldt *et al.*, 2019). This reflects a phenomenon of high **land concentration** in Europe in recent decades (Popescu, 2013; Daniłowska, 2018; Schuh *et al.*, 2019).

Figure 3-7: Evolution in the number of farms (right side) and the average utilised agricultural area per Member State (left side) between 2005 and 2016 (Source: Détang-Dessendre et Guyomard, 2023, Eurostat data).

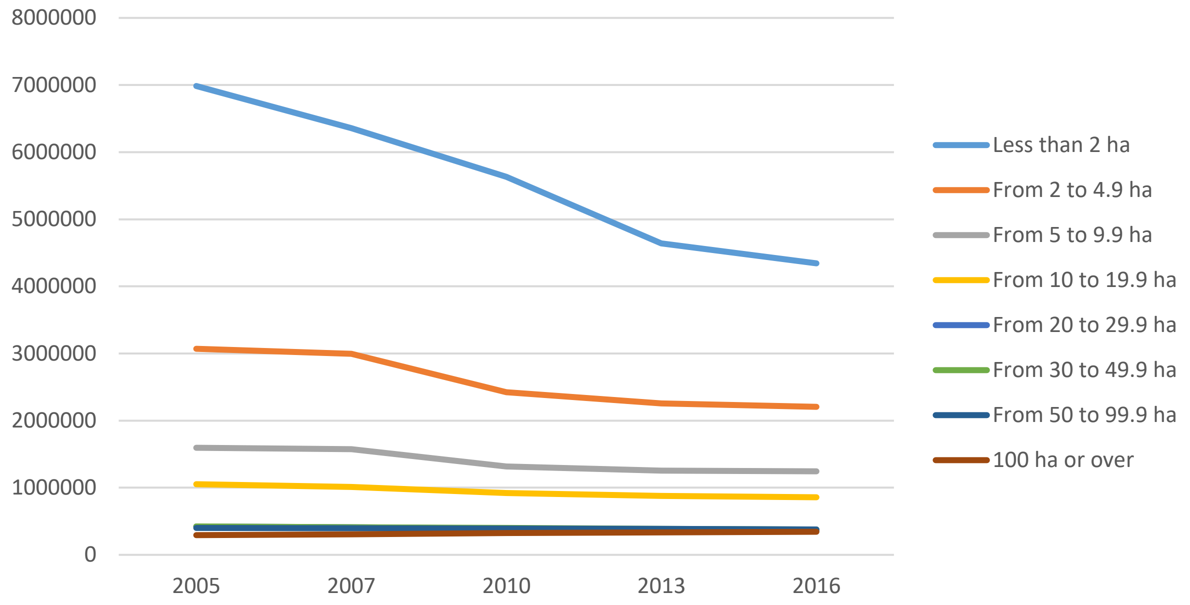
One, two or three stars linked to countries's names refer to the accession date in the European Union, respectively 2004, 2007 and 2013.



• The evolution in average farm size: A concentration of land

The **concentration of land** has occurred in favour of the largest farms (more than 100 hectares) (Daniłowska, 2018; Schuh *et al.*, 2019). Indeed, Figure 3-8 shows that between 2005 and 2016 the number of the smallest farms (less than 5 ha) fell very sharply, that the number of small farms (5 to 20 ha) also fell, and that the number of medium-sized farms (20 to 50 ha) remained stable while the number of the largest farms (>50ha) increased slightly.

Figure 3-8: Evolution in the number of agricultural holdings according to their size between 2005 and 2016 in the European Union (except Malta and Croatia) (Source: Eurostat, processed by authors)



However, this phenomenon varies from one Member State to another. The highest concentration of land in farms of more than 100 ha can be found in particular in the former socialist republics but also occurs in countries with high agricultural production levels such as France, Germany, Denmark and the Netherlands (Daniłowska, 2018). The concentration of land in a few very large farms in former socialist republics can be explained by the collectivisation of land during the communist regime and the agrarian reform that followed its collapse (Guiomar *et al.*, 2018). Nevertheless, the phenomenon of land concentration has been less significant in some Member States, with a still significant share of agricultural land cultivated by the smallest farms as observed in Poland, Romania and Slovenia (ibid.). In these Central and Eastern European countries, the very large farms originating from the former collective farms tend to be subdivided into several farms (always greater than 100 ha) and the smallest farms are expanding and being transformed into medium-sized ones (interview L. Piet, 2021).

If we take the example of Poland (Figure 3-9), the phenomenon of collectivisation during the communist era was not significant in the country (Guiomar *et al.*, 2018) and therefore the concentration of land in larger farms is low. Figure 3-9 shows that over the period from 2005 to 2016, small farms have grown and the decrease in their number has been in favour not only of large farms but also medium-sized farms, whose number and share of utilised agricultural area (UAA) have increased.

There is a different explanation for the significant share of large farms in France, Germany, Denmark and the Netherlands, where there has been a longstanding dynamic of land consolidation (Guiomar *et al.*, 2018). In Western European countries, the evolution of farm structures is more stable in general (interview A. Balmann, 2021). The main structural change over the past 20 years has been the expansion of the largest farms (> 50 ha), with farms of between 50 ha and 100 ha moving to the category of farms of more than 100 ha (interview L. Piet, 2021). However, there may be a maintenance of medium-sized farms, for example in Germany (Figure 3-10). We see that despite the importance of the largest farms in the utilised agricultural area (UAA), the concentration of land remains limited and the number of medium-sized farms is always substantial (Figure 3-10). Some of these medium-sized farms are part-time or 'leisure' farms, hence the maintenance of this category (interview A. Balmann, 2021).

Figure 3-9: Evolution of the distribution of the number of farms and of the UAA by size category in Poland between 2005 and 2016 (Source: Eurostat, processed by authors)

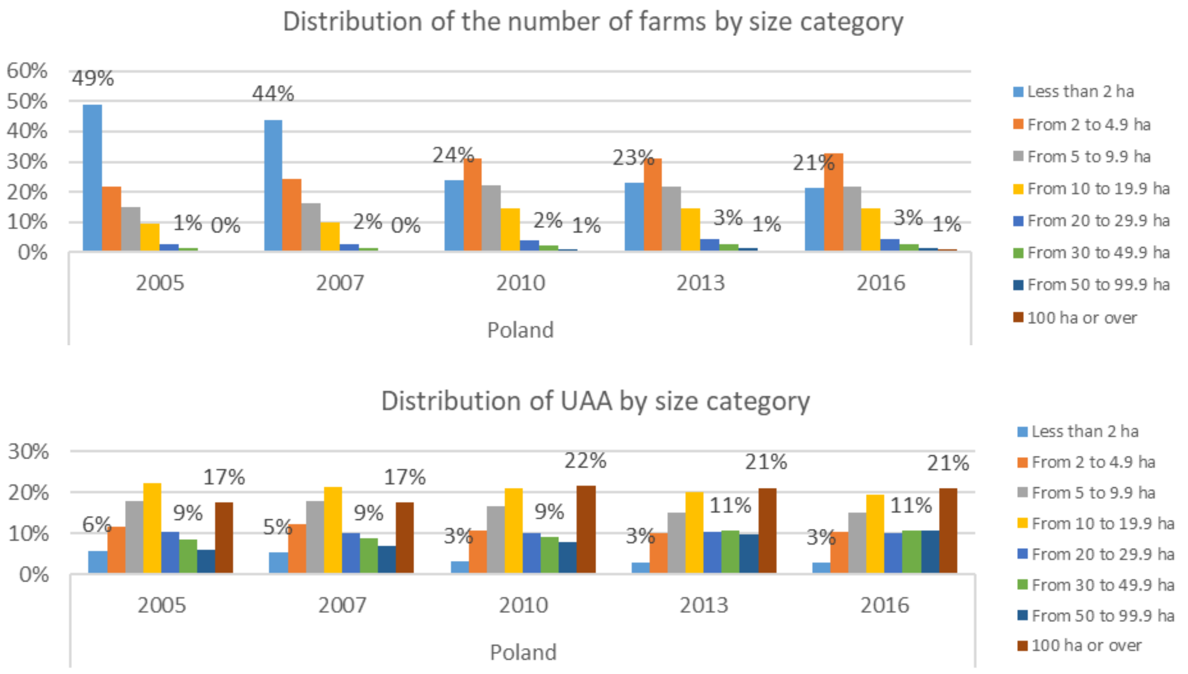
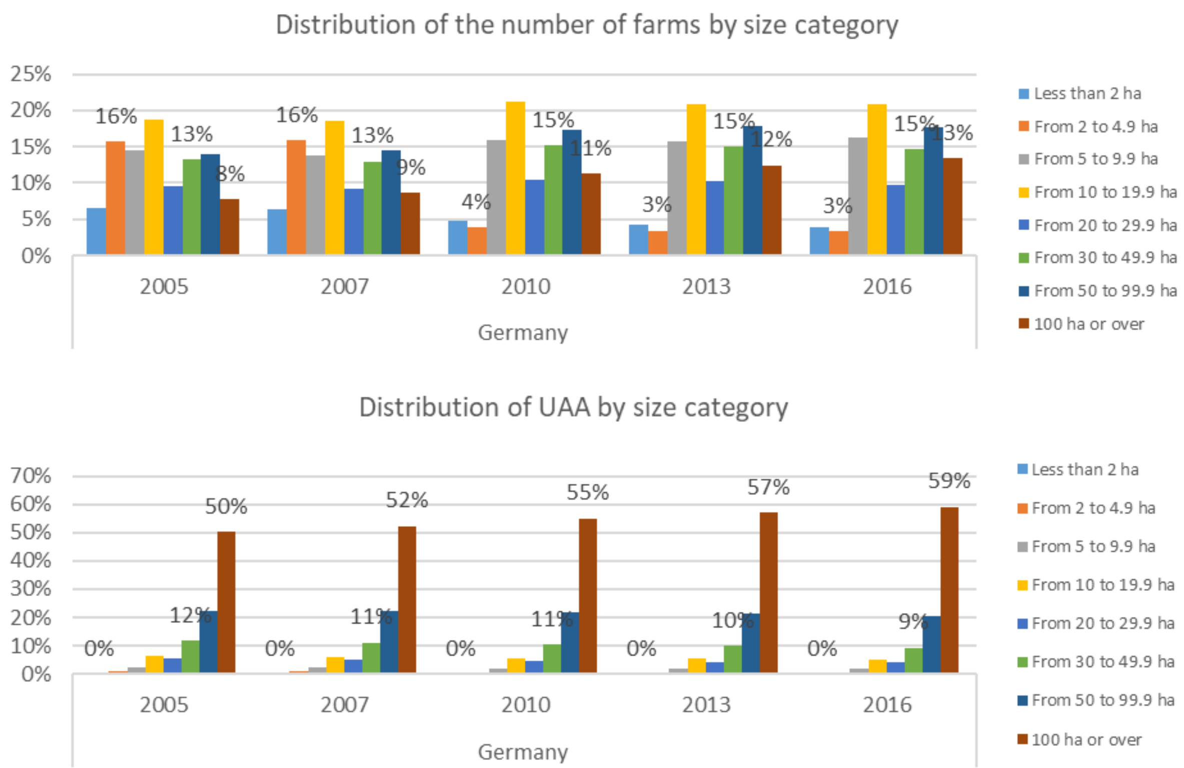


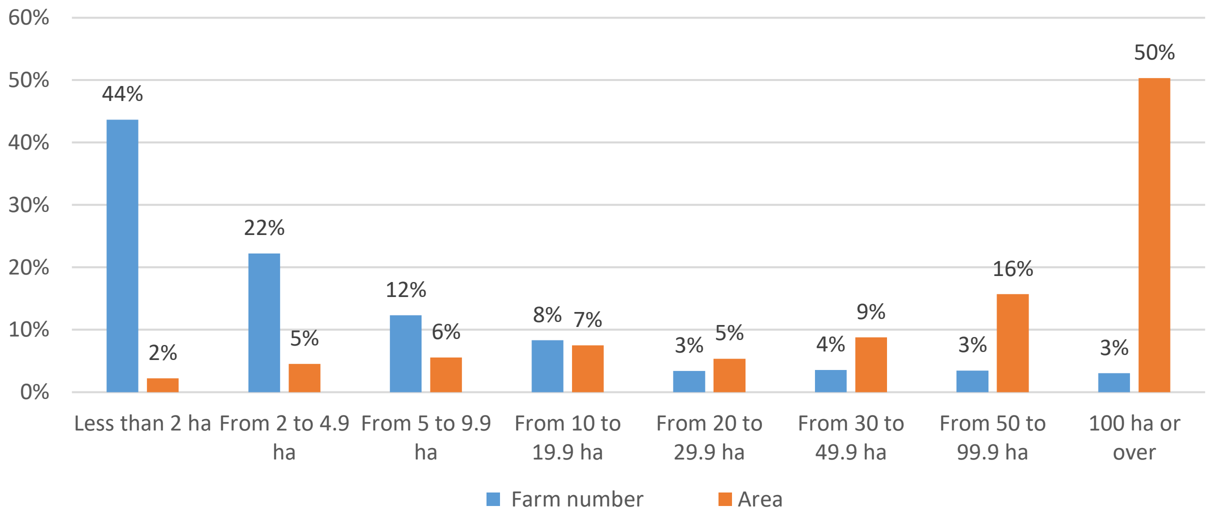
Figure 3-10: Evolution of the distribution of the number of farms and of the UAA by size category in Germany between 2005 and 2016 (Source: Eurostat, processed by authors)



A dual coexistence of agricultural structures

The increasing farm size trend has led to a **duality of agricultural structures in Europe** that can be seen in Figure 3-11. The largest farms represent a small share of the number of farms but occupy a large proportion of agricultural land. In contrast, the smallest farms represent a significant share of the number of farms but only cultivate a small part of the utilised agricultural area (UAA). In 2016, 13% of the largest farms occupied 80% of the UAA in Europe, while 80% of the smallest farms used 13% of the UAA (Figure 3-11).

Figure 3-11: Share of the number of farm and the utilised agricultural area by category of farm size in EU in 2016 (Source: Eurostat, processed by authors)



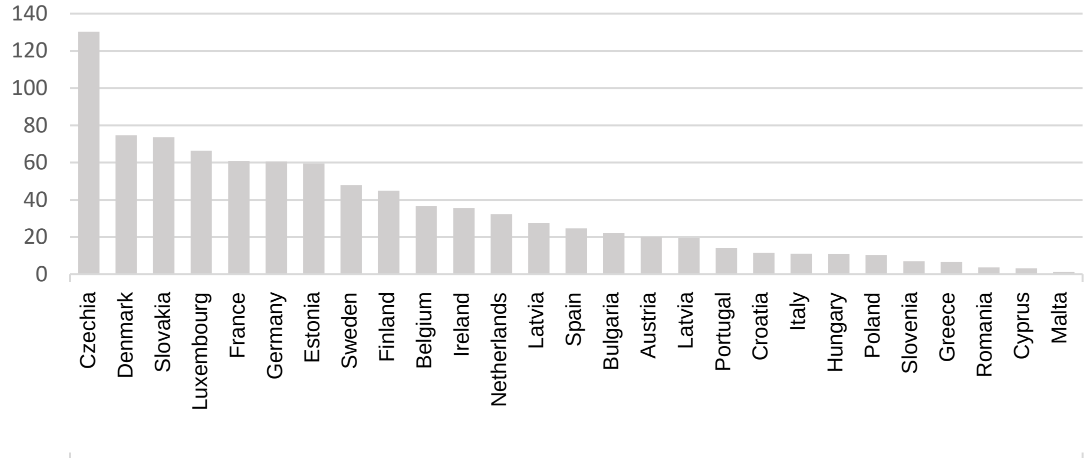
Farms remain diverse in Europe

However, there is a **great diversity in the farms found in the European Union** in terms of size, structure and type of farming, reflecting the coexistence of different farming models across the continent. These agricultural structures vary from small family farms (as found in southern Germany) to large farms of several thousands of hectares, of the agricultural holding type, with many employees (as in the new Member States) (Happe *et al.*, 2008). There is not only a diversity of farm structures between Member States but also between regions in the same country (Guiomar *et al.*, 2018).

• Average farm sizes differ from one Member State to another

The utilised agricultural area per farm differs greatly from one European Member State to another (Popescu *et al.*, 2016). In 2013, the average surface area of farms within the European Union was 16 ha, ranging from 3 ha in Romania to 133 ha in the Czech Republic, via 58 ha in France (ibid.). The low average surface area of European farms is due in particular to the weight of certain countries that have many very small farms, such as Romania, Italy and Poland (Piet, 2018). Figure 3-12 shows the differences in the average surface area of farms between European Member States. The countries with the largest farms are the Czech Republic, Denmark, Slovakia, Luxembourg, France, Germany and Estonia. The countries with the smallest farm sizes are Malta, Cyprus, Romania, Greece, Slovenia, Poland, Hungary and Italy.

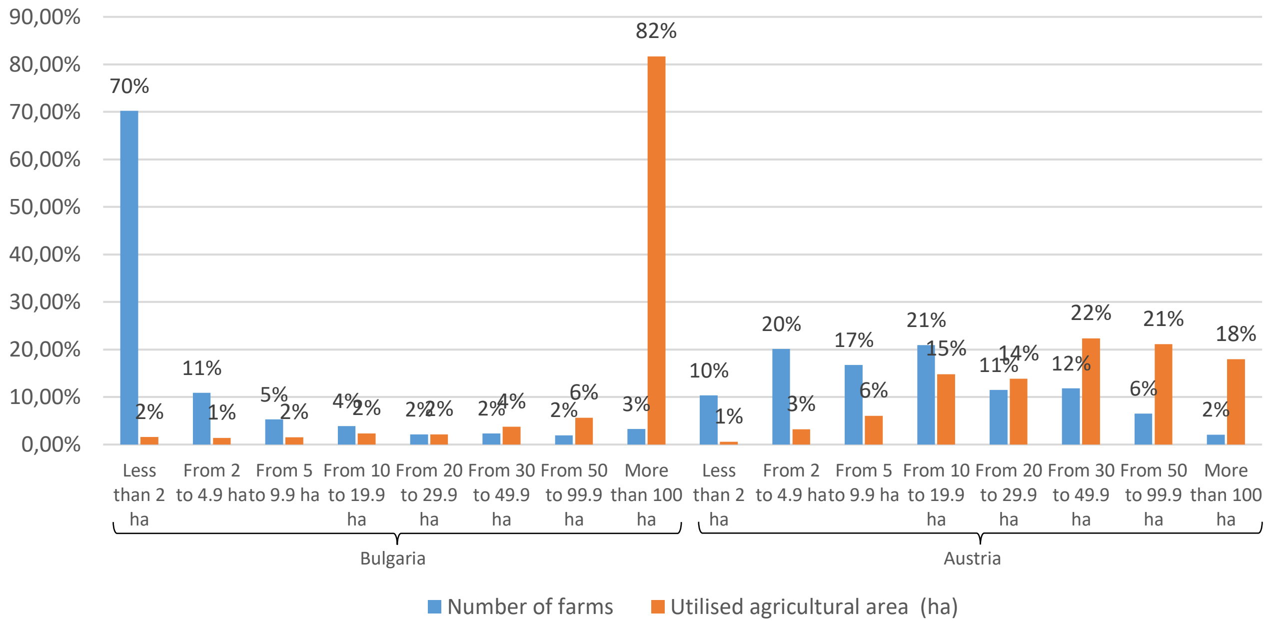
Figure 3-12: Average UAA of European farms in 2016 (ha) (Source: Eurostat, processed by authors)



• Dual or ternary distribution of land within Member States

The average utilised agricultural area (UAA) does not reflect the distribution of the size of farms and their share in the UAA. We have seen that farm structures are dual in Europe, but the distribution of the UAA can be very different from one Member State to another. Some Member States have a very dual land distribution, such as Bulgaria (Figure 3-13) where 3% of the largest farms (greater than 100 ha) use 82% of the total UAA, while farms of less than 2 ha represent 70% of farms but occupy only 2% of the total UAA. Other countries have a more homogeneous distribution of farm size and a more egalitarian distribution of the UAA, such as Austria, where a large number of medium-sized farms coexist with small and large farms (Figure 3-13). We can say that this coexistence of structures in Austria is **ternary**. We have already observed this type of ternary coexistence in Poland and Germany (Figures 3-9 and 3-10), where medium-sized farms have an important role in the distribution of farm structures.

Figure 3-13: Share of farms (in %) and share of UAA (in %) by farm size category in Bulgaria and Austria (Source: Eurostat, processed by authors)



The strong duality of structures in some Member States can be explained by the size of the largest farms (over 100 ha), which varies greatly across Europe. According to Piet (2018), in 2010, farms of more than 100 ha had an average size of 175 ha in France but could reach much larger average sizes in other countries: 275 ha in Germany, 400 ha in Hungary, 475 ha in Romania, nearly 700 ha in Bulgaria and the Czech Republic, and more than 780 ha in Slovakia. Piet (2018) also analysed the distribution of surface area in different countries by computing the share of surface area exploited by the 20% of largest farms. Hence, the most 'egalitarian' Member States are Ireland and Finland, where the 20% of largest farms occupy 50% of the UAA. In contrast, Hungary, Slovakia and the Czech Republic are very unequal with the 20% of largest farms using 95% of the land. France is in the middle, with 60% of the UAA occupied by the 20% of largest farms.

• Path dependence of farms and lack of convergence of agricultural structures

A hypothesis that was formulated very early on during the integration of Eastern and Central European countries into the European Union conclude that the integration would eventually lead to a convergence of agricultural structures within the European Union. However, the maintenance of a diversity of farms both between and within European Member States shows a completely different dynamic (Balmann *et al.*, 2006). Indeed, we have seen that the evolution and current state of farm structures strongly depends on the history of each country. There is therefore a path dependence for farms, in addition to historical factors (collectivisation, land consolidation, etc.). This path dependence can be explained by sunk costs in farming, which demand large investments (equipment and buildings) which are not taken into account in the future (Balmann, 1999; Balmann *et al.*, 2006).

Retrospective analysis: Specialisation of European farms and regions

Hyper-specialisation of farms and regions

• Technical and economic orientation of farms

European farms are increasingly specialised. On the one hand, there has been a reduction in mixed cropping, mixed livestock production and crop-livestock operations (Hansen, 2020; Figure 3-14). On the other, production is increasingly concentrated in already specialised farms (Desriers, 2011). For example, in parallel with a strong reduction in the share of farms with grain-eating livestock since the 1970s, the number of animals per farm specialising in pig production has increased very sharply in Denmark and the Netherlands (Hansen, 2020).

Figure 3-14: Changes in the specialisation of farms between 2005 and 2016 in the European Union 28 (except Croatia and Malta) (Source: Eurostat, processed by authors).

The technical-economic orientation corresponds to the contribution of the different productions to the margin or standard gross production of the farm.

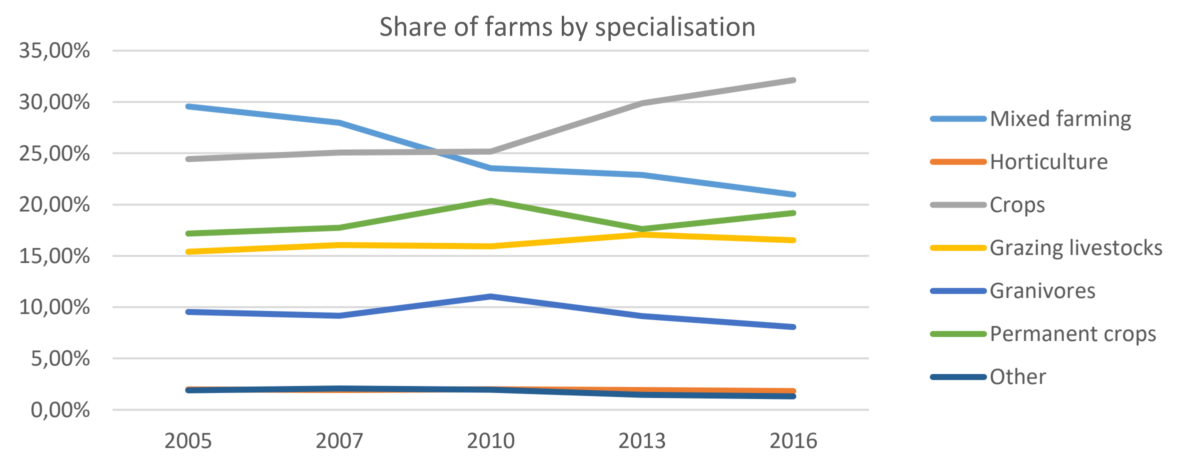


Figure 3-14 shows a reduction in the percentage of mixed farms (mixed crops or livestock and crop-livestock approaches). Since 2005, this has been accompanied by an increase in the share of arable farms. Overall, the percentage of farms specialising in livestock and permanent crops remains stable. According to Eurostat (2022), the share of mixed farms fell by 9 percentage points and that of crop production farms (arable crops, permanent crops and horticulture) rose by 9 percentage points between 2005 and 2016.

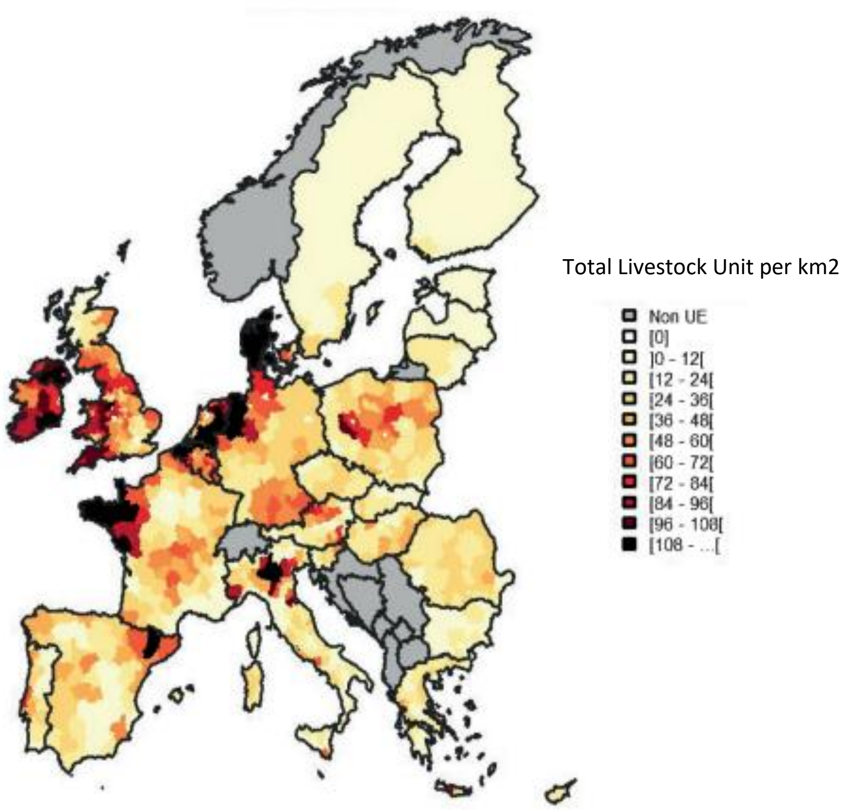
The technical and economic specialisation of farms is mainly reflected in the specialisation of their production. In crop production, this manifests itself in a reduction in crop diversity, a simplification of crop rotations and a reduction in the genetic diversity of cultivated plants (Fuzeau *et al.*, 2012; Barbottin *et al.*, 2018). In the livestock sector, farms specialise in one type of animal production (dairy cattle, beef cattle, sheep, pigs or poultry), moving from mixed crops with livestock or mixed livestock (a combination of beef and dairy cattle, for example) to a single activity (Schott *et al.*, 2018).

• Specialisation of regions and the geographical concentration of agricultural production

There is also a **specialisation in European regions with a geographical concentration of production** (Eurostat, 2022; Roguet *et al.*, 2015).

In particular, there is a high concentration of animal production in areas with a high density of livestock and in increasingly large farms (Roguet *et al.*, 2015). Figure 3-15 shows these European production areas: Denmark, Northwest Germany, the Netherlands, Flanders in Belgium, Western France, Northern Italy (Po plain), Northeast Spain (Catalonia), Ireland, Western Great Britain and, more modestly, Southern Germany, central Eastern Poland and around France's Massif Central. This concentration of livestock farming in certain more competitive areas is observed in all Member States but at different rates (Roguet *et al.*, 2015).

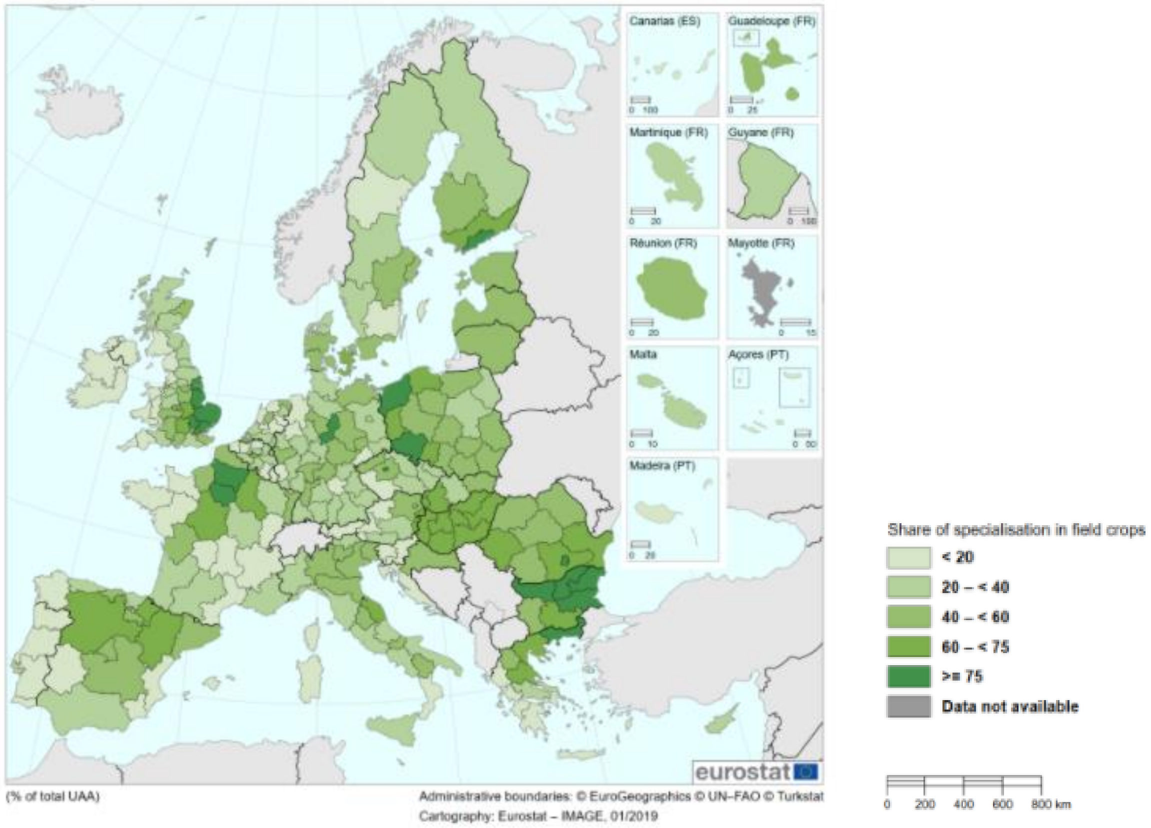
Figure 3-15: Density of livestock in the EU-27 in 2010 expressed in total Livestock Unit (LU) per km2 (NUTS 3 scale) (Sources: Roguet *et al.*, 2015; based on Eurostat)



Other European regions have specialised in arable crops (cereals, oilseeds, protein crops, root crops, field vegetables, tobacco and cotton, see EC Regulation 1242/2008) (Eurostat, 2022). This is not so much due to a concentration of crop production but reflects the gradual abandonment of livestock farming in favour of arable farming, leading to a geographical expansion of arable production, particularly in the most agronomically favourable regions (Schott *et al.*, 2018; Hardelin and Schwoob, 2021).

Figure 3-16 shows the regions specialised in arable crops in Europe, with the percentage of area under arable crops at the NUTS 2 level. Some regions are highly specialised in arable crops, with 75% of the UAA operated by farms specialised in arable crops: Northern and Eastern Bulgaria, Northeast France (Ile-de-France and Picardie), Central Germany (Brunswick), Northeast Greece (Eastern Macedonia and Thrace), Western Poland (West Pomeranian and Lower Silesian Voivodeships), Southern Finland (Helsinki-Uusimaa) and Eastern Great Britain.

Figure 3-16: Share of UAA managed by farms specialised in arable crops at NUTS 2 level, 2016 (Source: Eurostat, 2022)



These regional specialisations have led to a spatial dissociation between crop and livestock production and go hand in hand with farm expansion (Chatellier and Gaigné, 2012; Roguet *et al.*, 2015).

There is also a strong geographical concentration of particular types of production, such as viticulture, market gardening and arboriculture in France (Dussol *et al.,* 2004; Schott *et al.*, 2018). This specialisation is older and we have not observed any dynamics of specialisation since the 1990s, because these sectors are linked to particular geographical constraints (ibid.). There is also a concentration of permanent crops in the Mediterranean regions. In some regions, more than half of the UAA is occupied by farms specialised in permanent crops: Southern Greece, Southern Spain and Southern Portugal (Eurostat, 2022).

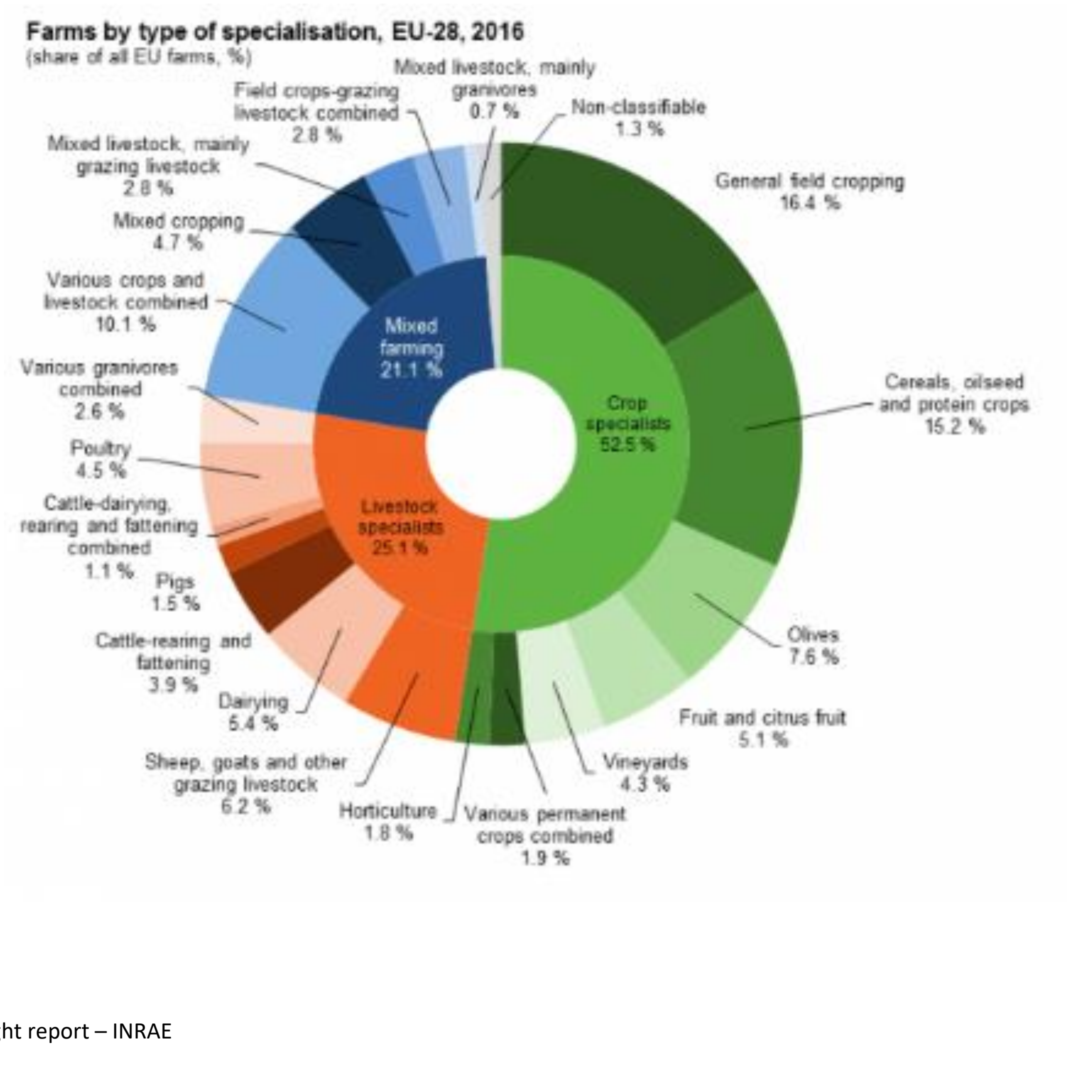
Several factors can explain the expansion of farms:

- Their specialisation;
- "Economies of scale" (i.e. an increased production of a good accompanied by a reduction in average production costs (Chatellier and Gaigné, 2012);
- The weakness of economies of scope (defined as lower costs due to joint production compared to the separate production of equal quantities of goods (ibid.));
- The geographical concentration of production;
- Economies of agglomeration (defined as lower costs due to spatial concentration of production);
- Agricultural policies;
- Globalisation and the geographic expansion of incoming and outgoing flows;
- The organisation of sectors and value chains (Balmann *et al.*, 2006; Chatellier and Gaigné, 2012; Roguet *et al.*, 2015; Therond *et al.*, 2017; Hansen, 2020; Hardelin and Schwoob, 2021).

A diversity of technical and economic orientations in Europe

Despite the specialisation of European farms and regions, European agricultural production remains diversified. There is a diversity of technical and economic orientations within Europe, where many types of agricultural production are represented (Figure 3-17). In the EU in 2016, 31.6% of farms specialised in field crops, 18.9% in permanent crops, 16.6% in herbivorous livestock, 8.6% in grain-fed livestock, 12.9% in mixed crops-livestock, 4.7% in mixed cropping, 3.5% in mixed livestock and 1.8% in horticulture.

Figure 3-17: Diversity of farms by specialisation in Europe in 2016 (Source: Eurostat, 2021a)



There is also a great diversity in specialisations between European Member States (Figures 3-18 and 3-19). Almost all European countries have a Simpson's diversity index greater than 0.5 (this measures the diversity of a community, the closer it gets to one the greater the diversity) (Figure 3-19).

Figure 3-18: Breakdown of the farm specialisations in selected European countries in 2016 (Source: authors, based on Eurostat 2016 data)

Mixed farming represent mixed livestock, mixed crops and mixed crop-livestock farms (for other specialisations, see EC Regulation 1242/2008)

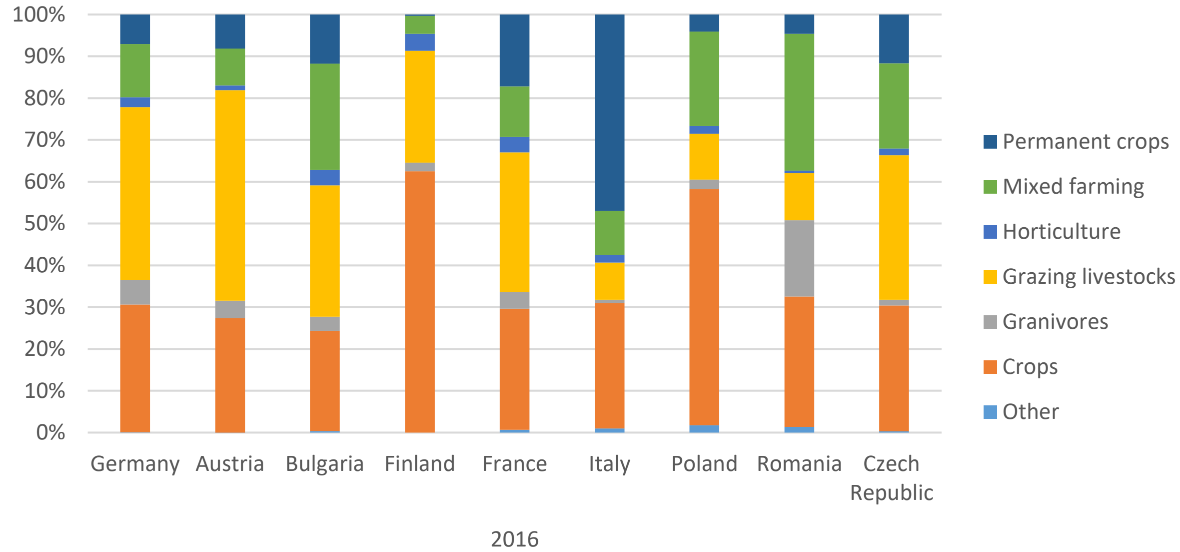
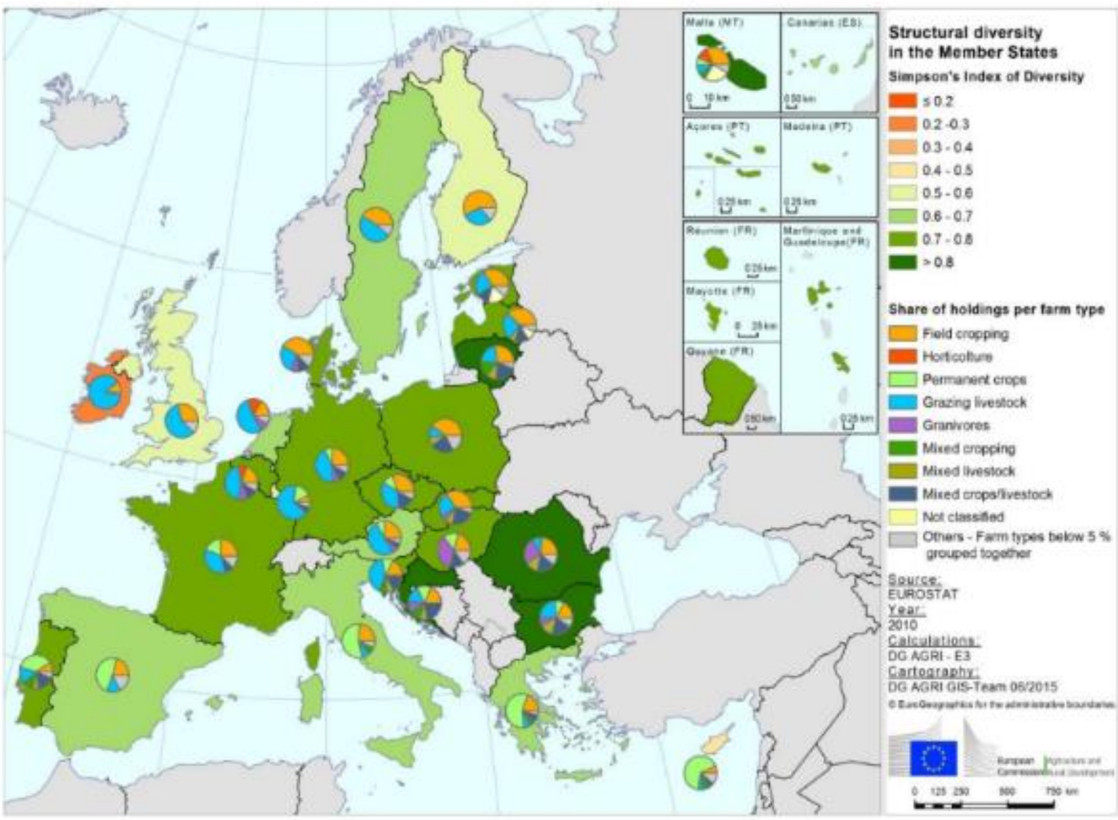


Figure 3-19: Diversity of technical and economic orientations between Member States, 2010 (Source: DG Agriculture and Rural Development, 2018)



Nevertheless, some Member States are specialised in certain sectors. Mediterranean countries and Portugal are specialised in perennial crops, Northwest European countries (Ireland, the Netherlands, Luxembourg and the United Kingdom) are more specialised in herbivorous livestock. The countries of Eastern Europe are those that have maintained the greatest diversity of technical and economic orientations and still have a significant proportion of grain-eating livestock and mixed farms (Figure 3-19). Most Member States have several specialisations, which also reflects the great diversity of specialisation between regions.

The limits of hyper-specialisation

The strong specialisation of farms and regions has significant limits and generates many negative externalities.

Cooper *et al.* (2009) identify many public goods provided by agriculture, both environmental and social. However, the provision of these public goods depends on the type of agricultural structure and the practices employed. They found that extensive livestock and mixed farming systems are particularly important for producing agriculture-related public goods.

The specialisation of farms is linked to intensified production and input use (Eurostat, 2022). This intensification leads to a reduction in crop rotation diversity and genetic diversity, and also to a **simplification of landscapes** (enlargement of fields, fragmentation of landscapes and reduction of semi-natural habitats). This simplification leads to a **loss of biodiversity** and therefore reduced ecosystem quality (Eurostat, 2022; Tscharntke *et al.*, 2005; Reidsma *et al.*, 2006).

The high geographic concentration of livestock also leads to several negative environmental externalities through the creation of localised **pollution** hotspots (Tamminga, 2003). This leads to the pollution of water (nitrates and phosphorus) and soil and air (ammonia and pathogens) (Roguet *et al.*, 2015). In fact, farms specialising in livestock production with a high animal density have a surplus of manure that they cannot spread entirely on their land. This is all the more problematic in regions entirely specialised in animal husbandry where there is no possibility of spreading this surplus on neighbouring farms (Eurostat, 2021a). Excess nitrogen in coastal zones can lead to a proliferation of green algae. This phenomenon is well known in some regions such as Brittany, France, where animals have died and people have been intoxicated, leading to fierce controversy (Brun and Haghe, 2016). Areas with high livestock density pose other concerns too, in particular, a high **health risk** (epizootics, zoonoses and antibiotic resistance) and **degradation of the landscape** (high density of livestock and factories, smells and noise) (Roguet *et al.*, 2015).

These negative externalities can lead to **neighbourhood disputes** that hinder the establishment of farms or modernisation projects (Delanoue and Roguet, 2015).

The spatial dissociation between animal and crop production areas has also led to farms having a strong dependence on nitrogen fertilisers and imports of vegetable proteins. In turn, this translates into a strong dependence on world markets and the geopolitics of energy (Hardelin *et al.* Schwoob, 2021).

Towards de-specialisation?

Faced with the numerous problems linked to specialisation, several authors have suggested that a territorial de-specialisation and a re-diversification of crops would be advantageous for reducing the negative externalities linked to regional specialisation (biodiversity, water, air and soil quality, and relations with neighbours), alongside strengthened interactions between livestock production and agriculture (Chatellier and Gaigné, 2012; Hardelin and Schwoob, 2021).

The rise in input and energy prices, the possible increase in transport costs and the volatility of cereal prices could lead to a re-association of crop and animal production within the same territory, however there are many factors which may hamper this (Chatellier and Gaigné, 2012).

Similarly, a re-diversification of crops would allow territories to become less vulnerable to climatic and economic shocks and to reduce the use of chemical fertilisers. However, the re-diversification of crops also faces several obstacles (agronomic and socio-technical) (Meynard *et al.*, 2014). Of course, public policies can have an influence on de-specialisation (Chatellier and Gaigné, 2012; Ansaloni and Fouilleux, 2006).

Hypotheses of change for the coexistence of farms in Europe in 2050

Based on the literature analysis and interviews with experts, several hypotheses of change for the coexistence of farm structures in Europe in 2050 have been built. They aim to describe what the landscape of agricultural structures in Europe will be in 2050. These hypotheses consider both changes in farm size, the number of farms and the degree of specialisation or diversification of farms in Europe in 2050. These hypotheses of change are presented in Table 3-1 below.

Table 3-1: Hypotheses of change for the coexistence of farms in Europe in 2050

Component	Hypothesis 1	Hypothesis 2	Hypothesis 3
Co-existence of farm structures in EU	Dual organisation of farm structures in EU and regional specialisation	Ternary organisation of farm structures in EU and re-diversification at regional level	Ternary organisation of farm structures in EU and re-diversification at farm level

- **Hypothesis 1: Dual organisation of farms and regional specialisation**

This first hypothesis is based on a duality of farm structures in 2050 with, on the one hand, a few very large farms occupying the majority of agricultural land and, on the other, many small farms. This duality can already be observed in some European Member States. Under this hypothesis, the number of small and medium-sized farms continued to decline rapidly and land concentration increased with fewer and fewer farms becoming larger and larger. However, alongside large farms many small farms will remain in 2050. The trend towards the specialisation of farms and the geographical concentration of production has continued, resulting in a regional hyper-specialisation of agriculture throughout Europe.

- **Hypothesis 2: Ternary organisation of farms in Europe and re-diversification on a regional scale**

In the second hypothesis, the structural organisation is ternary with a coexistence in 2050 of large, medium and small farms. The reduction in the number of farms, particularly small ones, has been significant, leading to an increase in the number of medium and large farms. However, land concentration has slowed, and medium and large farms coexist alongside small farms which have created market niches. This organisation has also been driven by a de-specialisation of the major regions, in response to the environmental, social and systemic problems posed by over-specialisation. Within the same region, farms remain specialised (including a minimum of crop diversification to ensure the sustainability of rotations), but several specialisations coexist in the same region. On a regional scale, we can see interactions and synergies between structures specialised in crop production and those concentrating on livestock production (animal feed and organic fertiliser). So, a re-association is built between crop and animal production on a regional scale.

- **Hypothesis 3: Ternary organisation of farms in Europe and re-diversification at the farm scale**

In the third hypothesis, the structural organisation of farms is also ternary but with limited land concentration. Faced with the many environmental and social problems caused by the over-specialisation of farms and regions, a de-specialisation movement has taken place. Mixed crop-livestock farms have been promoted and have been able to maintain themselves, even re-develop in Europe. In the case of mixed crop-livestock farms, the complementarity of plant and animal production takes place on the farm. Crop production farms have diversified their crops and lengthened their rotations. Livestock farms have a large portion of their land allocated to crop production and have developed feed self-sufficiency for their livestock (particularly the protein component).

3.1.1.2. The governance of farm structures in Europe

Definition of governance structures

According to Donnars *et al.* (2018), the governance of farm structures is defined by the decision-making methods concerning the mobilisation and combination of production factors and the different actors involved in the decision-making process: "*who takes decisions about production factors and the combination of outputs, and how other actors make their voices heard*".

Highly **diverse actors** can be involved in this governance: not only agricultural households, but also farmers' collective organisations such as cooperatives, local actors and consumers, agro-industrial companies, large-scale distributors and financial investors (Donnars *et al.*, 2018).

This governance can be achieved in **different ways,** through short distribution channels (with few intermediaries between the producer and consumer) or longer chains (with many intermediaries), but also through contracts and the standardisation or labelling of products (Lamine *et al.*, 2019; Therond *et al.*, 2017).

Retrospective analysis: A governance in the hands of various actors and inserted into various value chains

Traditional family governance

Essentially, the European agricultural model is built on what Hervieu and Purseigle (2009) have described as "modern family farming" inserted into markets, where agricultural activities are based on a multi-active couple who have chosen this profession.

However, there are other models of family farming in Europe. For example, Hervieu and Purseigle (2009) observed in certain regions of the EU, particularly the Polish and Romanian Carpathians, forms of "peasant" family farming motivated by the safeguarding and handing on of a family heritage, and where marketing does not go beyond the village scale. Another recent form of family farming is corporate family farming (see paragraph 3.1.3.4), where land ownership and capital remain family-owned but are dissociated from agricultural work (Jeanneaux *et al.*, 2020). This type of farming is export-oriented and its organisation moves away from traditional family farms (ibid.).

Cochet (2018) defines the "family" nature of an agricultural production unit as "*the fact that most of the work required is conducted by the farmer (head of the farm) or a member of their family*", and that labour and capital are in the same hands (whether or not the farmer owns the land). In this type of family farm, the added value created and received by the farmer is allocated to the household income (ibid.).

European family farming is characterised by a predominantly family agricultural workforce. In Europe in 2016, nine out of 10 agricultural workers were farmers or members of their family (Schuh *et al.*, 2019).

It is considered that the governance of family farms responds to a patrimonial logic (Dufumier and Bergeret, 2002).

Nevertheless, European family farming is changing. Farms are less often passed on as an inheritance from one generation to another. Increasingly, farms will be taken over by people from outside the family framework, with the profession of farmer becoming the subject of personal choice and where knowledge is transmitted by peers (Jeanneaux *et al.*, 2020). Family farms are also increasingly resorting to paid labour and the delegation of certain activities (ibid.).

Concerning farm governance in the strictest sense, the family character can be seen as the fact that farmers and their families make the decisions, that they own or rent their land and can decide where they get their inputs and to whom they sell their products (Donnars *et al.*, 2018).

European family farming has to face many challenges: market access, its place in the ecological management of the planet, its relationship with the rest of society, the opening of markets and the arrival of new financial actors (Hervieu and Purseigle, 2009). All of this leads to questions about the exclusively family governance of European farms and requires a consideration of the role of other actors in farm governance.

Farmers' collective organisations

Farmers organise themselves collectively to respond to various challenges and to pool resources such as inputs, equipment, infrastructure, work, employees, production and land (Lucas *et al.*, 2014). Collective organisations have played a central role in agricultural modernisation, in particular by promoting the sharing of production tools and encouraging exchanges between peers, but also for the organisation of particular agricultural sectors through the emergence of cooperatives.

These organisations are even more interesting as they can promote innovation and the transition of agricultural systems towards new practices (Lucas *et al.*, 2014; Lecole and Moraine, 2021; Cardona *et al.*, 2021).

• Agricultural cooperatives: Collective organisations that have helped structure European value chains

- Cooperatives: key players in agricultural value chains

Cooperatives currently have an important place in European agricultural value chains. Bijman and Iliopoulos (2014) estimate that for agricultural products the market share of all agricultural cooperatives in the EU was 40% in 2010. Cooperatives have an even greater presence in some countries and some sectors. They contribute to more than 60% of agricultural production in the EU-15[1]. In certain sectors, this can reach 90%, such as in dairy production in Denmark, Austria and Finland, in pig production in Denmark and in flower production in the Netherlands (Juliá Igual and Meliá Martí, 2008). In contrast, cooperatives have a much smaller presence in Central and Eastern European Member States (Gijselinckx and Bussels, 2014; Juliá Igual and Meliá Martí, 2008). Figure 3-20 clearly shows the difference in farmers' membership of cooperatives between EU Member States. In general, the vast majority of farmers belong to cooperatives in the Western European Member States and few do so in the countries of Eastern Europe.

- Cooperatives: a traditional form of collective organisation

Forms of collective organisation between farmers, including the pooling of resources, have existed for a long time in Europe, the oldest dating from the 9th century in France's Puy-de-Dôme. We can also cite the example of orchards in Jura, France, dating from the 13th century and common pastureland in England in the Middle Ages (Valiorgue *et al.*, 2020; Oosthuizen, 2013). These forms of solidarity and collective action have enabled farmers to protect themselves from the hazards and difficulties associated with agriculture and to face problems that are difficult to overcome individually. They then became institutionalised and equipped with legal tools through cooperatives (Valiorgue *et al.*, 2020).

In most European countries, cooperatives were created in the 19th century (Gijselinckx and Bussels, 2014).

[1] The EU-15 corresponds to the first countries that joined the European Union, i.e.: Germany, Belgium, France, Italy, Luxembourg, the Netherlands, Denmark, Ireland, United Kingdom, Greece, Spain, Portugal, Austria, Finland and Sweden. It is distinguished from the EU-12 that concerns the countries that joined the EU after the 2000s, namely: Poland, Lithuania, Latvia, Estonia, Czech Republic, Slovakia, Hungary, Slovenia, Malta, Cyprus, Romania, Bulgaria and Croatia.

Figure 3-20: Intensity of cooperative membership in Member States (Source: Gijselinckx and Bussels, 2014)

- The rationale for evolving cooperatives

Compared to private companies, cooperatives are characterised by a mode of governance where the decision-making power belongs to each member of the cooperative (one member, one vote) (Sentis, 2014; Candemir *et al.*, 2021). They constitute a form of collective governance of farmers where the latter are brought together around common objectives. Cooperatives seek to maximise profits and therefore the well-being of members and to provide economic benefits to their members (Candemir *et al.*, 2021). Members have a double identity since they can be both an owner of shares and a customer, supplier, employee or entrepreneur in the cooperative (Lapayre *et al.*, 2016).

Agricultural cooperatives can also influence the governance of structures through their choice of practices. Valiorgue *et al.* (2020) observe that French agricultural cooperatives have strongly influenced agricultural activities by actively participating in farm modernisation and technical progress. They have set up research and development teams working on improving the use of resources to increase agricultural yields (ibid.). The dissemination of this knowledge and the evolution of practices is achieved through their advisory work. Since cooperatives are a key link in food value chains, their agricultural advisory role makes it possible to steer the production of member farmers so that it meets the downstream requirements of value chains (specifications, standards, societal expectations, etc.) (Filippi and Frey, 2015). In particular, cooperatives can direct their members towards specific products through production contracts (Cholez *et al.*, 2015).

Nevertheless, cooperatives changed their strategy in the 1990s in order to adapt to a competitive environment and globalised markets. They have diversified and internationalised their activities and opened up to outside capital (Koulytchizky and Mauget, 2014). This has led to the consolidation of large international cooperative groups with several thousand members (Juliá Igual and Meliá Martí, 2008). Cooperatives have therefore moved away from their initial model and moved closer to how private companies function (Valiorgue *et al.*, 2020). In these large cooperative groups, the number of members is too large to allow for democratic governance and the governance of the cooperative moves away from the model of a farmers' collective organisation (Candemir *et al.*, 2021). In Europe, there are still small, locally anchored cooperatives where governance remains collective and in the hands of farmers (Barbot *et al.*, 2020).

• Other farmers' collective organisations

While cooperatives are the most widespread and institutionalised form of collective organisation for farmers, there are other forms too.

- Collective organisation to promote production (brands, quality and origin labels)

In order to differentiate their production and thereby increase its value, farmers can organise themselves collectively through producer organisations in conjunction with other actors in the value chain, developing, for example, local brands and geographical indications. (Lamine *et al.*, 2019). This type of initiative has developed differently in each Member State. Renting *et al.* (2003) observed that in Mediterranean countries (France, Italy and Spain) farmers have greatly developed the promotion of quality products linked to a region (through geographical indications). This is much less the case in Member States such as Germany and the Netherlands, where the notion of quality is not linked to the territory. Lamine *et al.* (2019) identify European initiatives involving the organisation of farmers' collectives. The establishment of Protected Designations of Origin or regulated geographical indications at the EU level, but also the grouping of several producers to develop their own processing infrastructure, establish collective regional brands or producer shops, and even the creation of an original network of producers where prices are based on the cost of production and working time. These initiatives often supported by local authorities and various institutions result primarily from collective actions between farmers, in conjunction with residents, shops, restaurants etc. (ibid.).

- Collective organisation to pool production tools (equipment, infrastructure, work, employees and land)

Groups of farmers can also pool production tools in various ways. This can be a pooling of equipment, for example, through cooperatives for the use of agricultural equipment (known as CUMA in France) allowing joint investment in expensive equipment. It can be the pooling of fixed capital investments (storage infrastructure, anaerobic digestion, drying facilities etc.), the pooling of work and agricultural employees through groups of employers or thanks to the status of agricultural groups operating in common (known as GAEC in France) where farmers become partners (Lucas *et al.*, 2014; Lecole and Moraine, 2021). Finally, this may go as far as the pooling of land, for example in collective pastoral systems (Lecole and Moraine, 2021).

Collective action between farmers can also provide access to resources that are difficult to access from agricultural suppliers. For example, farm seeds adapted to a territory through seed exchange networks, or specific equipment requiring coordination to co-design machinery with equipment manufacturers (Lucas *et al.*, 2014).

- Collective organisation to share intangible assets (knowledge, common vision etc.)

Participation in an agricultural collective also makes it possible to pool intangible resources, particularly knowledge acquisition and dissemination, but it also extends to the development of social and symbolic links (common commitments, recognition of the collective, common values, mutual aid etc.) (Lucas *et al.*, 2014; Lecole and Moraine, 2021).

New practices are often adopted through peer-to-peer exchange networks. This is particularly the case within so-called 'alternative' agricultural movements (such as the conservation agriculture movement and France's Réseau Semences Paysannes (peasant seed network), where knowledge sharing takes place horizontally between peers within a network and is accompanied by the collective recognition of a defined project (Mawois *et al.*, 2019; Demeulenaere and Goulet, 2012).

- Collective organisation to implement and adopt practices

The collective organisation of farmers can have an impact on their practices, in addition to facilitating the knowledge acquisition and dissemination. Collective organisation makes it possible to ensure the adoption of new practices (shared investments, economic viability ensured by the collective establishment of chains and greater bargaining power, accessibility to strategic resources etc.) (Lucas *et al.*, 2014). Collective organisation also allows farmers to work together to deploy practices that go beyond the scale of the farm, for example, collective actions at the territorial scale such as management at the landscape scale of non-organic biodiversity or water or directed pollination etc. (ibid.; Group of Bruges, 2014).

Involvement of local actors and consumers in the governance of farm structures

Lamine *et al.* (2019) observed that the transition of territorial agri-food systems results from combined actions between farmers, civil society actors, private actors and local authorities. Farmers are then included in a broader process that includes local actors and consumers.

The involvement of consumers and local actors can be achieved in different ways. Firstly, through direct sales (farmers' markets, on-farm shops, pick your own etc.) where the direct interaction between consumer and producer makes it possible to establish a relationship of trust (Renting *et al.*, 2003). These direct relationships can expand through producer stores or regional brands supported by local actors, as mentioned above. The community-supported agriculture (CSA) movement (see AMAP in France, for example) has also developed significantly since the 2000s in Europe (Urgenci, 2016). Despite the diversity of forms of CSA, CSA can be defined as "*a direct partnership between a group of consumers and one or more producers in which the risks, responsibilities and benefits of agricultural activities are shared through long-term agreements*" (ibid.).

Some farmers also develop diversification activities such as landscape management and agritourism (Rentings *et al.*, 2003) which, in fact, concern local actors.

Finally, local actors (individuals, landowners, local authorities and intermediaries in the agricultural sector) can participate in the financing of agricultural land in order to promote access to land for farmers. Generally, these projects allow young farmers to establish their own farms, revitalising agricultural territories and developing practices that respect the environment; for example, within the "Terres de Liens" network in France (Nguyen *et al.*, 2017).

Through these examples, we can see that consumers and local actors are sometimes stakeholders in farm governance and can influence the decisions taken there on the use of production factors.

The role of agro-industrial companies involved in the governance of agricultural structures

Agri-food systems have become globalised, standardised and industrialised in increasingly long value chains producing standardised generic products (commodities) (Murdoch *et al.*, 2000; Therond *et al.*, 2017). This has led to a concentration of value chain power in large corporations (including cooperatives) and international distributors, impacting the distribution of added value and guiding decisions at the farm level (Murdoch *et al.*, 2000; Renting *et al.*, 2003; Therond *et al.*, 2017).

• Vertical coordination and contractualisation

We can observe increasing levels of vertical cooperation within value chains through contractualisation between farms and agro-industrial actors (Balmann *et al.*, 2006). Several forms of contracts exist that induce a more or less significant integration of farms within the chain:

- **Market or marketing contracts**: this type of contract is an agreement between a buyer and a producer, it fixes a price (or a mechanism to fix the price) and an outlet for the product. It often includes the quantity and quality of output and a delivery schedule (Zheng *et al.*, 2008). In this type of contract, the producer remains autonomous in their decision-making (ibid.).

- **Production contracts**: in the livestock sector, this type of contract is an agreement between a purchaser or principal (integrator or company) and a producer, where the producer raises animals belonging to the integrator according to specific practices in exchange for financial compensation. The producer provides the land, infrastructure, water, electricity and labour. The integrator retains ownership of the animals and provides inputs (feed, medicine etc.) and various services (technical advice etc.) (Zheng *et al.*, 2008). In crop production, production contracts determine "certain crop production conditions" such as the choice of varieties, the technical itinerary and the inputs used, often provided by the integrator (Cholez *et al.*, 2017). The producer has a lower margin of autonomy in this type of contract (FranceAgriMer, 2011).
- **Vertical integration**: in the case of vertical integration, the agro-industrial structure controls all the links in the chain, both upstream and downstream (feeding the animal until it is slaughtered). Production itself is conducted by employees (FranceAgriMer, 2011).

The degree to which vertical coordination takes place depends on the sector and the country. In Europe, contracting is particularly prevalent in the poultry sector. In France, for example, more than 95% of poultry meat is subject to production or integration contracts (Bouamra-Mechemache *et al.*, 2015). Contractualisation in the pig sector has developed strongly in Spain, Italy and the United Kingdom but remains very marginal in some countries, such as France (FranceAgriMer, 2011). Cereal production is less subject to contractualisation, except for specific crops, in particular quality cereals (Balmann *et al.*, 2006; Cholez *et al.*, 2017).

Through contractualisation, particularly production contracts and vertical integration, agro-industrial companies (but also cooperatives) directly influence farmers’ choices and therefore the governance of farms.

• Voluntary standards and labels

Since the 2000s, public and private voluntary standards (or norms) have been developing. They may, or may not, take the form of labels with the aim of encouraging practices that are more respectful for health and the environment at the farm level (Djama *et al.*, 2011; Fouilleux and Loconto, 2017). These standards establish specifications which are implemented by the producer and can be identified by consumers, for example, organic farming labels (Fouilleux and Loconto, 2017). Agro-industrial actors initiate these voluntary standards, which encourage producers to use certain practices. For example, in Germany, a major distributor has decided to sell only fresh meat that meets high animal welfare standards, gradually forcing producers to adapt their production or change distributors (interview A. Balmann, 2021). Sonnino and Marsden (2006) underline that in Northern European Member States (Germany, Netherlands and the United Kingdom) the differentiation of quality products is based on criteria for environmental sustainability and animal welfare, guaranteed by legislation and promoted through private brands. While in Southern European countries, quality is linked to the territory and promoted through quality and origin labelling.

Farms as investment possibilities for financial actors

More recently, we have seen the arrival of new financial actors in agriculture’s upstream sectors, such as investment funds, large groups in the agri-food sector and other private actors, including individual investors (Nguyen *et al.*, 2017). Since the financial crisis of 2008, agricultural land has appeared to be a safe investment (Purseigle *et al.*, 2017a). Financial actors invest either in the purchase of agricultural land or in the capital of high value-added businesses (viticulture and protected crops) with a medium-term target (5-6 years) (Nguyen *et al.*, 2017). The opening of a farm to external capital involves a change in farm governance, with the investor participating directly in the decision-making process. Farmers are no longer the only owner, nor the only decision-maker (ibid.).

Retrospective analysis: A governance underpinned by different logics: patrimonial or shareholder

The patrimonial or family logic of farm governance

The patrimonial logic aims to ensure that the farm (land and capital) is handed down within a family framework (Cochet, 2018). This desire to hand on the farm as a legacy is generally accompanied by a search for the accumulation of capital and land in order to provide the next generation with a valuable asset (Dufumier and Bergeret, 2002).

Furthermore, a farm underpinned by a family logic seeks primarily to remunerate its workforce. The farm's economic performance provides an income supporting farmers and the agricultural household. Secondly, this economic output is invested in the farm's means of production (renewal and improvement of equipment, expansion of the land owned etc.) (Dufumier and Bergeret, 2002; Cochet, 2018).

Nevertheless, as underlined above, the family logic currently found on European farms is moving away from the purely patrimonial logic of handing on the farm within the family. Increasingly, people from outside the family circle are taking on these farms and developing multiple activities within the agricultural household (Jeanneaux *et al.*, 2020, Hervieu and Purseigle, 2009).

The shareholder logic of farm governance

The shareholder logic of farm governance is purely financial. Capital owners do not work on the operational side and seek to maximise the return on invested capital (Dufumier and Bergeret, 2002; Nguyen *et al.*, 2017). The expected return on investment must cover the risks (induced by the management of capital by others) and the return on capital (Nguyen *et al.*, 2017). Profitability objectives are generally in the medium-term of 5-7 years (Nguyen *et al.*, 2017). This means the shareholder logic is much shorter term than the patrimonial approach.

Hypotheses of change for the governance of European farms in 2050

From this retrospective analysis, several hypotheses of change for farm governance in Europe in 2050 have been constructed (Table 3-2).

Table 3-2: Hypotheses of change for the governance of European farms in 2050

Component	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisations of farmers (cooperatives, collective agreements, etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic

- **Hypothesis 1: Governance by financial investors**

In the first hypothesis, farms in 2050 are mainly governed by external investors (investment funds, banks, industrial groups etc.) who commit their capital to agricultural production while waiting for a return on investment, thereby becoming farm shareholders. The logic is a shareholder one, with the operation seen as one asset among others in a portfolio, with a search for short-term profitability. Operational management is delegated to a salaried manager who implements the strategic decisions made by shareholders.

- **Hypothesis 2: Governance by agro-industrial firms**

In the second hypothesis, large agro-industrial groups are at the heart of farm governance. In 2050, farms are inserted into long value chains where large groups (cooperatives, agro-industrial businesses and distributors) have a significant influence. These actors downstream in the value chains influence the decisions taken within farms through contracts, standards and labels, whereby farmers must respect a particular production direction or a technical itinerary. These actors sometimes invest capital directly in farms. Farmers, integrated into a chain, therefore have little leeway in farm governance. Highly supervised, they produce on behalf of a dominant actor downstream in the chain (cooperatives, agro-industrial companies and distributors). It is only at the collective level that agricultural structures can claim to influence the decisions that concern them.

- **Hypothesis 3: Governance by collective organisations of farmers**

In this hypothesis, farm governance is conducted through the collective organisation of farmers. Decisions are made collectively between farmers. This process is conducted in different ways. For example, in small-scale cooperatives where the collective decision-making process is possible (one member, one vote), the means of production may be pooled and knowledge exchanged. Furthermore, there may be common approaches to promote their production (quality and origin labels). Farm management depends on how farmers organise themselves with other farmers.

- **Hypothesis 4: Shared governance with local stakeholders and/or consumers**

In this hypothesis, farm governance is shared between farmers and non-agricultural actors, such as consumers, downstream actors (restaurants, small processors and traders), local residents and authorities and public establishments. Many territorial initiatives promoted by consumers and/or farmers and/or local actors allow different actors to become involved in farm governance. These include, for example, direct interactions to buy the farm's production (direct or local sales), a system for promoting production (brands and producer stores) or the acquisition of land, or the establishment of partnerships (community-supported agriculture, landscape management). This is conducted through a common recognition of the multifunctionality of agriculture. In this governance, the family logic is extended to include the participation of other non-agricultural actors.

- **Hypothesis 5: Family governance**

In this hypothesis, governance is in the hands of farmers and their family members. The farm household makes decisions about the farm (management, practices, inputs, production etc.), owns or has the right to use the land it occupies and owns the farm's capital. However, farms are poorly capitalised and weakly integrated in marketing networks and the local territory. The farm is governed by a sectoral logic, which makes it highly dependent on the fluctuations of public agricultural policies.

3.1.1.3. The organisation of production factors

Retrospective analysis on agricultural work in Europe

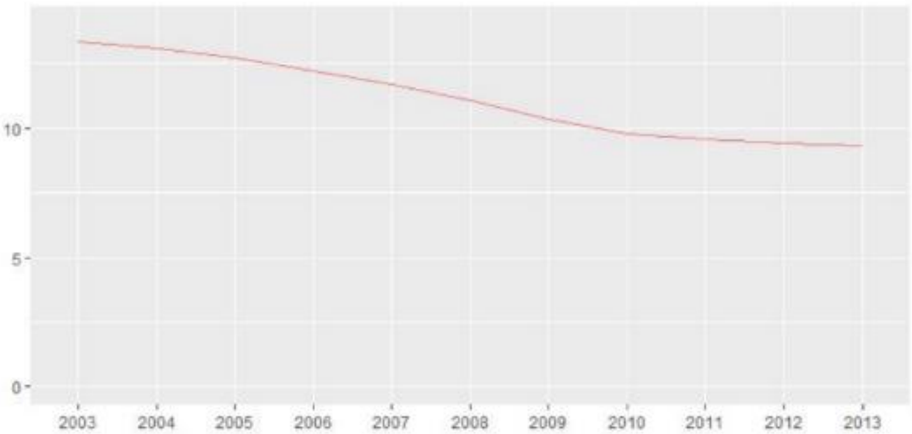
Agricultural work still accounts for a significant share of European employment, representing on average 4.2% of total employment in the EU in 2016 (Eurostat, 2021b). Agricultural work has an important place in the employment of some European Member States, representing almost a quarter of total employment in Romania (23%), 17% in Bulgaria and 10% in Greece and Poland (Eurostat, 2021b).

In 2016, there were 9.5 million people working in agriculture in Europe (in full-time equivalent positions, called Annual Work Unit (AWU)). A large proportion of the agricultural workforce works part-time in agriculture (Eurostat, 2021b).

The shrinking European agricultural workforce

The European agricultural workforce has been in sharp decline for several decades. Schuh *et al.* (2019) observed a 30% reduction in the European agricultural workforce between 2003 and 2013 (Figure 3-21). The European Commission (2013a) noted a reduction in the agricultural workforce of 5.2% per year between 2005 and 2010.

Figure 3-21: Evolution of the workforce employed directly by farms (in million AWU) in the European Union (EU-27), between 2003 and 2013 (Source: Schuh *et al.*, 2019; Eurostat data)



This pace of this decrease in the European agricultural workforce is not uniform across countries and is greatest in the new Member States (European Commission, 2013a). For the European Union as a whole, nearly 2.5 million workers left the agricultural sector over the period 2007-2017 (Schuh *et al.*, 2019).

The sharp decline in agricultural employment can be explained by various factors:

- The reduction in the number of farms and their concentration thanks to economies of scale; technical advances, including increased mechanisation and adoption of new technologies;
- In addition, the difference in income between the agricultural sector and other sectors, particularly in the new Member States, where joining the EU has provided new employment opportunities (Schuh *et al.*, 2019).

As a result, agricultural jobs are now fewer in number but more productive than before (European Commission, 2013a).

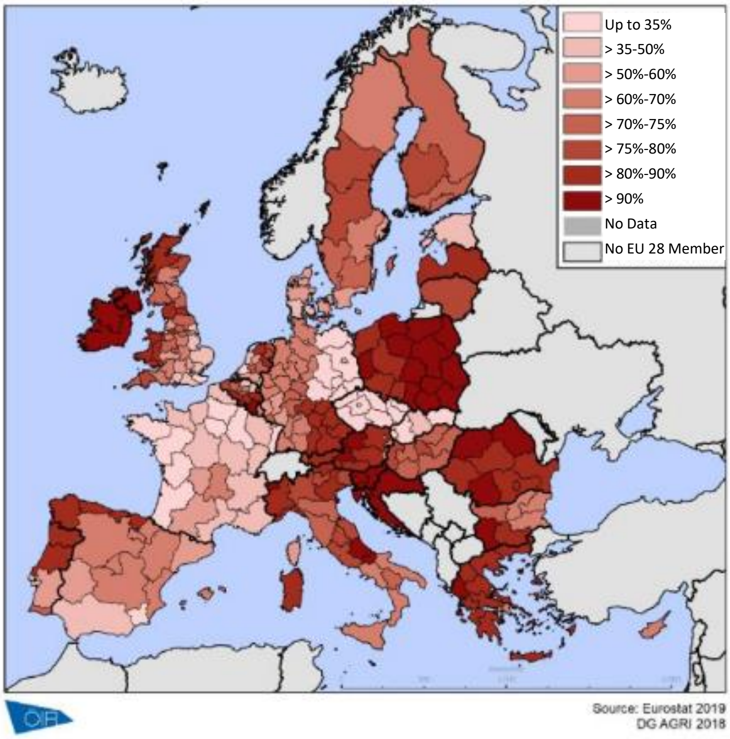
Agricultural labour still very family-based but increasingly frequent use of salaried labour on farms

• Still a very family-based workforce

The European agricultural workforce remains very family-based. In 2016, nine out of 10 people working on a regular basis in agriculture were farmers or their family members (Eurostat, 2021b). Similarly, 92% of work on farms is conducted by family labour (European Commission, 2013b).

Nevertheless, the share of family labour varies from one European location to another (Figure 3-22). Figure 3-22 shows that some countries rely very heavily on family labour in the agricultural sector: Poland, Romania, Bulgaria, Greece, Croatia, Slovenia, Austria, Ireland, Northeast Spain and Portugal, and some regions of Italy. In contrast, other locations have a fairly small family agricultural workforce: France, Eastern Germany, Estonia, the Czech Republic and Slovakia.

Figure 3-22: Share of family labour in the agricultural workforce in Europe, scale NUTS 2 regions (Source: Schuh *et al.*, 2019; Eurostat data)



• Use of salaried and immigrant labour

Although mainly family-based, the European agricultural workforce increasingly uses hired labour (Schuh *et al.*, 2019). Dries *et al.* (2012) believe that salaried labour has replaced family labour.

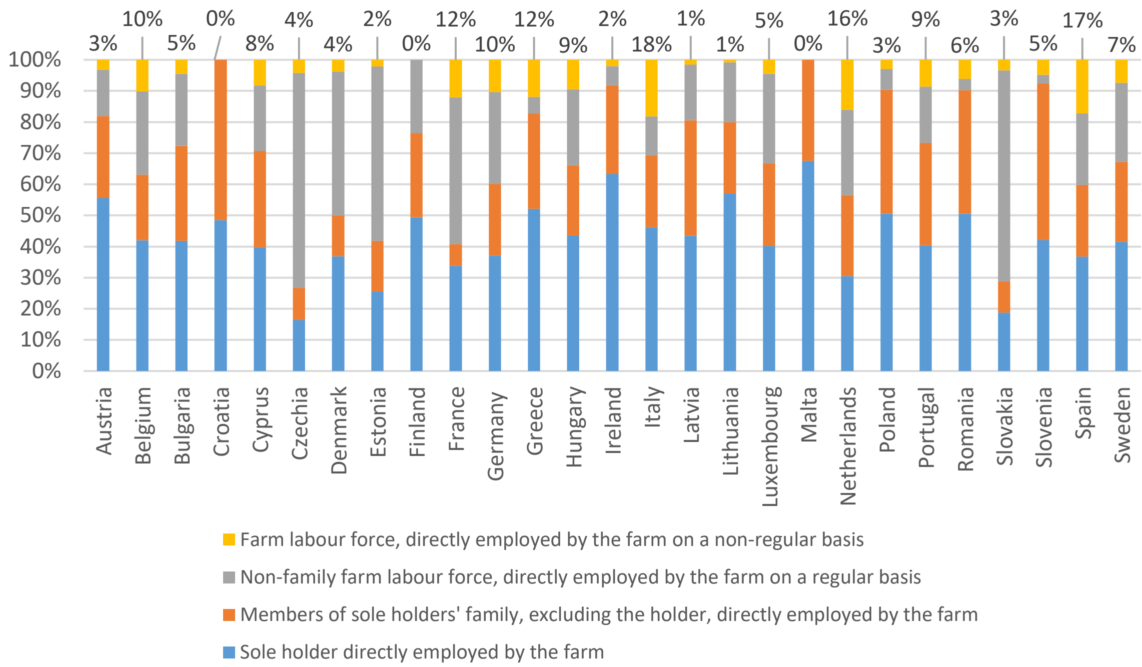
This salaried workforce (regular and seasonal) is particularly significant in some countries, where it represents more than 50% of the agricultural workforce: Denmark, France, Estonia, the Czech Republic and Slovakia (Figure 3-23).

Some countries also rely heavily on irregular labour, which represents more than 10% of the agricultural workforce in Mediterranean countries, France, Belgium, Germany and the Netherlands (Figure 3-23).

The demand for irregular labour is linked to distinct peaks in work in some agricultural sectors, particularly for fruit and vegetable picking (Schuh *et al.*, 2019). Some agricultural regions are highly dependent on this seasonal labour (ibid.).

The regions dependent on seasonal labour often use immigrant labour. This is a growing phenomenon with the share of immigrants in agricultural labour growing from 4.3% to 6.5% between 2011 and 2017 across the European Union (Natale *et al.*, 2019). This workforce comes from other EU Member States or from European countries outside the EU, North Africa, Asia and Central and South America (ibid.).

Figure 3-23: Distribution of the agricultural workforce in the different member states in 2016 (Source: Eurostat, processed by authors)



A predominantly pluriactive agricultural workforce in Europe

• Definition of pluriactivity

Pluriactivity refers to activities other than agricultural work on the farm. In general, these activities are remunerated. These activities may be conducted off the farm in agricultural or non-agricultural sectors, or on the farm in non-agricultural sectors (European Parliament Research Service, 2016). It concerns only farmers in the European databases (Eurostat) and we consider here pluriactivity at the scale of the agricultural household.

The diversification of activities on the farm is therefore a form of pluriactivity, but not the only one. Many forms of diversification have developed within the European Union: agritourism, crafts, processing of agricultural products, production of renewable energy, processing of wood, contract work (with or without a connection to agricultural activities, transport, landscape management etc.), and forestry (European Parliament Research Service, 2016).

The diversification of agricultural holdings remains weak in Europe. In 2013, 5.2% of European farms were diversified, but this diversification varies greatly from one country to another. The share of diversified farms was very low in Mediterranean and Eastern European countries, but quite significant in Northern European countries (Denmark, Sweden and Finland) and in Germany (ibid.).

• Significant pluriactivity in Europe but heterogeneous according to the Member State and type of farm

The majority of people working on a regular basis in agriculture also conduct other activities. In 2016, only 17% of agricultural workers conducted this activity full-time, with 83% of the European agricultural workforce carrying out several activities (Eurostat, 2021b). In some European Member States, agricultural activity on the farm is a secondary activity for more than 40% of farmers. These countries include Bulgaria, Sweden, Finland and Denmark (Figure 3-24). In contrast, in other Member States, the majority of farmers work full-time on their farm. These countries include Portugal, Italy, Croatia, Greece, Romania, Belgium, the Netherlands and Latvia (Figure 3-25).

Figure 3-24: Share of farms where the agricultural activity of the farm is a secondary one for the farmer in Member States in 2013 (Source: Schuh *et al.*, 2019)

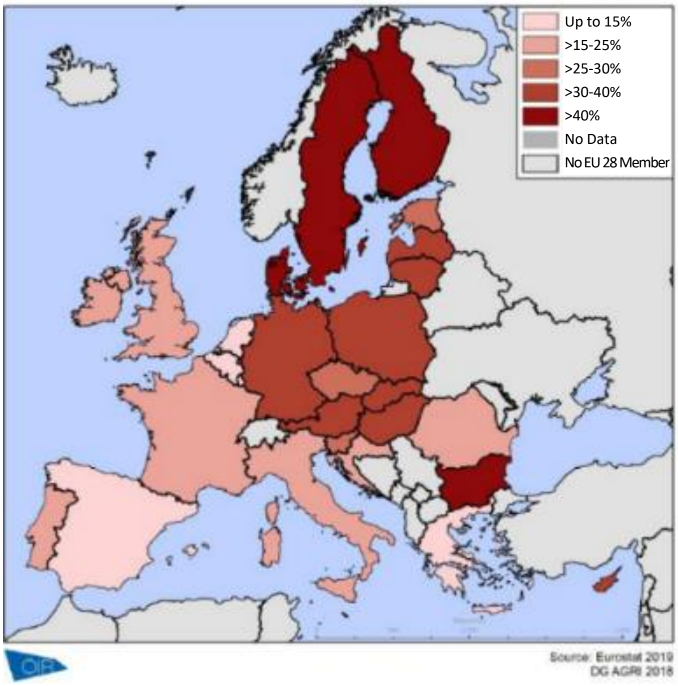
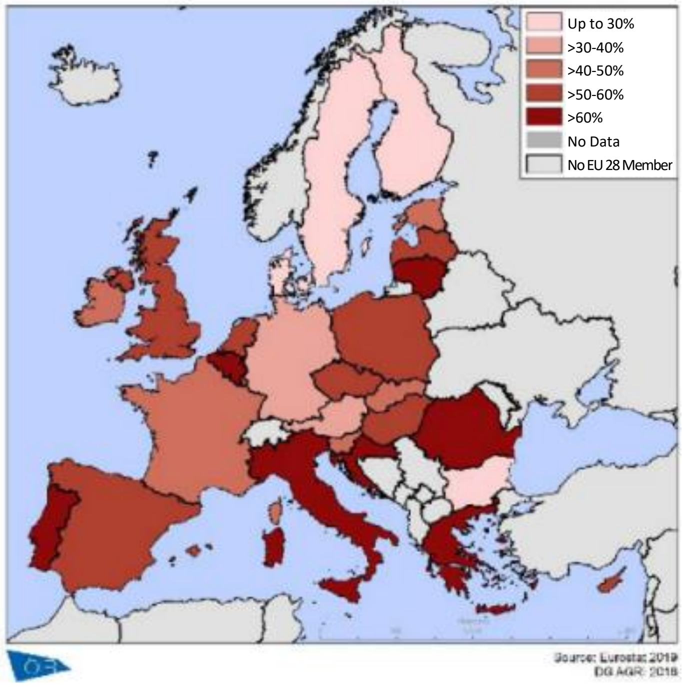


Figure 3-25: Share of farms where the farmer works full-time on the farm in Member States in 2013 (Source: Schuh *et al.*, 2019)



The heads of small farms mostly work part-time, unlike those working on large farms who are mostly full-time. So, 60% of farmers on farms of less than 5 ha spend less than a quarter of their working time on their farming activities, while 70% of farmers on farms of more than 100 ha work full-time in agriculture (European Commission, 2013a).

The on-farm employment of household members is often flexible, making it possible to adjust the share of work allocated to the farm and to work beyond the farm (Dries *et al.*, 2012). The pluriactivity of household members should therefore be greater than that of farmers themselves. According to Shahzad and Fischer (2021), off-farm or diversification activities as a main activity decreased between 2005 and 2016 in Europe. However, the proportion of farmers with such activities as secondary activities increased.

• Factors influencing pluriactivity

When the income generated on a farm is insufficient, agricultural households turn to other jobs off the farm as this allows agricultural households to increase their income (Schuh *et al.*, 2019). In addition, the diversification of activities allows them in turn to diversify their sources of income and therefore be less dependent on a single source of income (ibid.). Some part-time farms can be explained by the development of ‘hobby farms’, with farmers considering their farms as a secondary leisure activity. This is the case in Southern Germany, for example, where inheritance rules push heirs to keep agricultural land without being professional farmers (interview A. Balmann, 2021).

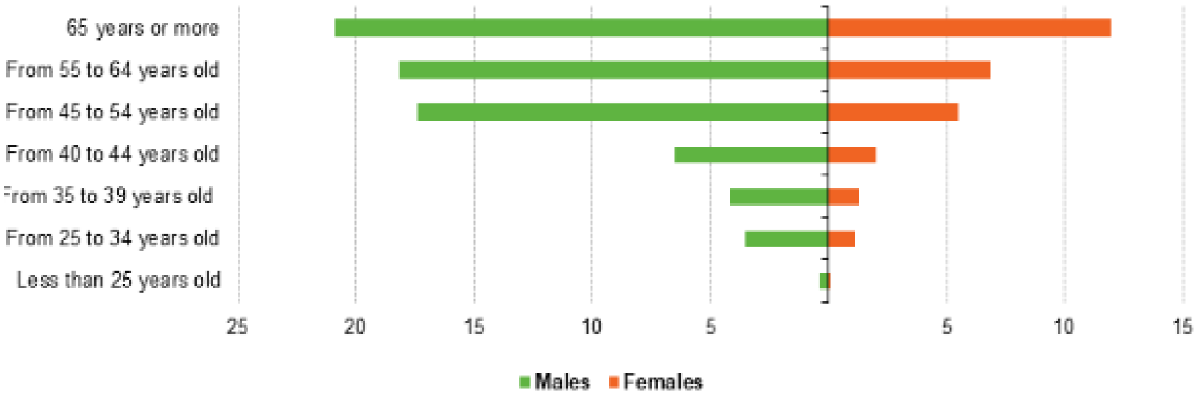
A number of factors that influence pluriactivity can be found the scientific literature (see Shahzad and Fischer, 2021):

- The characteristics of the farm and farmer (size and speciality of the farm, age and gender of the farmer);
- The level of training of farmers and the agricultural household;
- The location of the farm (proximity to an urban centre, tourist areas, accessibility to markets, landscape attractiveness);
- Agricultural policies.

The ageing of the agricultural population and the difficulty of handing on farms

The European agricultural population is structurally old, with the vast majority of farmers being over the age of 45 (Figure 3-26). In 2016, 58% of farmers were aged 55 and over (Eurostat 2021b).

Figure 3-26: Age group of farmers, by gender, in the EU-28 in 2016, in percent of all farm managers (Source: Eurostat, 2021b)



There has been an increase in the share of farms managed by farmers over the age of 65 in the majority of European Member States (Schuh *et al.*, 2019). In some countries the proportion of farmers over 65 can be very high. For example, more than two-fifths of farmers were over the age of 65 in 2016 in Portugal, Cyprus, Romania and Italy (Eurostat, 2021b).

However, older farmers tend to manage small farms. Indeed, many farmers continue to work on their small farms after retirement age for economic reasons or by choice (European Commission, 2013a).

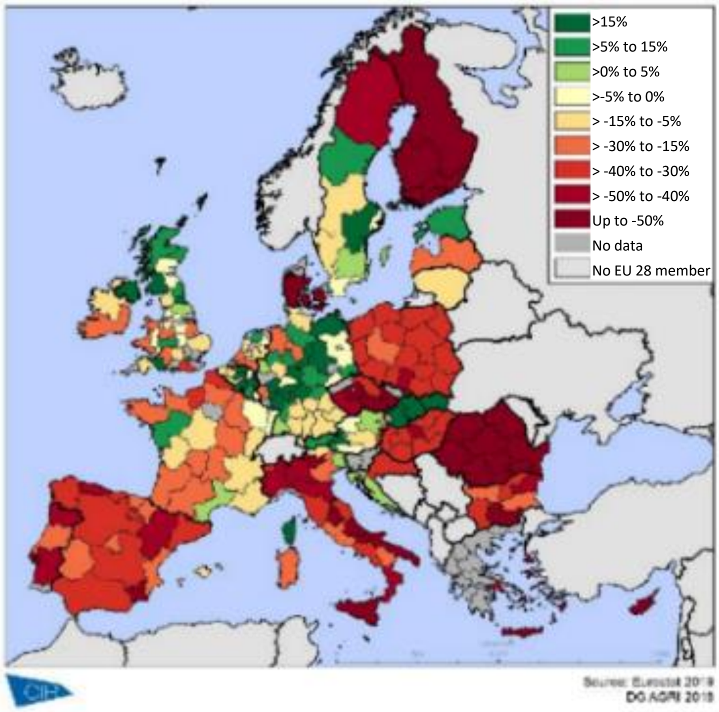
In addition, it is increasingly difficult for young farmers to establish their own farms. They have difficulty accessing agricultural land over which there is strong tension (Kay *et al.*, 2015) and increasingly large and capitalised farms are difficult to transfer (Nguyen *et al.*, 2020).

Most European regions are experiencing a sharp decrease in the number of farms run by farmers under the age of 35, particularly Spain, Portugal, Italy, Finland, Denmark, Poland, Romania, Bulgaria, Hungary and the Czech Republic (Figure 3-27). This raises the question of generational renewal in agriculture by 2050.

• Training and qualifications of the European agricultural workforce

The question of the training and qualifications of the agricultural workforce also arises. Indeed, the development of new technologies in agriculture requires many skills (Jeanneaux, 2018). However, the majority of the European agricultural workforce has not received any training (seven out of 10 people in 2016) (Eurostat, 2021b). The most educated members of the rural workforce tend to turn to non-agricultural jobs (Tocco *et al.*, 2013). This means farmers suffer from a lack of qualified agricultural labour (Interview Balmann, 2021).

Figure 3-27: Percentage change in total number of farms managed by farmers aged 35 and under between 2010 and 2016, NUTS 2 regions (Source: Schuh *et al.*, 2019)



The use of outsourcing and delegation of agricultural work in Europe

Subcontracting dates back many years. This phenomenon first concerned "*certain technical operations [delegated] by the farmer to a third party*" and affected small farms that did not have the equipment necessary to conduct this work (Bignebat *et al.*, 2019; Nguyen *et al.*, 2020).

The use of subcontracting has grown significantly over the past 20 years. For example, in France the number of farms making significant use of subcontracting increased by 53% between 2010 and 2016 (Bignebat *et al.*, 2019). Subcontracting has also changed in nature. While it was originally used for certain specific tasks in order to make up for a lack of equipment, it has developed towards a complete delegation of some work, even of the entire operation, ranging from "*capacity or economic outsourcing"* to *"specialty or strategic outsourcing*" responding to new patrimonial strategies (Nguyen *et al.*, 2020). New operations are also outsourced such as administrative tasks and advisory functions (ibid.). Nguyen *et al.* (2020) describe the development of several forms of subcontracting and work delegation:

- **The subcontracting of one or more tasks**, whether they be crop operations (such as harvesting, spreading fertiliser, treatments, tillage or sowing) or livestock operations (herd monitoring, prophylaxis or artificial insemination). Farms can use it to manage certain peaks in work. This subcontracting is carried out by 'classic' subcontractors (known as ETA in French) and compensates for a lack of skills and specific equipment;
- The **"total delegation of agricultural work"**, known as the "A to Z" for one or more production sites. This is defined as the process which leads to delegating to a third party the management of all the operations of the farm. It is a delegation through a "refocusing" where the operator entrusts the management of less strategic or less profitable production to a subcontractor. This particularly concerns livestock farmers who outsource tasks related to crop production in order to focus on animal husbandry;
- The "**integral delegation of the farm**" which consists of entrusting to a third party not only the conduct of all the work on the farm but also the economic and administrative management of the operation (decisions about rotations and technical itineraries, livestock management,

marketing, management of the teams on site, accounting management and CAP declarations). This delegation leads "*to a total separation between property rights and the operational management of the company*". "*The owner can retain some control over strategic decisions, but all operational decisions are transferred to a third party*." The full delegation of small farms has existed for a long time and concerns non-farming owners who have become owners through an inheritance. The management of the farm is generally taken over by neighbouring farmers who amortise their equipment through the provision of services. The delegation of medium and large farms is more recent and is due to the difficulties of handing on and taking over ever larger and more specialised farms.

According to Nguyen *et al.* (2020), these forms of full delegation promote the development of new actors in subcontracting:

- ‘Multi-service’ subcontractors offering full management of farms and often working in a network in order to have a large fleet of equipment. They can harvest the equivalent of several tens of thousands of hectares. They may develop storage and trading activities in order to sell their harvest directly to agri-food manufacturers;
- Cooperatives for the use of agricultural equipment (known as CUMA in France) developing new so-called ‘comprehensive’ **provision of services**;
- Cooperatives acting as intermediaries between subcontractors and members or offering **services** through their subsidiaries;
- Consulting organisations;
- **Farm management companies**. These corporate-like companies do not have their own fleet of equipment but head up a network of subcontractors who they call on to intervene when needed on behalf of owners who have delegated the management of their entire operation. They can thereby establish joint crop rotations covering several tens of thousands of hectares. Already well established in the United Kingdom and Belgium, these companies are developing in France.

The development of the full delegation of farms opens the way to new forms of agriculture "*where the family dimension loses its centrality*", with a dissociation between land, labour and capital (Nguyen *et al.*, 2020).

Retrospective analysis on agricultural land: from family farming to the concentration and expansion of farms and the emergence of land grabbing strategies

As we saw earlier, European agriculture is still very family-based (Hervieu and Purseigle, 2009) with the characteristic of a unity of production factors (labour, land and capital) (Cochet, 2018). Nevertheless, the model of family farming is eroding due to the high concentration of land and the emergence of the phenomenon of land grabbing (Kay *et al.*, 2015).

There is a high concentration of land in Europe at the expense of small family farms (Kay *et al.*, 2015). Farmland is "*concentrated in an ever-decreasing number of large farms under the control of a few corporations*" where many farmers lose part of their livelihood and control of their land (van der Ploeg *et al.* 2015; Kay *et al.*, 2015).

Another phenomenon called ‘land grabbing’ is currently limited but increasingly present in Europe (van der Ploeg *et al.*, 2015). Van der Ploeg *et al.* (2015) define land grabbing as "*in the first instance, the taking over of a large tract of land*" at odds with locally existing land use and family farming. While land grabbing is much less widespread than in other world regions (Africa, Asia and Latin America), it can be observed within the European Union, particularly in Eastern European Member States (ibid.). The seizure of several tens of thousands, even hundreds of thousands of hectares of agricultural land by various actors has been observed in Romania, Bulgaria, Hungary, Poland, Slovakia, the Czech Republic, Lithuania and Latvia, and this phenomenon is increasing (Kay *et al.*, 2015). Although limited, land grabbing is ‘creeping in’ in other EU countries (van der Ploeg *et al.*, 2015).

The actors behind this land grabbing are varied: international or local, state or private, natural or legal persons. And alongside traditional actors (agri-food empires, commercial producers and banks), new actors have been investing in agricultural land since the 2008 financial crisis: traders, investment funds (including European pension and investment funds) and private equity firms (van der Ploeg *et al.*, 2015; Kay *et al.*, 2015). Indeed, since the financial crisis of 2008, agricultural land has appeared to be a safe bet (Purseigle *et al.*, 2017a).

Due to the concentration of land within increasingly large farms, land grabbing, as well as the phenomenon of artificialisation (a change of land use from agricultural to non-agricultural purposes), agricultural land is becoming increasingly rare and expensive for future farmers (van der Ploeg *et al.*, 2015). Would-be farmers face difficulties in acquiring land and setting up their farms (ibid.).

Kay *et al.* (2015) consider that capital determines access to land. This means the capital and land production factors are closely linked, particularly during the farm acquisition and establishment phase, we will see below that access to capital and a source of financing can determine access to land.

Retrospective analysis on capital: a mainly internal source of financing and a trend to open up to external capital

A farm's capital corresponds to its means of production for which the farm has had to invest. A distinction is made between fixed operating capital, "*which is the value of goods used for several production cycles*" (tools, machinery, buildings etc.) and working capital, which is the "*value of goods consumed during a production cycle*" (seed, fertiliser, feed etc.) (Dufumier and Bergeret, 2002).

Farms can use different types of financing to invest in their means of production. Since the Common Agricultural Policy was established in 1962, in Europe a farm's "*own funds and bank debt have been, and remain, the preferred tools for financing agricultur*e" (Nguyen *et al.*, 2017). The development of increasingly large and increasingly well-equipped farms, in particular with technological tools, does not prevent them from maintaining a family dimension using internal capital on the farm (Cochet, 2018).

Despite everything, these farms are increasingly indebted and can have problems financing their investments (through bank loans), particularly during the periods when farms are transferred and new farmers are setting up their businesses and during the development of farms (Nguyen *et al.*, 2017). In order to respond to the difficulties of investing in increasingly expensive equipment and the transfer of increasingly capitalised farms, one solution may be to resort to the delegation of labour (see above and Nguyen *et al.*, 2020).

Alongside this, Nguyen *et al.* (2017) have observed new financial actors (investment funds, private actors etc.) who invest in farms, which are seen as a secure investment. This means an increasing number of farms are using external capital. Nguyen *et al.* (2017) define external capital broadly, as "*all sources of financing, other than self-financing and bank debt*". Nguyen *et al.* (2017) define four ideal-types of agricultural financing through external capital, with different actors and logics:

- **Shareholder governance** mainly guided by a **financial logic**, where investors are non-local and unknown and whose objective is financial returns;
- **Shareholder governance of the family capitalism type** (which we will detail in the familial agroholdings paragraph below). The financiers are members of the extended family but they are not operators, the objective here is to be able to manage a family heritage;
- **Entrepreneurial-type shareholder governance** that is close to the full delegation of operations. The investors are "farmers-investors", themselves from the agricultural community, whose objective is to turn around farms in decline and to obtain a return on their investment;
- **Solidarity-type shareholder governance**: for the most part investors are in close contact with farmers and wish to "*promote access to agricultural land for young farmers*". The logic is ethical and supportive;

In these ideal-types, financing can be achieved either by taking a stake in the capital of the farm (total or partial), or by making it available through rental/lease or leasing.

Therefore, the capital of European farms, although still predominantly family owned (own funds and bank debt), is gradually opening up to the outside world through various types of financing. These different modes of financing also raise the question of the unity of production factors, with forms of agriculture where capital, land and labour, although partly family-based, can find themselves segmented and in the hands of various actors.

Retrospective analysis on the organisation of production factors

As we have seen, European agriculture is mainly family-based, with structures where the production factors of labour, capital and land rest in the same hands (Hervieu and Purseigle, 2009; Cochet, 2018). Nevertheless, these production factors tend to be increasingly segmented within European farms.

Firstly, the relationship between labour and capital is changing with the mechanisation of agriculture and the development of digital agriculture (see below, paragraph 3.1.3.4).

In addition, we are seeing new forms of agriculture that throw into question the organisation of production factors. These include the development of new approaches to organisation of labour (significant use of salaried labour, delegation of work) (Schuh *et al.*, 2019; Nguyen *et al.*, 2020), appropriation of land by financial actors (van der Ploeg *et al.*, 2015), and openness to external capital (Nguyen *et al.*, 2017). Below we present two types of agricultural structure whose production factors are segmented: familial agroholdings and corporate farming.

From mechanisation to digital agriculture, the substitution of capital for labour and new relationships between capital and labour

The technical and technological progress made possible by the mechanisation of agriculture, and now the development of digital agriculture, have thrown into question the relationship between labour and capital within farm structures.

Indeed, over the past 50 years, the substitution of capital for labour has enabled significant productivity gains. There has been an increase in agricultural production volumes despite a sharp reduction in the agricultural workforce (Jeanneaux, 2018). Thanks to machines, this "first machine age" or "industrial revolution" allowed humans to increase their physical strength tenfold (ibid.).

The era of digitisation (or "second machine age") is now developing within agriculture, with many digital tools being adopted by farmers (Jeanneaux, 2018; Klerkx *et al.*, 2019). Klerkx *et al.* (2019) define digitisation as "*the socio-technical process of applying digital innovations*" and identify many digital technologies: big data, the Internet of Things (IoT), augmented reality, robotics, sensors, 3D printing, system integration, ubiquitous connectivity, artificial intelligence, machine learning, digital twins and blockchain. Many concepts try to grasp the application of digital technology in agriculture (smart farming, precision agriculture, digital agriculture, agriculture 4.0, etc.) (Klerkx *et al.*, 2019).

In the scientific literature (Jeanneaux, 2018; Klerkx *et al.*, 2019), it is expected that digital agriculture will provide new productivity gains by optimising agricultural systems (reduced working time and costs, maximisation of yields, response to environmental and social expectations), in particular through:

- The collection of numerous data by various monitoring tools (sensors, machines, drones and satellites), their processing and the selection of the best solution (decision support tools);
- The production, exchange and appropriation of knowledge;
- The automation and the robotisation of tasks.

New technologies also allow for the expansion of farms, and in particular, the emergence of "agroholding" type farms (Hermans *et al.*, 2017).

However, the development of digital technology in agriculture raises many questions about the relationship between capital and work, in particular about farmers' relationships with their job and their autonomy in decision-making (Jeanneaux, 2018). Digital tools throw into question the governance of farms by highlighting important new actors: information becomes a "strategic asset" which can give an important place to actors in the field of agricultural equipment, data scientists, data managers and service companies capable of collecting, processing and enhancing data (ibid.). For example, it also provides large retailers with the possibility of ensuring product traceability (Schretr, 2018).

In addition, these new technologies are demanding in terms of capital and skills, which requires farmers to adapt and reorganise the farm's work and capital, to organise themselves collectively (pooling of resources and skills), to call on third parties (delegation of work), or to use external capital (Jeanneaux, 2018; Nguyen *et al.*, 2017).

Familial agroholdings, family farms that look like companies, dissociating agricultural work from farm capital

A new form of agricultural structure is emerging in Europe, both family-based and capital-intensive, described as "corporate family farming", of the "family capitalist" or "family holding" type (Hervieu and Purseigle, 2009; Nguyen and Purseigle, 2012). We will call them familial agroholdings.

Hervieu and Purseigle (2009) observed the development of agroholdings in France (in the Landes and around Paris), in Italy (on the Po plain) and in Eastern Germany (in the new Länders). Nguyen and Purseigle (2012) have studied their emergence in the French Camargue.

These farms are family through their capital, which is essentially family capital, but are of the corporate type in terms of their organisation. These farms are similar to corporate agriculture, where labour and farm capital are separated (Hervieu and Purseigle, 2009). The logic of these farms is patrimonial, with capital and land in the hands of members of the extended family, who own shares in the farm and receive an annuity. The management of the farm is generally handled by a single representative of the family and employees (Nguyen and Purseigle, 2012). Family member shareholders do not really take part in the governance of the farm and are only involved in a "sporadic and non-controlling way", in strategic decision-making for example (Nguyen *et al.*, 2017). This type of operation can be a solution for farms that are "*difficult to transfer to a single member of the family […] because of their high level of capitalisation*" (ibid.).

These familial agroholdings have related activities and offer services to neighbouring farms. This includes the provision of agricultural work, resale of inputs, supplier credits and advances on the harvest, storage, packaging and processing of products, even the full management of farms, especially since they have "*an abundant workforce and a sufficiently powerful selection of equipment*" (Nguyen and Purseigle, 2012). This allows them to free themselves from storage and supply cooperatives (ibid.). These farms also operate on a logic of "productive concentration" "*based not only on the acquisition of land [...] but also on rental, production and supply contracts with neighbouring farmers, or shared crop rotation*s", allowing them to reach crop rotations covering several thousand hectares (ibid.).

'Corporate' structures with a strong segmentation and mobility of production factors

"Agroholding", "mega-farm", "capitalistic" or "corporate" type structures are also developing in which the arrangements between land, capital, work and family are revisited (Hermans *et al.*, 2017; Hervieu and Purseigle, 2009; Nguyen and Purseigle, 2012; Purseigle *et al.*, 2017b). These structures also have shareholder-type governance, but this time the logic is purely financial and the management of the farm is fully delegated (Nguyen and Purseigle, 2012).

Hermans *et al.* (2017) define an agroholding as "*an agricultural organisation whose majority block of shares is held by a joint-stock company*". These corporate structures have other specific characteristics that differentiate them from family farming (Purseigle *et al.*, 2017b; Hermans *et al.*, 2017):

- Their very large size of several thousand or even tens of thousands of hectares;
- Their industrial nature (mass production, significant equipment and rationalisation);
- Their integration and concentration capacity both upstream and downstream;
- Their complex organisation with a separation of operational management and ownership and "*a plurality of decision-making centres*";
- Their capacity for innovation, adaptation and anticipation.

This type of structure has highly segmented production factors, with capital and land owned by shareholders, and operational management and labour delegated to a hired workforce. The production factors are also mobile since the farm can be the subject of several sales and takeovers over a short space of time "*if its short-term profitability is called into question*" (Nguyen and Purseigle, 2012).

The owners of the capital can be multinational firms or investment funds looking for financial profitability, but also sovereign funds wishing to secure the food supply of their country (Nguyen *et al.*, 2017; Hervieu and Purseigle, 2009).

In the development of large subcontracting companies managing entire work programmes, even entire farms, Purseigle *et al.* (2017b) see a form of corporate agriculture that is able to negotiate directly both upstream and downstream and participate in a form of land concentration.

Nevertheless, these farms are fragile and may find it difficult to make a profit (Hermans *et al.*, 2017), in particular because they are too focused on short-term profits for shareholders to the detriment of long-term strategies based on production (Kuns *et al.*, 2016). In addition, they are not firmly anchored in their territory and are the subject of controversy due to their industrial nature and negative local impacts (Nguyen and Purseigle, 2012; Purseigle *et al.*, 2017a).

Retrospective analysis on urban and peri-urban farm structures: between opportunities and constraints

Historically, European cities have depended on nearby food production from peri-urban areas (Zasada *et al.*, 2012). These local food flows have diminished in favour of inter-regional or global food flows, which have been made possible by improved transport and storage (ibid.). In addition, agriculture in urban and peri-urban areas faces many constraints. To begin with, agricultural land in peri-urban areas is subject to strong land pressure and the phenomenon of the artificialisation of land, in particular due to urban sprawl (van der Ploeg *et al.*, 2015). For example, Busck *et al.* (2008) observed a reduction in agricultural production and the number of full-time farmers near Copenhagen between 1984 and 2004. Proximity to a city creates other disadvantages for farmers: uncertainty about urban development, disadvantages for agricultural production, particularly livestock (restrictions on increasing production and for the spreading of manure), as well as problems related to the entry of people on their private property (Busck *et al.*, 2008).

However, urban and peri-urban agriculture is receiving growing interest. It is increasingly of interest in municipal or regional policy making, as a response to many challenges such as growing consumer demand for local products and the supply of non-agricultural goods and services (landscape management, leisure and recreation areas, other ecosystem services, shared gardens) (Duží *et al.*, 2017; Zasada *et al.*, 2012). Nahmías and Le Caro (2012) have identified three categories of cohabitating urban and peri-urban agriculture: "*an agriculture oriented towards the supply of raw materials to the market, an agriculture organised in short distribution channels, and an agriculture practiced without professional objectives by city dwellers*". Accordingly, the proximity of a city provides access to other non-agricultural income-generating activities, but also to diversification possibilities on the farm through easy access to new markets, for example, agritourism or farm gate sales (Busck *et al.*, 2008). Peri-urban agricultural land can be seen as an investment. For example, in 2022 an investor bought 3,000 ha of land near Berlin in order to supply the city and its outskirts with local and organic products, which is a very profitable market (AEsP workshop, 2022).

These constraints and opportunities have an impact on the structure of urban and peri-urban farms. These are more often recreational and part-time farms (Busck *et al.*, 2008) but they have a greater reliance on hired labour and generate more income per hectare (Zasada *et al.*, 2012). These farms are also more often specialised in market gardening, horticulture and livestock (Zasada *et al.*, 2012).

Finally, urban and peri-urban agriculture may be practiced non-professionally by individuals, whether through gardening (in gardened areas around the residence, on balconies or terraces, in shared gardens or allotments or on rented or loaned ground on the urban fringe or in the suburbs), or leisure agriculture (breeding of horses or sheep, non-professional crop production etc.) (Nahmías and Le Caro, 2012). This is motivated not only by the production and consumption of healthy food but also socio-territorial motivations (social spaces, living environment etc.) (ibid.).

Hypotheses of change for the organisation of production factors in 2050

From this retrospective analysis, we have formulated several hypotheses of change about the organisation of production factors in 2050. To do this, we first created hypotheses of change for each of the production factors taken separately. We then combined these in order to build hypotheses of change on the organisation of production factors taken together.

Hypotheses of change for production factors taken individually

- Labour:

Work can be conducted by farmers and/or members of their families and thereby be family-based. It can also rely on hired labour. Finally, work can be outsourced to a third party, either partially or totally.

- Land:

Land may or may not belong to the family and the family may have usage rights over land without owning it. In contrast, the land may belong to the agricultural household, which delegates the work entirely to a third party. The question is rather whether land is linked to labour or whether it is linked to capital.

- Capital:

Capital can be financed through a family's own funds or through bank debt and therefore remains internal to the operation. Conversely, capital can come from entities outside the agricultural world and external to the farm. Finally, there can be a mixed approach, with part of the farm's internal capital and opening up to external capital.

We obtained the following table of hypotheses for the three production factors (Table 3-3):

Table 3-3: Hypotheses of change for the evolution of each production factor

Production factor	Hypothesis 1	Hypothesis 2	Hypothesis 3
Labour	Family	Salaried	Externalised
Land/property	Linked to labour	Linked to capital	
Capital	Internal	Mixed	External

Hypotheses of change for the organisation of production factors in 2050

From Table 3-3, we have established four hypotheses of change on the organisation of production factors:

- **Hypothesis 1: Unity of production factors**

The first hypothesis is the unity of production factors (Table 3-4). It corresponds to family-type farms where the family owns all the production factors. Labour comes from the family and the family owns the capital and the land (or has user rights on the land).

Table 3-4: Organisation of production factors for the unity of production factors hypothesis (selected hypotheses in green)

Production factor	Hypothesis 1	Hypothesis 2	Hypothesis 3
Labour	Family	Salaried	Externalised
Land/property	Linked to labour	Linked to capital	
Capital	Internal	Mixed	External

- **Hypothesis 2: Outsourcing of work**

This hypothesis is based on the fact that work is entirely outsourced and delegated to service companies. The land remains in the hands of the farmer but the work is outsourced. Though the capital is in the hands of the farmer, part of the equipment belongs to the service company that does the work, so the capital is mixed (Table 3-5).

Table 3-5: Organisation of production factors for the outsourcing of work hypothesis (selected hypotheses in green)

Production factor	Hypothesis 1	Hypothesis 2	Hypothesis 3
Labour	Family	Salaried	Externalised
Land/property	Linked to labour	Linked to capital	
Capital	Internal	Mixed	External

- **Hypothesis 3: Familial agroholding**

This hypothesis depicts situations of familial agroholdings (Table 3-6), described earlier (paragraph 3.1.3.4). Capital is currently family-owned and we hypothesise that this type of operation will open up to external capital by 2050. A family member and employees conduct the work. The management of the land correspond to a profitable patrimonial logic and is linked to the capital.

Operational management and capital are separate, but there remains a family dimension to these farms and there is a form of hybridisation of production factors.

Table 3-6: Organisation of production factors in the familial agroholding hypothesis (selected hypotheses in green)

Production factor	Hypothesis 1	Hypothesis 2	Hypothesis 3
Labour	Family	Salaried	Externalised
Land/property	Linked to labour	Linked to capital	
Capital	Internal	Mixed	External

- **Hypothesis 4: Corporate farming**

In this hypothesis, we envisage the generalisation of corporate agriculture in Europe (Table 3-7). External investors invest in farms according to a strictly financial logic. The capital and land belong to shareholders, and the management and work are delegated to employees or to external companies. These farms are easily sold and taken over by other entities. This hypothesis includes situations where many farms have entirely delegated their management to 'business-like' management companies, covering significant cropping areas. Production factors are segmented and mobile.

Table 3-7: Organisation of production factors in corporate farming hypothesis (selected hypotheses in green)

Production factor	Hypothesis 1	Hypothesis 2	Hypothesis 3
Labour	Family	Salaried	Externalised
Land/property	Linked to labour	Linked to capital	
Capital	Internal	Mixed	External

In summary, for the organisation of production factors component, the four hypotheses constructed are presented in Table 3-8 below.

Table 3-8: Hypotheses of change for the organisation of production factors component

Component	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4
Organisation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors

3.1.2. Building microscenarios of European farm structures in 2050

3.1.2.1. Construction of types of farm structures in 2050

From the components covering farm governance and the organisation of production factors, we have defined several types of agricultural structure in 2050 (Tables 3-9, 3-10, 3-11 and 3-12). These structures in 2050 are the result of discussions within the expert committee on October 5, 2021, and reworked within the project team on December 20, 2021.

First type of farm structures in 2050: Persistent family farming

This type of **persistent family farming** structure is based on family governance of farms and the unity of production factors. All the production factors belong to the family that makes the decisions. This description is consistent with the structure of family farms as they are traditionally represented. They will still have an important presence in Europe in 2050. The members of the farm household who work on the farm and who own the capital and the land take the decisions. In 2050, this family farming frequently coexists with other types of farms.

Table 3-9: Persistent family farming

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Organisation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	

Second type of farm structures in 2050: Familial agroholdings

The **familial agroholding** type of structure corresponds to the development of family agroholdings (presented in paragraph 3.1.3.4). In 2050, large farms have evolved moving away from the family model. Though the capital has remained within the extended family, the operational organisation has been delegated to a single member of the family and employees conduct work. These farms have also opened up to external capital. There is a hybridisation of production factors. The family does not necessarily own all the land used because part of it may belong to other owners and be managed in full (work, marketing and asset management) by the manager and his employees, in the form of the provision of services. Thanks to the delegation of work, we are witnessing a concentration of production. In 2050, these farms are in direct contact with the large agro-industrial and agri-food firms that influence their governance. The extended family has only a minor role but is still consulted on strategic decisions.

Table 3-10: Familial agroholdings

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Organisation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	

Third type of farm structures in 2050: Financialised agriculture in a global economy

This type of structure combines governance by agri-food firms and financial investors with a strong segmentation and mobility of the production factors. By 2050, farm structures of the corporate farming type presented earlier (paragraph 3.1.3.4) have become widespread. The capital is external to the farms and the work conducted by employees in a logic of profitability. These farms reach substantial sizes (several thousand hectares). They have developed in a 'liberal' economic context, with a financial and globalised economy and a liberalisation of the land market. However, these types of large farms can be quite fragile in the face of market variations. Due to their disconnection from the territory, these farms regularly face opposition from the local population and environmental associations, who denounce their negative local impacts.

Table 3-11: Financialised agriculture

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Organisation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	

Fourth type of farm structures in 2050: Territorial agriculture

In 2050, farms that are well anchored in their territory have developed. These family structures combine governance shared with local actors and/or consumers and collective farmers' organisations. These family farms can delegate part or all of the farm work. These agricultural structures have been able to integrate territorial issues (local food, protection of biodiversity, landscape and heritage, quality of life and the health of local residents), through partnerships with local actors and by offering local, quality products.

In order to respond to the various territorial challenges, strategic decisions concerning agricultural structures are taken collectively in cooperatives that have been able to develop a democratic process in which each member has one vote, or in other forms of farmers' collectives at the territorial scale (sharing of resources and knowledge).

Table 3-12: Territorial agriculture

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Segmentation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	

3.1.2.2. Narratives of micro-scenarios for European farms in Europe in 2050

Based on the hypotheses on the types of agricultural structures and the coexistence of farms in 2050, three micro-scenarios were developed during a project team workshop on December 20, 2021, then re-worked with the expert committee on 14 January 2022.

These micro-scenarios describe what farm structures could be in 2050, without tackling the question of pesticide use (Tables 3-13, 3-14 and 3-15). In a second step, we will ask ourselves how these structures can make a transition towards chemical pesticide-free agriculture.

Microscenario 1: Specialisation and financialisation of farm structures with residual family farms

Table 3-13: Specialisation and financialisation of farm structures with residual family farms

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Segmentation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	
Co-existence of farm structures in EU	Dual organisation of farm structures in EU and regional specialisation	Ternary organisation of farm structures in EU and re-diversification at regional level	Ternary organisation of farm structure in EU and re-diversification at farm level		

In 2050, agricultural structures are financialised and highly specialised. In a context of financialisation and globalisation of the economy, large agricultural companies (several thousand hectares) financed by external capital from investors or shareholders (holding companies) concentrate agricultural land. In these companies, production factors are segmented and mobile. Capital comes from financial investors, while employees conduct the work and the land is regularly bought and sold back and forth from one company to another. The high productive concentration of agricultural land is also achieved through corporate-like farm management companies, which fully manage a large number of farms on behalf of their owners. These companies do not have a fleet of machines but have a whole network of service companies who perform services on behalf of their customers.

These farms respond to a purely financial and speculative logic by seeking economic profitability. In 2050, they are part of long and standardised value chains, operating on raw material markets ('commodities'). They are highly specialised. Constantly on the lookout for new markets, they can invest in specific sectors with high economic returns. In particular, they can invest in peri-urban areas near large cities to develop production geared towards supplying urban consumers. This allows them to meet the strong demand in the urban population for fresh and local products and participate in a lucrative market.

Nevertheless, residual small family farms coexist alongside corporate structures in 2050. These family farms have few financial means to develop and remain small. Those working on the farm develop pluriactivities by taking a job outside of the family farm. Depending on their location, family farms develop local distribution channels to market their products and achieve better prices.

In 2050, the coexistence of these two types of farms has generated a landscape of dual structures at the European scale, with a high concentration of land within corporate structures. Medium-sized farms no longer exist. There has also been a strong specialisation both within farms and in agricultural regions, with a geographical concentration of production.

Microscenario 2: Regional diversity of farm structures

Table 3-14: Regional diversity of farm structures

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Segmentation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	
Co-existence of farm structures in EU	Dual organisation of farm structures in EU and regional specialisation –	Ternary organisation of farm structures in EU and re-diversification at regional level	Ternary organisation of farm structure in EU and re-diversification at farm level		

Since 2022, the limits and criticisms of regional specialisation have pushed value chain actors to promote the diversification of sectors within the major European regions. In 2050, we observe a heterogeneity of farm structures and a diversity of production within the regions. However, each farm structure remains highly specialised.

Distributors/processors and cooperatives have organised regional chains, in particular through contracts, standards and labels. Establishing these chains has led farms to position themselves in different production categories within the same region and to specialise in them while maintaining a family nucleus.

Several types of farms coexist in the regions. The largest farms are familial agroholdings that have a form of hybridisation of production factors. The capital is mainly from the family, governance is through shareholders (each family member owns shares) and farm management is ensured by a member of the family or an employee, while employees conduct the work. These agroholdings produce high volumes and have direct contact with processors and distributors.

In 2050, alongside these familial agroholdings, family farms also persist. These family farms can be large (greater than 50 ha but smaller than familial agroholdings) and are also medium and small in size. Large and medium-sized farms are specialised and integrated into cooperatives. Since 2022, cooperatives have remained key players, linking farms to processors and distributors. They are large in size and operate like private companies. The heads of family farms frequently use service providers. This delegation allows them either to refocus on an activity that creates added value (for example, concentrating on livestock by fully delegating cropping activities), or to fully delegate the management of the farm in order to devote themselves to other income-generating activities beyond the farm. The smallest farms are residual, and not linked to the cooperatives.

In 2050, the supply to urban regions is mainly ensured by actors in regional value chains. These guide farms near urban areas towards production intended for city dwellers (market gardening, arboriculture, etc.).

In this micro-scenario, the landscape of farm structures on a European scale is organised in a ternary fashion, with small, medium and large farms coexisting. While we can see a plurality of technical and economic approaches within the same region, for the most part farms remain highly specialised.

Microscenario 3: Territorialisation and diversification of farm structures

Table 3-15: Territorialisation and diversification of farm structures

Components	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4	Hypothesis 5
Governance of farm structures	Governance by financial investors – Stock company logic	Governance by agro-industrial firms (standards, labels) – Family business or stock company logic	Governance by collective organisation of farmers (cooperatives, collective agreements etc.)	Shared governance with local stakeholders and/or consumers – Family business enlarged logic	Family governance – Family business logic
Segmentation of production factors	Unity of production factors	Outsourcing of work	Familial agroholding – hybridisation of production factors	Corporate farming – segmentation and mobility of production factors	
Co-existence of farm structures in EU	Dual organisation of farm structures in EU and regional specialisation – high dependence between regions	Ternary organisation of farm structures in EU and re-diversification at regional level	Ternary organisation of farm structure in EU and re-diversification at farm level		

In 2050, agricultural structures are intertwined with the actors and activities in their territory.

Since 2022, agricultural structures have responded to various challenges raised by the various actors in the territory: local food, protecting biodiversity, landscape and heritage, quality of life and the health of local residents etc. In 2050, farms are family-run, land concentration is limited and new farmers are supported in establishing their farms, particularly small ones. Farms are diverse: small, medium and large ones are found in the same area. It is particularly through 'living labs' that local farms have developed shared governance involving actors in the territory.

In order to meet the various territorial challenges, farms have diversified their production. They are also organised collectively, particularly within small cooperatives where decisions are taken collectively, or producer organisations implementing quality or geographical labels. This collective organisation has also taken place through the pooling of equipment (to limit investment costs), services, land and the sharing of experiences etc. Some of these farms, particularly the larger ones, delegate some of the work done on the farm.

Agricultural production is mainly marketed through local and more extensive distribution channels. Residents, consumers and local actors are involved in the governance of value chains, particularly local distribution channels, but also in longer value chains, while farms remain rooted in the territory in order to meet the area's various challenges.

In 2050, cities are supplied by relocated food systems where peri-urban farms provide diversified, local, seasonal and quality products. Some members of the urban population produce part of their own food through private or shared urban gardens.

3.2. Food value chains in Europe for chemical pesticide-free agriculture: Past trends and future changes in 2050

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Table of contents

Introduction

Developing scenarios of chemical pesticide-free agriculture in Europe in 2050 not only involves developing scenarios at the cropping system and farm level. Imagining alternative crop protection strategies involves considering changes in the downstream of food value chains of which farms are part. It involves questioning the values of consumers driving the production of chemical-pesticide free food, the governance and organisation of activities within food value chains in relation to these values, the nature of the information on chemical-pesticide free food provided to consumers, means to provide this information, as well as means to store and preserve food between harvesting and consumption. In this Section we therefore explore trends and weak signals of changes, to build hypotheses of change on these topics for 2050. We finally build microscenarios of value chains for chemical pesticide-free agriculture and food in 2050 that combine mutually consistent hypotheses of change.

Materials and methods

This Section is based on seven semi-structured interviews with academic scientists and actors of food value chains (see Table A7 in the Appendix of the report) and a snowball literature review. Three interviews were conducted with experts: a researcher in the socio-economics of food systems, a researcher in the sociology of food and eating, and an expert in general informational watch. Four interviews were conducted with actors of food value chains: a network dedicated to agri-food innovation, an application for the evaluation of food products, an online platform for the distribution of food products and a consumer organisation. The note includes some past European trends, weak signals of change and hypotheses on:

- Food purchasing behaviour and consumption;
- The organisation of activities among actors and the governance of food value chains;
- Information provided to consumers;
- Technologies to sort, store, process and/or preserve food.

The Section follows (i) a presentation made at the Third meeting of the Expert Committee (October 5, 2021) to discuss challenges and changes necessary to build chemical pesticide-free food value chains by 2050; and (ii) a presentation made at the Fourth meeting of the Expert Committee (January 14, 2022) to build hypotheses on value chains for chemical pesticide-free agriculture and food in 2050. It was therefore enriched by discussions with the foresight expert committee.

3.2.1. Food purchasing behaviour and consumption

3.2.1.1. Trends and weak signals of change in food purchasing behaviour and consumption

According to the latest Eurobarometer survey, Europeans prioritise taste, food safety and cost over sustainability concerns when purchasing food products (EC, 2020a) (Table 3-16). Sustainable food products and diets are primarily associated with nutrition and health but also with little or no use of pesticides, affordability, and environmental protection (localness, environmental impact) (Table 3-17). Environmental aspects of sustainable food products are particularly important for Northern-European consumers: local or short supply chains is the most important characteristic of sustainable food in

Sweden, Finland and Austria ; low environmental or climate impact is the most important characteristic in the Netherlands, Ireland and Denmark, and the second most in Sweden and Belgium (EC, 2020a).

According to the three last Eurobarometer surveys, Europeans are aware and worried about health risks associated with pesticide residues in food products (EC, 2020a; EFSA, 2019, 2010).

Table 3-16: Key factors influencing European consumer food purchase from answers to the question 'When you buy, which of the following are the most important to you? Firstly? And then? (MAX. 3 ANSWERS)' (Source: EC, 2020a)

Factors influencing food purchase	% of respondents
Taste	45
Food safety	42
Cost	40
Where the food comes from	34
Nutrient content	33
Amount of available shelf-life	20
'Minimally processed'	16
'Ethics and beliefs' (e.g., animal welfare)	16
Environmental and climate impact	15
Convenience	9
Other (spontaneous)	0
Don't know	0

Table 3-17: Main characteristics of sustainable food according to European consumers from answers to the question 'Which of the following do you consider to be the most important characteristic of sustainable food? Firstly? And then? (MAX. 3 ANSWERS)' (Source: EC, 2020a)

Food is sustainable when	% of respondents
It is nutritious and healthy	41
It has been produced with little or no use of pesticides	32
It is affordable for all	29
It comes from 'local or short supply chains'	24
It has 'low environmental and climate impact'	22
It uses minimal packaging, no or little plastics	20
It uses high animal welfare standards	20
It ensures respect for workers' rights, health and safety and fair pay	19
It is organic	18
It is minimally processed, traditional	18
It ensures fair revenue for producers	16
It is available	10
Other (spontaneous)	0
Don't know	1

In their review, Asioli *et al.* (2017) also show that health concerns is a major driver affecting food choices in industrialised societies, which motivate consumers to choose 'free from' artificial additives/ingredients, natural and organic food products. Consistent with these data, data from Euromonitor International show an increasing trend of consumption of 'health and wellness' food products both in Western and Eastern Europe with a smallest change in sales between 2009 and 2019 in Western Europe than in Central and Eastern Europe but higher sales (Bumbac, 2019) (Figure 3-28 and 3-29).

Figure 3-28: Health and wellness food in Western Europe, 2005-2024 (euros capita^{-1} year^{-1})

Health and wellness food products include: (i) 'better for You' food products with a lower amount of unhealthy substances (e.g. sugar, fat, salt); (ii) 'fortified/functional' food products with added healthy ingredients and/or nutrients (e.g. vitamins, calcium, omega-3); (iii) 'naturally healthy' food products (e.g., high fiber food, wholegrain, fruits, honey, olive oil); and (iv) organic products (Source: Bumbac, 2019)

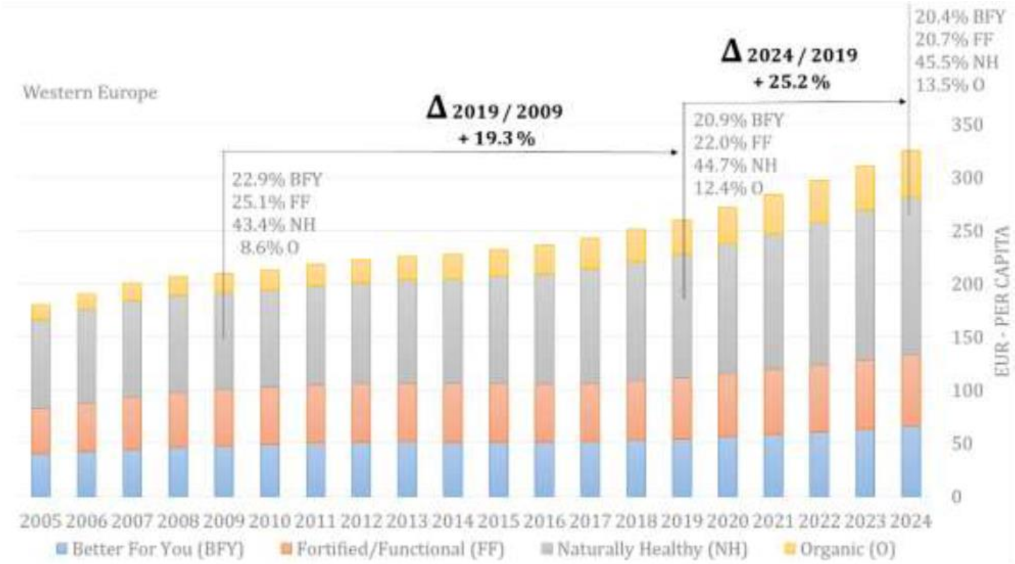
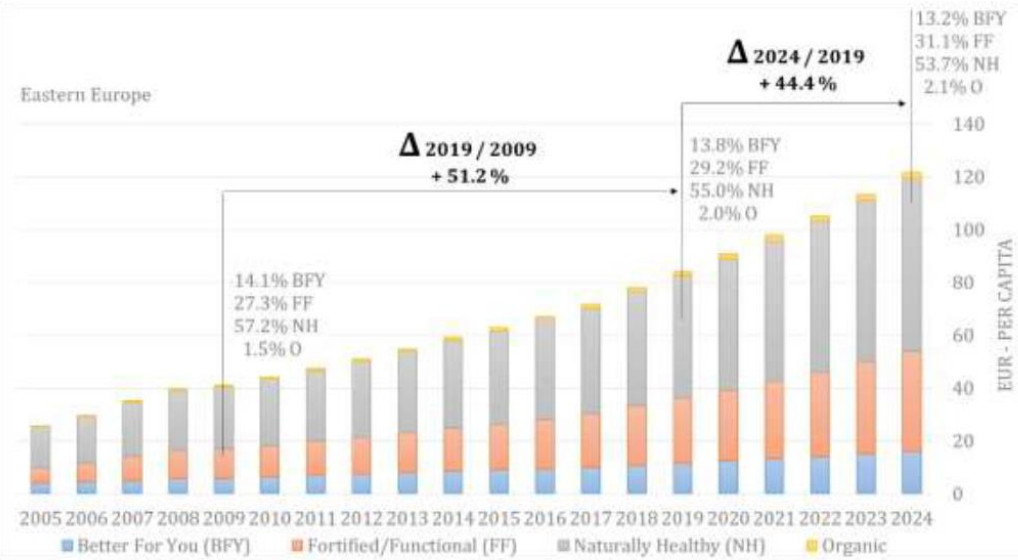


Figure 3-29: Health and wellness food in Eastern Europe by type, 2005-2024 (euros capita^{-1} year^{-1}) (Source: Bumbac, 2019)



The EC (2019a) and Willer *et al.* (2021) report an increasing trend of consumption of organic food products since 2000 (Figure 3-30), although consumption appears to have plateaued in some countries (e.g., in Sweden) (Figure 3-31).

Figure 3-30: Growth of organic retail sales in Europe and the European Union, 2000-2019 (Source: Willer *et al.*, 2021)

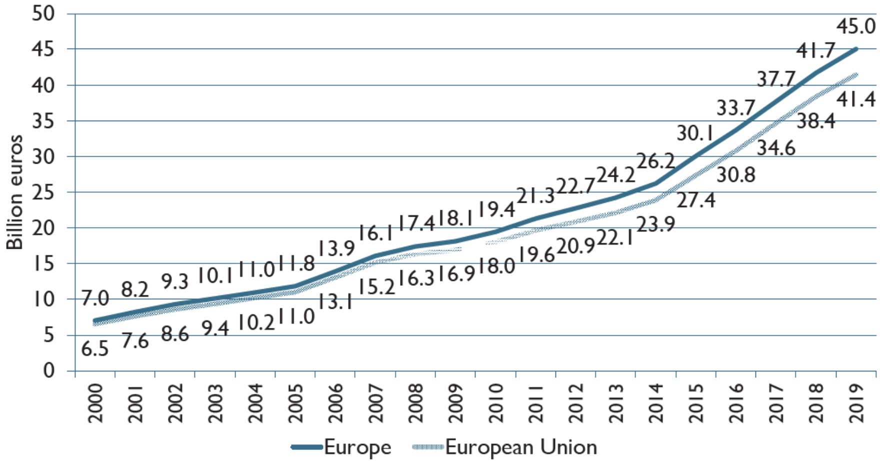
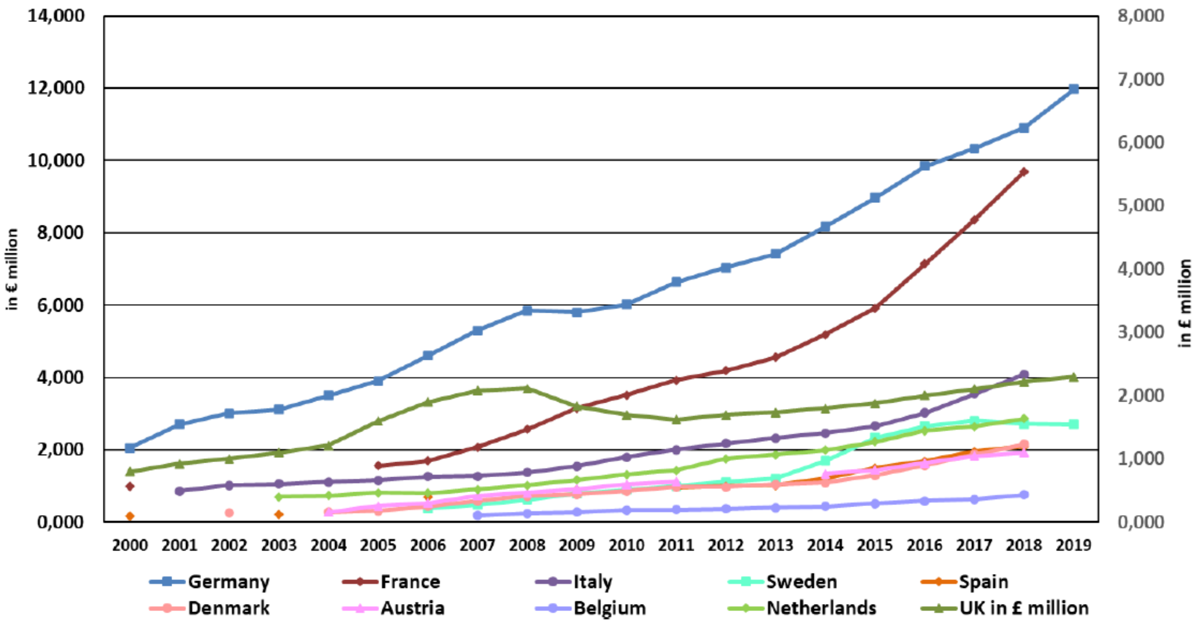


Figure 3-31: Evolution of the main EU organic markets (in € million except for the United Kingdom) (Source: EC, 2019a)



N.B.: The Swedish organic market did not shrink, but increased little between 2017 and 2019. With the graph showing only 2 different currencies, the Swedish krona was converted to euros. Source: Agence BIO/Many European sources

Additionally, the growing interest in locally produced food products is a well-established consumer trend, intensified by the COVID-19 pandemic, and likely to continue to grow (EPRS, 2016; Feldmann and Hamm, 2015; Hobbs, 2020 ; Muresan *et al.,* 2021). This interest is found to be associated with (i) higher quality standards and healthy eating; (ii) more environment-friendly production methods; (iii) direct contact with producers; (iv) knowledge about the provenance of food products; and support to local agriculture and the economy by purchasing food at a fair price (EPRS, 2016). However, the term "local" is not well defined (Feldmann and Hamm, 2015). The distance between the point of production and the point of sale can vary greatly and short food value chains should be distinguished from local food value chains, as short value chains (i.e., with one or fewer intermediaries between producers and consumers) may not be local and vice and versa (European Network for Rural Development, 2012).

At the same time, Asioli *et al.* (2017) show that convenience is also a major driver affecting food choices in industrialised societies (Asioli *et al.,* 2017). In line with this, the EC (2019b) reports an increasing trend of online purchases of food products since 2007 in the EU (Figure 3-32) with heterogeneous data among EU countries but overall no clear duality between Western and Eastern European countries (Figure 3-33).

Figure 3-32: Percentage of online purchases of food/groceries in the EU (28 countries) over the last decade by individuals [Eurostat: isoc_ec_ibuy] (Source: EC, 2019b)

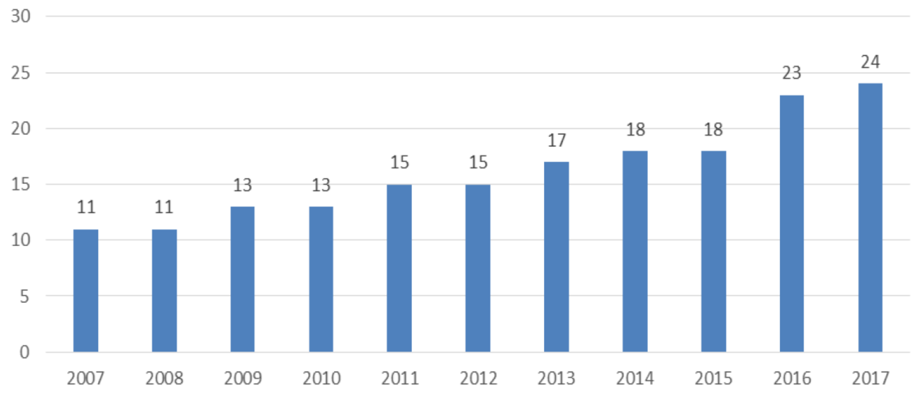
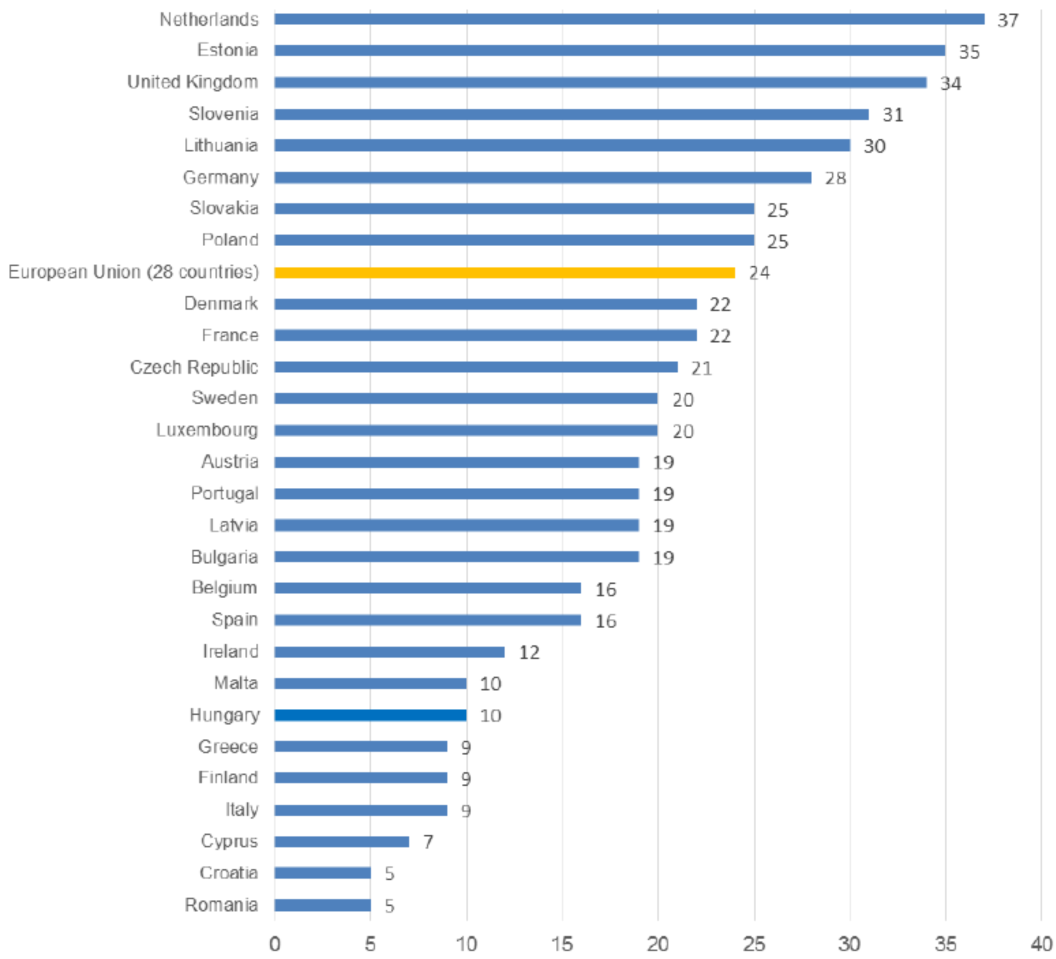


Figure 3-33: Percentage of individuals who ordered food or groceries, over the Internet, for private use, in member states for 2017 [Eurostat: isoc_ec_ibuy] (Source: EC, 2019b)



Moreover, Vandevijvere *et al.* (2019) show an increasing trend of ultra-processed food products[2] sales both in Western and Central and Eastern Europe with a smallest change in sales between 2002 and 2016 in Western Europe than in Central and Eastern Europe but higher sales (Figures 3-34 and 3-35). Juul and Hemmingsson (2015) provide detailed data for Sweden and show that, between 1960 and 2010, the consumption (in kg or litres per capita) of ultra-processed and processed food products increased by 142% and 116%, respectively, while the consumption of processed culinary ingredients and unprocessed/minimally processed food decreased by 34 and 2%, respectively (Figure 3-36).

Figure 3-34: Change in annual total volume sales (kg capita^{-1} year^{-1}) of ultraprocessed food products (UPF) by major region, 2002-2016 (Source: Vandevijvere *et al.*, 2019)

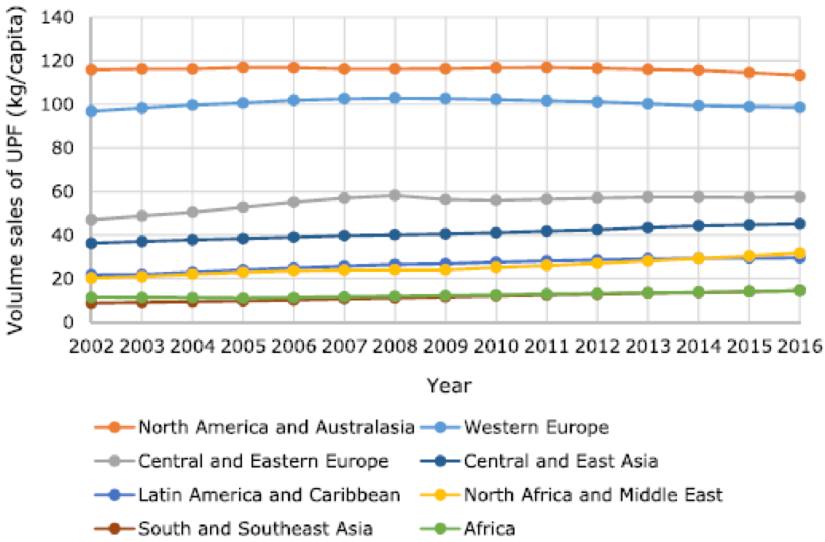
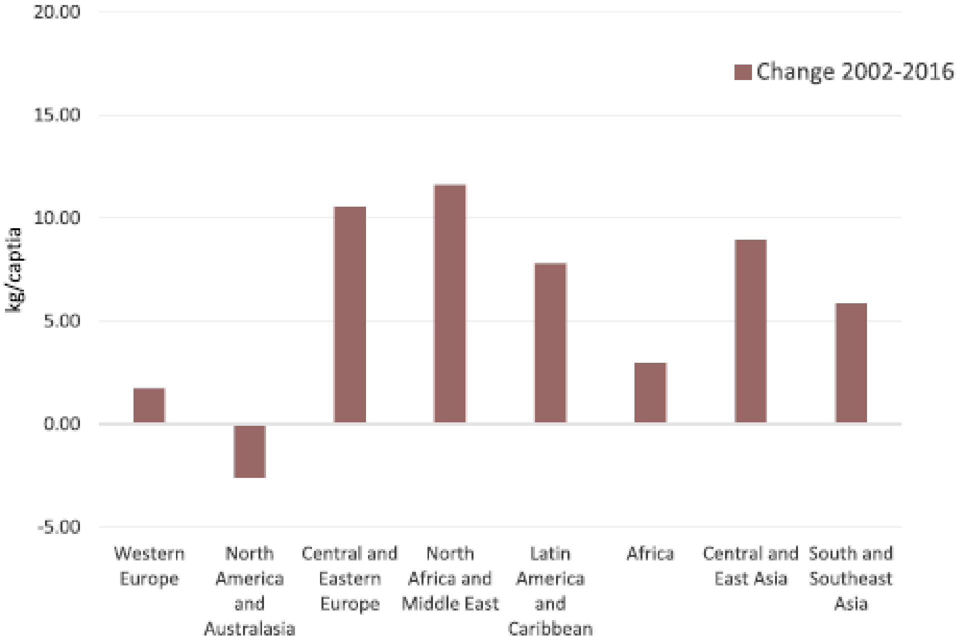
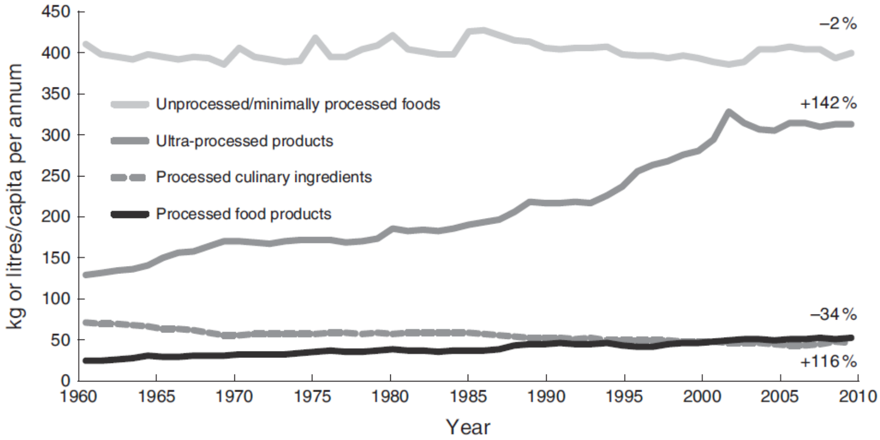


Figure 3-35: Change in total volume sales of ultraprocessed food products (UPF) over the period 2002-2016 (Source: Vandevijvere *et al.*, 2019)



[2] Ultra-processed food are defined aby Monteiro *et al.* (2019) as « formulations of ingredients, mostly of exclusive industrial use, that result from a series of industrial processes »

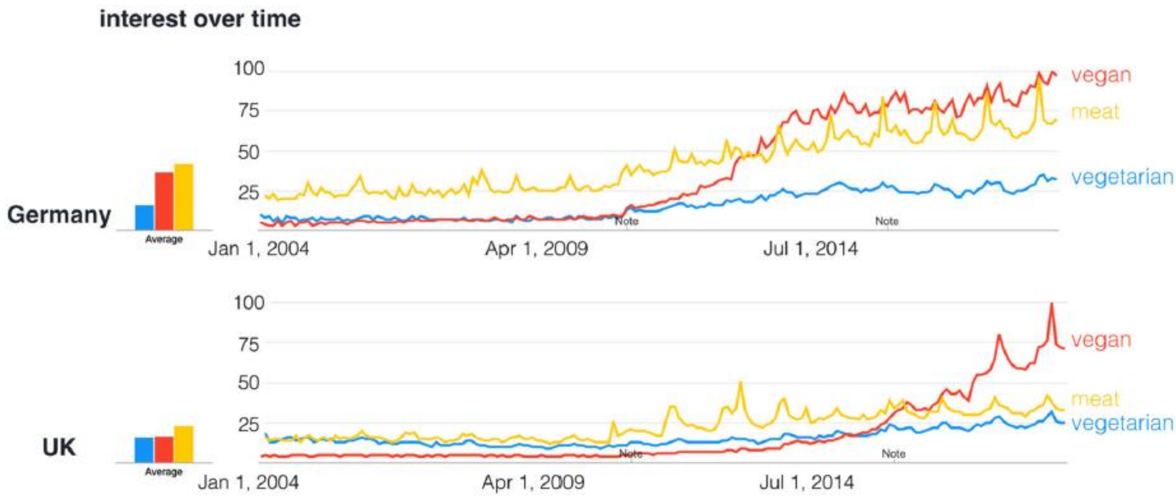
Figure 3-36: Annual per capita consumption (kilograms or litres) of food and non-alcoholic beverages in Sweden, 1960–2010, according to degree of industrial food processing by the NOVA framework (Source: Juul and Hemmingsson, 2015)



Medawar *et al.* (2019) show an increasing interest for vegan and vegetarian diets (Figure 3-37) since 2004 with 1 to 2% of British and 5 to 10% of German adults being reported to eat largely plant-based diets in 2015. IPES-Food & ETC Group (2021) report that 11.5% of the German population is vegan or vegetarian with an increase of more than 800,000 per year, and estimate, if this trend continues, that by 2045 as many as 42% of Germans will have plant-based diets. However, in France, if Fardet *et al.* (2021) showed diet revegetation for children and adults between 1998 and 2015, they also showed an increase in children's ultra-processed daily calories. In another study in France, Gehring *et al.* (2021) showed that a higher avoidance of animal-based foods is associated with a higher consumption of ultra-processed food.

Figure 3-37: Google Trends Search for search term hits for "vegan", "vegetarian" and "meat" in Germany (adapted to "vegetarisch", "vegan" and "fleisch") and the UK from 2004 to present (Source: Medawar *et al.*, 2019)

Note indicates technical improvements implemented by Google Trends. Data source: Google Trends. Search performed on 18 April 2019.



3.2.1.2. Hypotheses on food purchasing behaviour and consumption in 2050

Chemical pesticide-free food as a food safety standard

In this hypothesis, in 2050 consumers are willing to consume chemical pesticide-free food from chemical pesticide-free agriculture as they are aware and worried about the health risks associated with pesticide residues in food. Chemical pesticide-free food from pesticide-free agriculture thus become a food safety standard for consumers, just as no bacterial contamination of, e.g., some types of Escherichia coli, is now.

Healthy food in a healthy diet

In this hypothesis, consumers' concerns about their health are broader than in the first hypothesis. Consumers are willing to consume pesticide-free food but their concerns are not limited to this sole criterion and include (i) consuming healthy food (e.g., they avoid consuming ultra-processed food); and (ii) having a healthy diet, i.e., a diversified and balanced diet (with more fruit, vegetables, legumes, nuts and whole grains, and less animal-based based food, free sugars, fats and salt).

Food preserving human and environmental health (including biodiversity)

In this hypothesis, consumers' concerns are much broader than their own health. They also include environmental health with biodiversity conservation being of primary importance. Consumers are willing to consume food from pesticide-free agriculture to address these concerns.

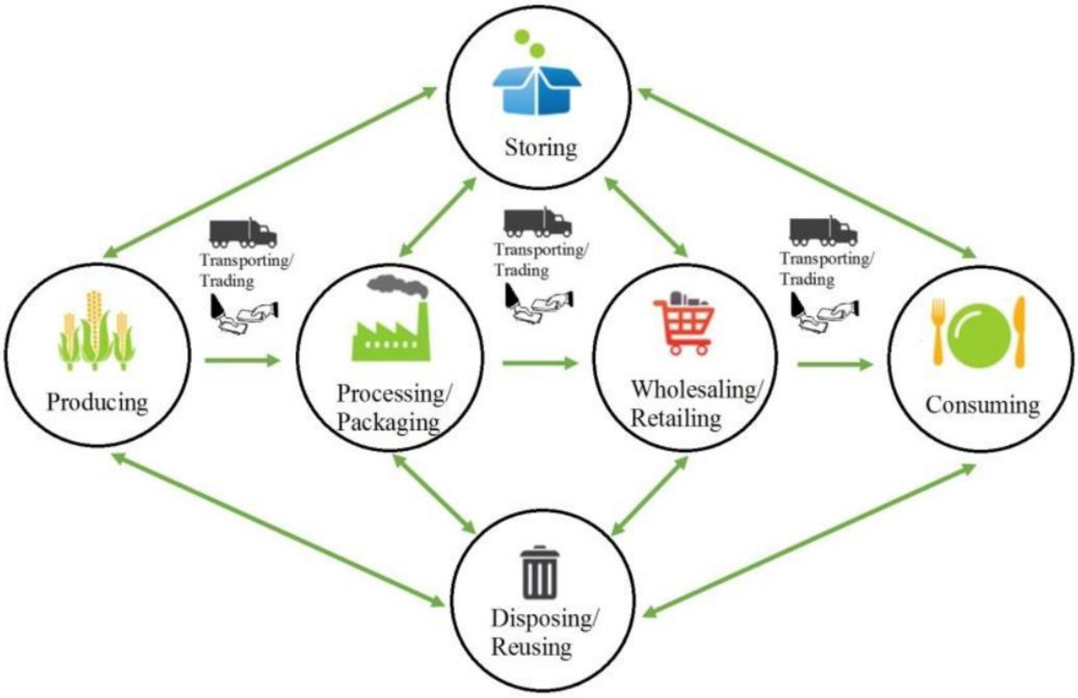
3.2.2. Organisation of activities among actors and governance of value chains

3.2.2.1. Trends and weak signals of change in the organisation of activities among actors and the governance of food value chains

Overview of current dynamics within the food value chain

A food value chain is the network of actors and activities that bring a basic agricultural product from production in the field to final consumption (FAO, 2005). Food value chains include the activities of storing, processing, retailing and disposing and/or reusing, and involve material and information flows (Ingram, 2019) (Figure 3-38). In Europe, a diversity of food value chains coexist. These can be characterised by their geographical spread (global or local), the number of intermediaries between producers and consumers (long or short), the production standards of food products (e.g., conventional or organic), the level of trust and commitment towards the chain and the power asymmetry among actors of food value chains (Gaitán-Cremaschi *et al*., 2019; Lee *et al*., 2012), and the values (including social, environmental and economic values) they are grounded on (van der Ploeg *et al*., 2019).

Figure 3-38: Activities of food value chains (Source: Ingram, 2019)

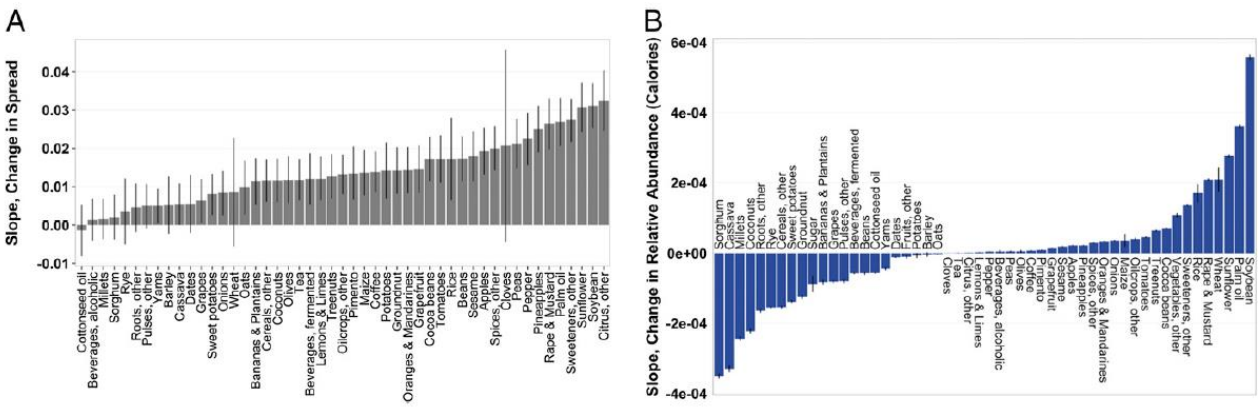


Globally and in Europe, companies are merging at and across levels of food value chains, capturing larger and larger market shares, and creating ever-bigger players in the processing and retail sectors with a huge bargaining power (Howard, 2021; IPES-Food, 2017). Such a bargaining power erods farmers' and consumers' ability to choose how to farm and what to eat (Gliessman et al., 2019; Howard, 2019), and encourages unfair trading practices (EC, 2015). Some companies are even taking over farmland (IPES-Food & ETC Group, 2021), including in European countries like France (Leclair, 2022). In 2011, the largest five retailers in thirteen EU members states (Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Luxembourg, the Netherlands, Portugal, Sweden and the United Kingdom) had a combined market share of over 60% (EC, 2014). In some countries, the retail market share exceeded 80% (e.g., in Portugal, Germany, Denmark, Estonia). Examples of European powerful retailers are LidL/Kaufland, Aldi, Carrefour and Tesco (IPES-Food, 2017) (Figure 3-39). Examples of European powerful processors are Nestlé and Danone (Howard *et al.*, 2021).

Figure 3-39: Top grocery retailers, 2014 (Source: IPES-Food, 2017)

In parallel to this, food supplies became more similar in composition during the period 1961 to 2009 globally and in Europe (Figure 3-40, 3-41 and 3-42).

Figure 3-40: Global change in spread and abundance of crop commodities in national food supplies from 1961 to 2009 (Source: Khoury *et al.*, 2014)



(A) Slope of the relative change in the geographic spread of crop commodities, defined as the change over time in the presence (i.e., value >0) of a crop commodity in contribution to any variable of food supply in a country in each year. Bars represent slope parameters [±95% confidence interval (CI)] from generalized estimation equations with a binomial error distribution, country as a grouping factor, and an autoregressive correlation structure. Sugar; vegetables, other; and fruits, other commodities are not depicted because they were nearly ubiquitous in spread globally throughout the study period and therefore did not change significantly. (B) Slope of the change in relative abundance of crop commodities in contribution to calories, as derived from the value contributed by a particular crop relative to the sum of all crops within a given country within a given year. Bars represent slopes (±95% CI) of the predicted values (1961–2009) for each crop from generalized linear mixed models, with year and crop as fixed effects and country as a random effect. Slopes for change in relative abundance for all measurements are depicted in Fig. S3.

Figure 3-41: Global change in similarity (homogeneity) of food supplies, as measured by Bray–Curtis dissimilarity from each country to the global centroid (mean composition) in each year, converted to similarity (Source: Khoury *et al.*, 2014)

(A) Global mean change in similarity to centroid of national food supplies. Points represent actual data, and lines are 95% prediction intervals from linear mixed-effects models. (B) Multivariate ordination of crop commodity composition in contribution to calories in national food supplies in 1961, 1985, and 2009. Red points represent the multivariate commodity composition of each country in 1961, blue points in 1985, and black points in 2009. Circles represent 95% CIs around the centroid in each year. Between 1961 and 2009, the area contained within these 95% CIs decreased by 68.8%, representing the decline in country-to-country variation of commodity composition (i.e., homogenization) over time. (C) World map displaying the slope of change in similarity to centroid of national food supplies for calories.

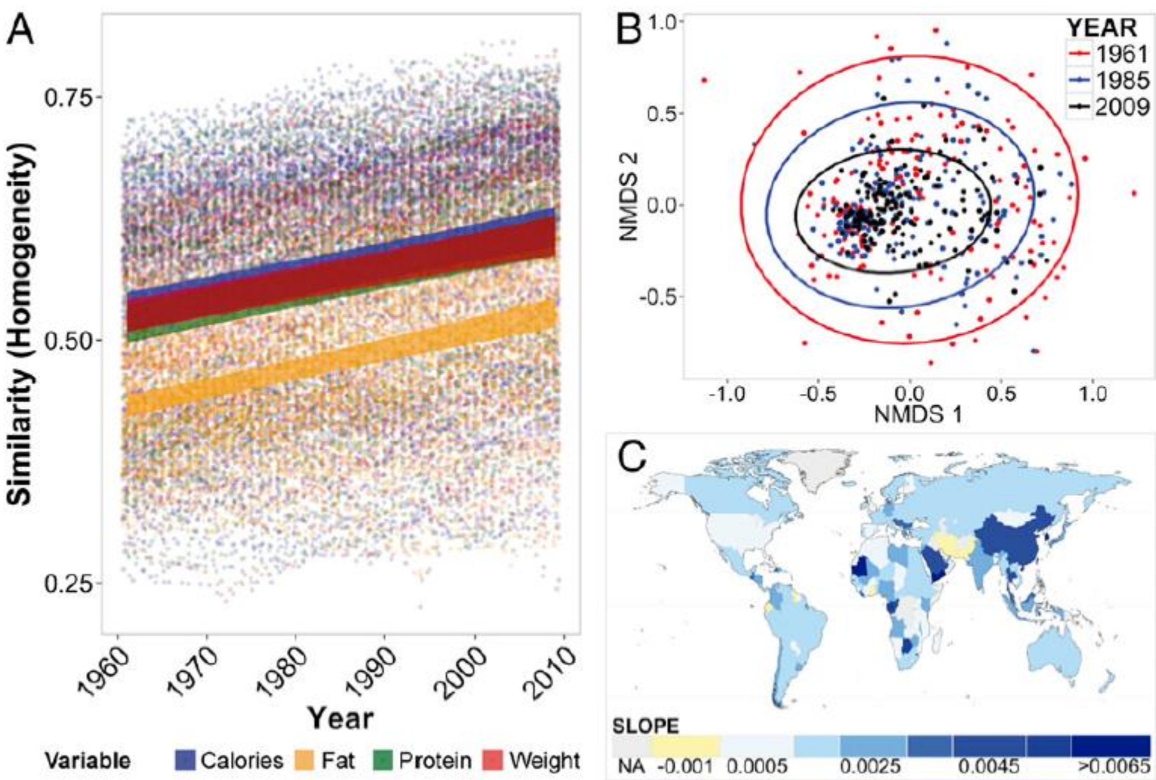
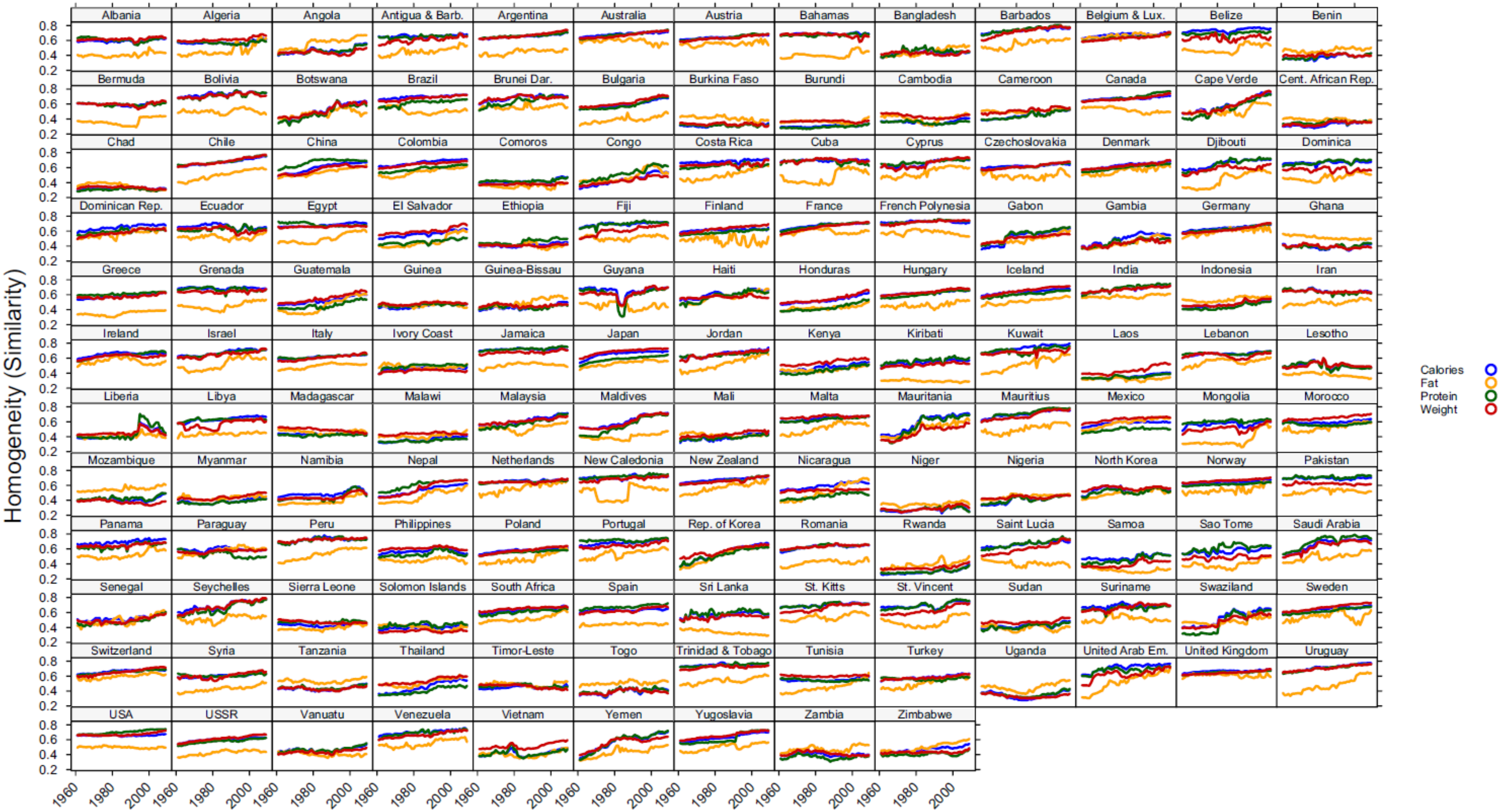
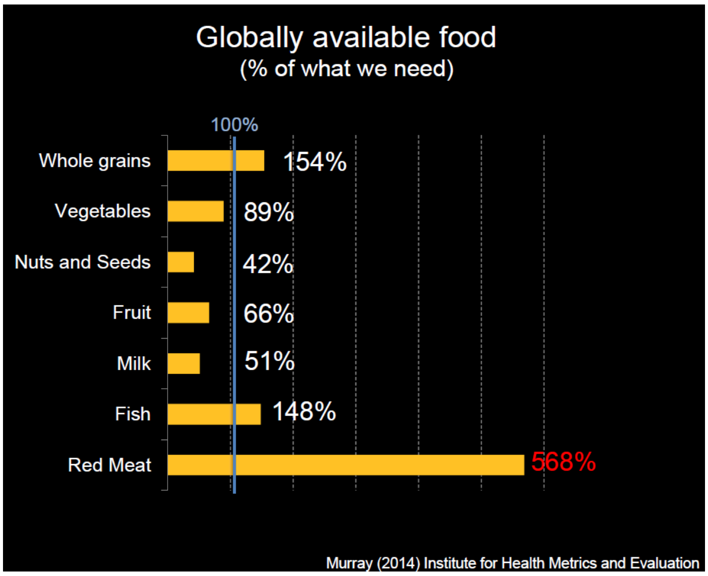


Figure 3-42: Per-country contribution to global homogenization, as measured by the change in similarity of the national food supply crop commodity composition in comparison with the global mean composition (centroid), for calories, protein, fat, and weight, 1961–2009
(Source: Khoury *et al.*, 2014, Supporting Information)



Large gaps between food production, food delivery and dietary recommendations are found globally (Cassidy *et al*., 2013; Tittonell, 2019) (Figure 3-43), and considerable food losses and waste occur with 270 kg of food losses and waste per capita per year from production to consumption in Europe (Secondi *et al*., 2015; Moller *et al*., 2019).

Figure 3-43: Gaps between food production and dietary recommendations globally (Source: Tittonell, 2019)

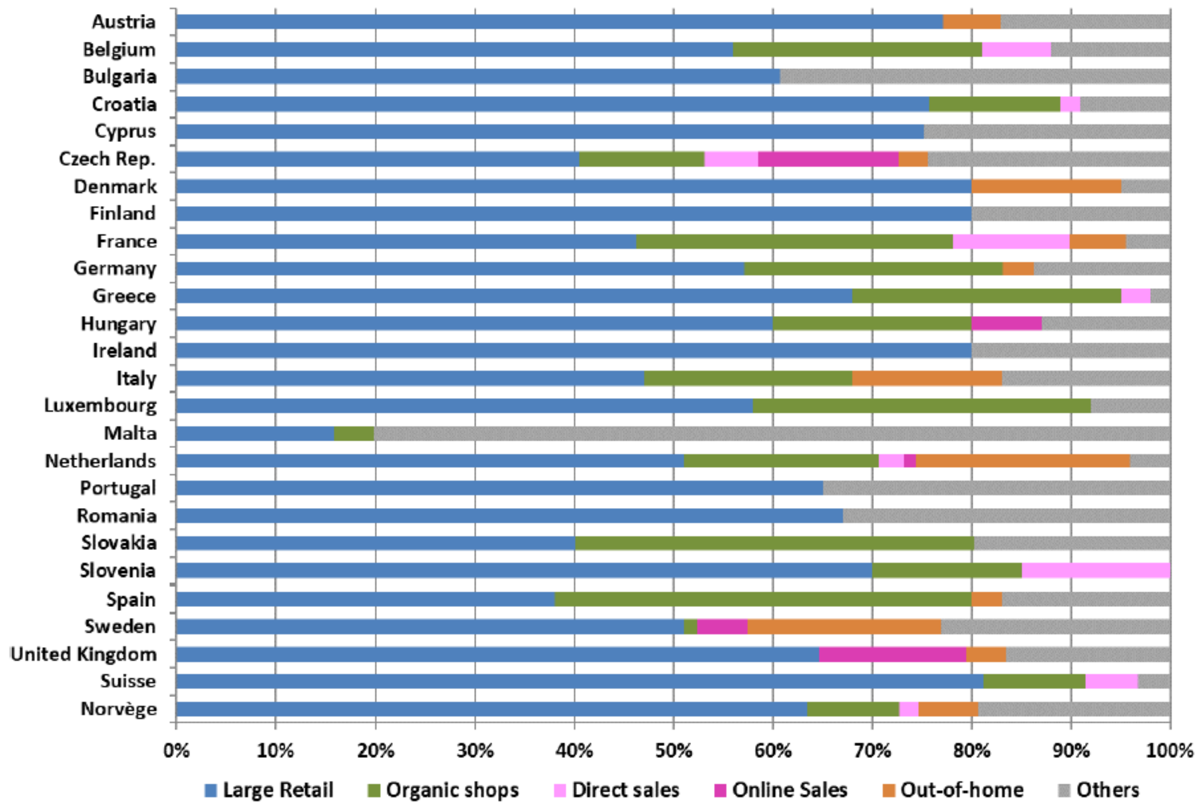


Involvement of retailers in changes under consumer pressure

To differentiate themselves to consumers, large-scale general retailers are excluding products not complying with higher private health and environmental standards than conventional standards (but lower or equal to organic standards), and by passing costs assumed by producers back down the chain. For example, in Germany, by 2030, Aldi Nord and Aldi Süd will switch their fresh pork, beef and poultry products standards to at least Level 3 of the 'Haltungsform' animal welfare private labelling scheme (ALDI, 2019). This move has prompted similar commitments in Germany from Rewe and Penny, Kaufland and Lidl, which are moving their pork supply to Level 2 of the labelling scheme. Besides, Aldi Nord and Aldi Süd already pay 6.25 cents per kilogram of pork or poultry sold to the 'Initiative Tierwohl' (the animal welfare initiative), which is then used to reward producers implementing the criteria of the animal welfare initiative (Sørensen and Schrader, 2019). At the same time, organic retailers are excluding products not complying with higher private standards than organic standards. For example, in France, Biocoop sells products with no chemical or 'natural' flavours when organic products can contain up to 5% nonorganic ingredients (Biocoop, 2018).

General retailers are also strongly involved in the marketing of organic products (Agence BIO, 2019) (Figure 3-44). Private organic brands have been developed (Agence BIO, 2019) with, e.g., in France, Carrefour supporting organic farmers with longer-term contracts that set future volumes and purchase prices in advance, as well as favourable prices during conversion years to organic (Carrefour, 2019). Partnerships with local organic associations and cooperatives have been founded, e.g., Bioland-Lidl, Naturland-Rewe, Demeter-Kaufland in Germany (Willer *et al*., 2021), Bio vom Berg-Mpreis in Austria (van der Ploeg *et al*., 2019), and the cereal producers-Migros partnership in Switzerland (MIGROS, 2022). Such partnerships are sometimes considered as value-based chains rather than value chains in that they are grounded on collectively shared non-economic values (van der Ploeg *et al*., 2019).

Figure 3-44: Importance of the different distribution channels for organic products by country (Source: Agence BIO, 2019)



Involvement of processors to answer consumers' and retailers' expectations

Under the pressure of both consumers and retailers (Moller *et al.*, 2019), large-scale processors set more stringent private specifications and higher production standards, with conditional support to farmers. For example, in the Vittel area, Nestlé makes access to land conditional on environmental clauses including not using chemical pesticides (Lavocat, 2021). In Italy, Mulino Bianco defined a charter for the sustainable cultivation of common wheat (Barilla, 2019) and supports famers in implementing defined practices with tailored producer prices accounting for local costs and benefits (Blasi *et al.*, 2019). Large-scale processors have also developed or acquired private organic brands (Howard *et al.*, 2021).

In Europe, food value chains are also comprised of 290,000 small and medium-sized enterprises (SMEs), making up 99% of the number of companies, and employing 58% of persons in the food and drink industry (Food Drink Europe, 2020). Local SMEs may play an important role in chemical pesticide-free food value chains as being able to handle small volumes of diverse local products, process them locally, and increase the level of trust and commitment towards the chain (Bliss *et al.*, 2019).

Involvement of consumers in changes in response to their concerns

In an attempt to offer solutions to some of the environmental, social and economic problems that have come to be associated with typical global long food value chains (IPES-Food, 2017), some consumers support local short food value chains through direct purchases and partnerships with farmers. The number of consumers involved in Community supported agriculture is increasing (URGENCI, 2016) (Figure 3-45 and 3-46). However, direct purchases account for only about 2% of the fresh food market in volume terms (EC, 2015).

Figure 3-45: Estimated number of eaters in European Community supported agriculture (Source: URGENCI, 2016)

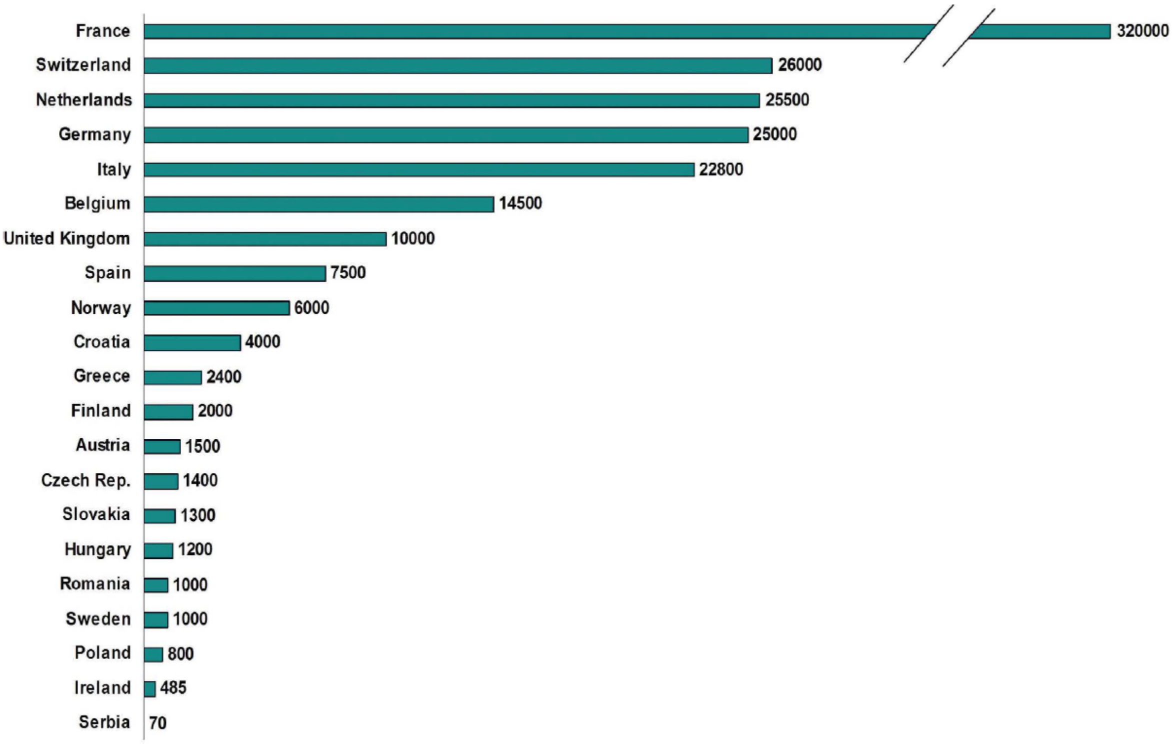
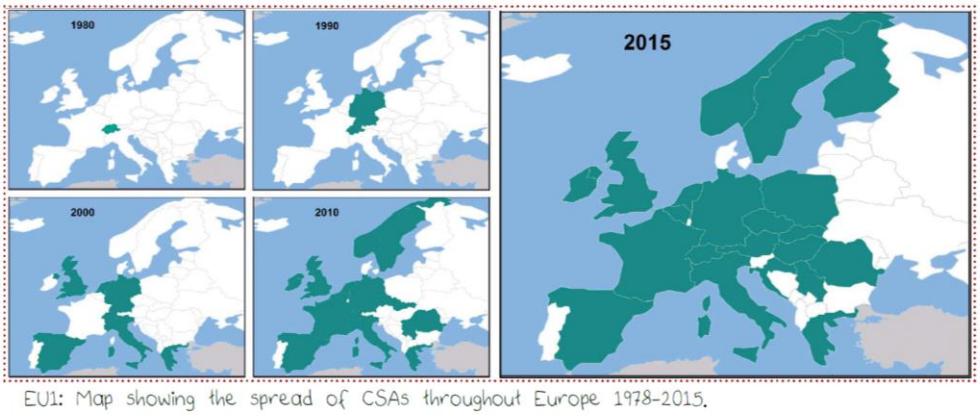


Figure 3-46: Map showing the spread of Community supported agriculture throughout Europe, 1978-2015 (Source: URGENCI, 2016)



Involvement of local authorities and citizens in response to societal concerns

Public sector spending amounts to a significant part of the economy (13.3% of the GDP in Europe in 2017 (EC, 2019c)) and the purchase of food products and catering services plays an important role within public procurement (Neto and Gama Caldas, 2018). Green Public Procurement (GPP) (primarily meant to address environmental concerns) and Sustainable Public Procurement (SPP) (when social and economic concerns are added to environmental concerns) provide the opportunity to drive local and regional economies towards more sustainable paths by, e.g., procuring organic and/or local food for consumption in public schools, kindergartens, hospitals and residential homes (Progress Consulting, 2018). GPP and SPP schemes are found in a number of EU countries, e.g., national schemes in Austria, Belgium, Italy, Malta, The Netherlands, Sweden, regional schemes in Spain, local schemes in Austria, France, Denmark, Italy, Spain, Sweden (Neto and Gama Caldas, 2018; Progress Consulting, 2018).

Additionally, food policy councils, i.e., groups sharing similar overall goals to make the food system more equitable, sustainable and resilient are emerging in Western Europe and Central Europe (Food Policy Networks, 2021). These vary in their organizational structure, relationships with government and funding sources. In parallel, community and household gardens, and initiatives to deliver quality food affordable for all (e.g., in France, the VRAC Association (Towards a Common Purchasing Network) (VRAC, 2021)) are developing. This trend is further described in Section 3.3 dedicated to public policies.

Online sale platforms as new players in food value chains

Consumers are increasingly purchasing food online (Figure 3-32) and the COVID-19 pandemic intensified this trend (Hillen, 2021; Hobbs, 2020). Online sale platforms are new intermediaries within value chains, with different features, including different production standards of food products, different networks (distribution channels and production-consumption relations), and different economic model and practices (Rosol and Barbosa, 2021). Platforms are not limited to linking producers and consumers, or retailers and consumers. They are also linking producers with companies like restaurants (e.g., Promus). Currently, platforms with a regional and small-scale producer focus (e.g., Harvie, Farmigo, La Ruche qui dit Oui !, Locavor) coexist with more conventional, international-scale platforms such as Amazon.

Amazon is now among the top ten retailers globally. It is rapidly expanding its direct delivery grocery business (Howard *et al*., 2021; Phillips-Connolly and Connolly, 2017), increasingly using 'dark stores' that are not open to the public, and used only to fulfil delivery orders. Amazon is also a leader in cloud computing infrastructure services and partners with agribusiness-led digital platforms to deliver weather, agronomic, and production data to and from precision farming systems (Goodman *et al*., 2022; IPES-Food & ETC Group, 2021). Big Tech transformation into Big Food is raising concerns (IPES-Food & ETC Group, 2021) as advancements in technology have expanded companies' ability to communicate with consumers, but also to store and analyse data on consumers (Rust, 2020; White *et al*., 2021).

According to a recent foresight study on the future of online food shopping (Ruffieux, 2021), platforms may evolve into: (i) low-cost centered platforms (selling low-cost food, and resulting in low quality food and consumers limiting their food budget); (ii) community platforms (tailoring products to communities and their values, resulting in fragmented value chains); (iii) personalisation platforms (using artificial intelligence to match products to consumers); (iv) commitment platforms (using a strategy to accompany consumers in making responsible food purchases with sometimes difficult and costly changes). These hypotheses differ in the way (i) food products are produced (including their design, geographical location); (ii) food products are matched to consumers and delivered (customer paths); (iii) food products are consumed and how (values associated with food); and (iv) value chains are regulated.

3.2.2.2. Hypotheses on the organisation of activities among actors and the governance of chains in 2050

Partnerships between producers/cooperatives, retailers and consumers

In this hypothesis, in 2050, the governance of value chains is shared among producers and cooperatives, processors, retailers and consumers through partnerships and contracts. Partners share a vision and values associated with food. Such partnerships allow for (i) building trust in food products; (ii) sharing risks associated with the production of chemical pesticide-free food along the chain; and (ii) better coordinating activities, sharing knowledge, and coupling innovations along the chain.

Strong relationships between producers and consumers through platforms or direct contact

In this hypothesis, the governance of value chains is shared between producers and consumers, who have a strong relationship built through either platforms or direct contact. Such partnerships allow for building trust and sharing risks between producers and consumers.

Retailers and consumers

In this hypothesis, large-scale retailers govern value chains. They control food supply but may be influenced by the pressure of consumers. They however try to respond to consumers concerns while maintaining their position of power within value chains.

Global processors and retailers (including platforms)

In this hypothesis, the governance of value chains is shared between the powerful big players that are global large-scale retailers and processors. These actors work closely together to control food supply and influence food demand.

3.2.2.3. Hypotheses on the spatial scale at which food value chains are organised in 2050

Territorialised, diversified and short food value chains with diversified crops within diversified landscapes (coordination and synergies)

In this hypothesis, a diversity of value chains dealing with a diversity of crops are rooted within territories and diversified landscapes.

Regional food value chains (states, districts, big city regions)

In this hypothesis, food value chains are organised at a regional level, i.e., at the level of states, districts or big city regions.

Complementarity between short and local food value chains and longer and more global food value chains

In this hypothesis, short and local, and long and global food value chains complement each other. Food is not necessarily produced in close geographical proximity and may be supplied by local, national, European or global value chains.

Global food value chains

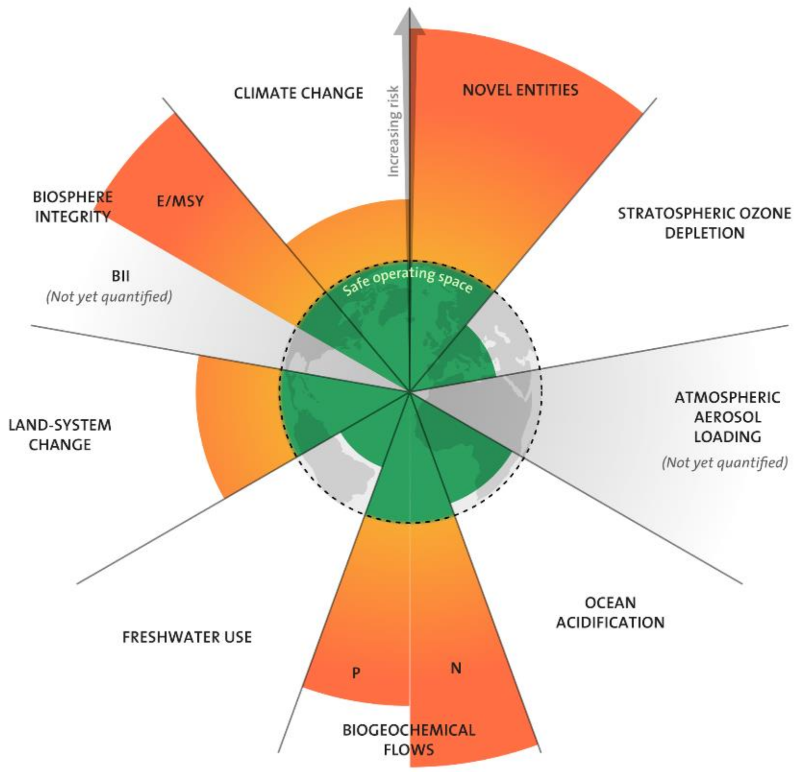
In this hypothesis, global food value chains are dominant among other food value chains.

3.2.3. Information provided to consumers

3.2.3.1. Trends and weak signals of change in information provided to consumers

Food safety scandals, reported on by media and generating products withdrawals from the market, e.g., on contamination of foods with banned pesticide ethylene oxide (Foodwatch, 2021), emphasise on the gap between the information available to food value chain actors and that available to consumers. Such scandals have increased consumers' distrust and need for greater transparency and information on food products (Asioli *et al.*, 2017; Azzurra *et al.*, 2019; Feldmann and Hamm, 2015; Meneses *et al.*, 2014). In parallel, researchers emphasise on the gap between, e.g., media coverage of biodiversity issues and the actual knowledge on risks associated with biodiversity loss (Legagneux *et al.*, 2018) (Figure 3-47 and 3-48). Civil society organisations emphasise on gaps between stated objectives of labels and their actual impacts, and recommend to develop evidence-based labels (BASIC *et al.*, 2021; UFC-Que Choisir, 2021a). Public authorities emphasise on the need for education on food and greater transparency in food value chains (De Sa and Lock, 2008; MAA, 2019; Trieu *et al.*, 2015). More generally, the literature points to the need to overcome information gaps and build trust among actors of food value chains so as to foster changes in consumption behaviour (Asioli *et al.*, 2017; EFSA, 2019; Feldmann and Hamm, 2015; Schäufele and Hamm, 2017). Eden *et al.* (2008) points out that trust is produced not merely by information, but by its source.

Figure 3-47: Planetary boundaries (Source: Stockholm Resilience Centre, 2022)

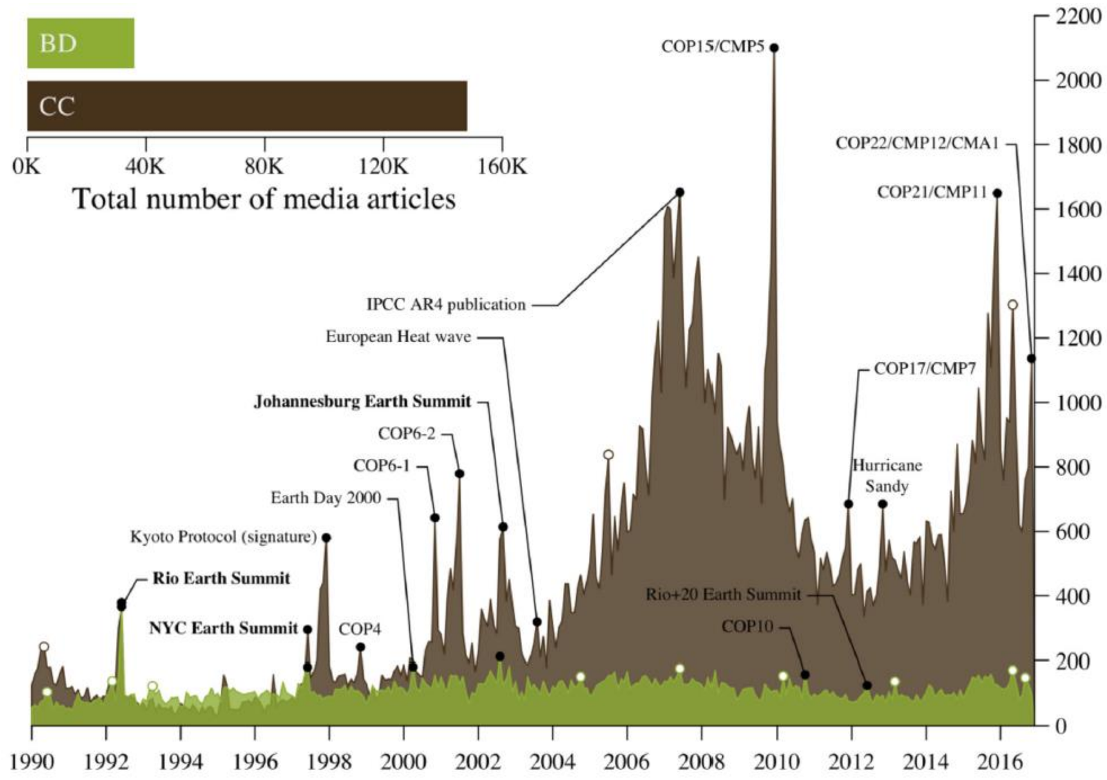


The inner green shading represents the proposed safe operating space for ten planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in five systems (environmental pollutants and other "novel entities" including plastics and pesticides, biodiversity integrity, human interference with nitrogen and phosphorus biogeochemical flows, land-system change, and climate change), have already been exceeded.

Designed by Azote for Stockholm Resilience Centre, based on analysis in Persson *et al.*, 2022 and Steffen *et al.*, 2015

Figure 3-48: Number of newspaper articles published per month on biodiversity (green) or climate change (brown) issues in US, Canada, and UK
(Source: Legagneux *et al.*, 2018)

Detected peaks (plain dots) and associated events are shown. Peaks without associated events (empty dots) could not be associated with a priori events. Events that embraced both climate change and biodiversity issues are written in bold



Different means of informing, accompanying or influencing consumers have been developed or are being developed by different actors: civil society organisations, and public and private actors. Labels are marks displayed on the surface of products to indicate that they have special qualities (Brice and Mallard, 2020).

The level and visibility of information conveyed through labels vary greatly: labels have various forms (from texts to traffic-lights, including logos and pictures) and are found on the front-of-pack or on the back-of-pack of a food product (Asioli *et al.*, 2017; Cecchini and Warin, 2016). Consumers' dependence on labels has increased with the distance between production and consumption of food and the massive introduction of food products (Zwart, 2000). Labels are supposed to give consumers the opportunity to take into account, among others, nutritional (e.g., the Nutri-Score), environmental (e.g., Organic), ethical (e.g., Fair Trade), geographical (e.g., Protected Designations of Origin), or cleanliness (e.g., Zero pesticide residue) considerations when making food choices (Asioli *et al.*, 2017; Cecchini and Warin, 2016; Flinzberger *et al.*, 2022; Grunert *et al.*, 2014; Janssen and Hamm, 2012). However, the growing number of private and public labels and associated standards on food products may be confusing and bring mistrust from consumers (BASIC *et al.*, 2021; Busch, 2020; Grunert *et al.*, 2014; Janssen and Hamm, 2012; Maruyama *et al.*, 2021). Researchers also emphasise on the lack of legal definitions and regulations of some labels (Asioli *et al.*, 2017; Maruyama *et al.*, 2021) and the misleading picture they can provide (Ketelsen *et al.*, 2020). This is the case of clean labels, the use of which appeared during the 1980s when consumers started to avoid E-numbers listed on food labels because they were associated with negative health effects, and exploded 15 years ago (Asioli *et al.*, 2017). In an attempt to address this issue, and in order to make the current regulatory framework[3] more stringent, the European Commission, as part of the Farm to Fork strategy, will examine ways to create a sustainability labelling framework, to better inform and empower consumers to make informed and sustainable food choices. This framework would cover the provision of information to consumers, related to nutritional, climate, environmental and social aspects of food products (EC, 2020b).

In addition to the information conveyed through labels on the products themselves, recent advancements in technology and communication have enabled the development of mobile applications, among which food applications (Flaherty *et al*., 2017; Joosse and Hracs, 2015; Schumer *et al*., 2018; Tosi *et al*., 2021). The number and range of food applications is growing along with consumer interest. Some applications are intended to assess food products based on a single or several criteria, e.g., the nutritional quality, acceptability of additives, degree of processing, or the impacts of food products on the environment (Open Food Facts, 2022; Siga, 2021; UFC-Que Choisir, 2021b; Yuka[4]). Some allow for dietary self-monitoring with more or less personalised options and more or less concerns on the privacy and security of personal data (Flaherty *et al*., 2017; IPES-Food & ETC Group, 2021; Schumer *et al*., 2018). Some provide geospatial services on where to source local or regional food (Joosse and Hracs, 2015). Others are intended to reduce food waste (Harvey *et al*., 2020; Vo-Thanh *et al*., 2021).

The literature shows contrasting approaches to informing consumers' choices and ensuring transparency in food value chains: from private to public approaches, including third party, participatory and blockchain approaches. Participatory guarantee systems (PGS) are locally focused quality assurance systems that certify producers based on active participation of stakeholders and are built on a foundation of trust, social networks, and knowledge exchange (IFOAM, 2020). In France and Italy, for example, such systems coexist with third party organic certification (Niederle *et al*., 2020; Sacchi, 2019). The literature emphasises the impact of PGS beyond economic and ecological benefits, pointing out that, by bringing producers and consumers together, they foster the social and political sustainability of organic food systems (Cuéllar-Padilla and Ganuza-Fernandez, 2018; De Lima *et al*., 2021; Niederle *et al*., 2020; Sacchi, 2019). In parallel with the certification of practices and with the rise of citizen science, citizens are also increasingly and voluntarily involved in, e.g., biodiversity monitoring programs (Chandler *et al*., 2017). Such an involvement offers a way to collect information that would otherwise not be affordable (Tulloch *et al*., 2013), and contributes to building scientific knowledge, informing policy and encouraging public action (Bonney *et al*., 2016; Dickinson *et al*., 2012; McKinley *et al*., 2017).

In a context where food value chains involve numerous distributed and untrusted intermediaries between producers and consumers, blockchains may appear as a promising technology towards transparent food value chains (Astill *et al*., 2019; Dasaklis *et al*., 2022; Feng *et al*., 2020; Kamilaris *et al*., 2019). A blockchain is a public or private digital transaction ledger, maintained by a network of multiple computing machines that are not relying on a trusted third party (Kamilaris *et al*., 2019). It is a means to make automated trusted digital transactions (IPES-Food & ETC Group, 2021) that can be used to record data at different levels within food value chains (Kamilaris *et al*., 2019). Kamilaris *et al.* (2019) report on a diversity of blockchain initiatives with different objectives: from ensuring food safety to supporting farmers (e.g., by facilitating insurance programs), including verifying standards and tracing food origin or reducing waste. However, Kamilaris *et al.* (2019) emphasise the different levels of maturity of these initiatives with those of large-scale being developed and ran by big companies, and indicate challenges to be met in terms, among others, of accessibility, governance, and regulation.

[3] A European regulation have been defining since 2011 the main rules related to Food Information to Consumers (EU regulation 1169/2011; EU, 2011). It sets harmonized minimum mandatory information to appear on every food product (ingredients lists, nutritional information, allergen labelling, etc.). It also provides that, in addition to the mandatory food information, other food information can be provided on a voluntary basis. These shall not mislead the consumer, shall not be ambiguous or confusing for the consumer and shall, where appropriate, be based on relevant scientific data.

[4] https://yuka.io/en/app/

3.2.3.2. Hypotheses on information provided to consumers in 2050

Third party web applications on which data on traceability of practices along food value chains are summarised

In the first hypothesis, data on the traceability of practices along food value chains are summarised on third party web applications, e.g., by using public blockchains. Consumers can search in the applications the information they want.

Evidence-based labels (e.g. "biodiversity friendly product") on the basis of actual impacts rather than stated objectives

In this hypothesis, data on the actual impacts of food products rather than stated objectives are summarised in the form of evidence-based labels so that current gaps and mistrust in labels are addressed.

Collaborative monitoring of impacts of food products by actors of food value chains or open-access statistics

In this hypothesis, consumers and other actors of value chains are involved in the data collection and monitoring of the impacts of food products. This collaborative process allows to (i) build trust in data and in food products; but also to (ii) make consumers responsible for their choice of consumption; and to (iii) make other actors of value chains responsible for their practices.

Public campaigns or information to improve knowledge on food issues

In this hypothesis, information is provided by public authorities through information campaigns to accompany and improve the knowledge of consumers on food issues.

Monopolistic access to data on food products by a retail platform

In this hypothesis, information is provided by retailers through their own platform. Retailers have a monopolistic access to raw data on practices along food value chains.

3.2.4. Technologies to sort, store, process and/or preserve food without chemical pesticides

3.2.4.1. Trends and weak signals of change in technologies to sort, store, process and/or preserve food products without chemical pesticides

The European Commission defines a pesticide as something that prevents, destroys, or controls a harmful organism ('pest') or disease, or protects plants or plant products during production, storage and transport[5] and a preservative as something added to prolong the shelf-life of foods by protecting them against micro-organisms[6]. There is therefore a continuity in the use of pesticides and preservatives along value chains, from production to consumption of unprocessed or processed food.

[5] https://food.ec.europa.eu/plants/pesticides_en (accessed 1.14.22).

[6] https://food.ec.europa.eu/safety/food-improvement-agents/additives_en (accessed 1.14.22).

Besides, some substances are considered as both a pesticide and a preservative, e.g., Sodium metabisulphite (E 223), which is classified by the EU as both a fungicide (not approved in the EU)[7] and a preservative[8]. Another example is benzoic acid (E210), approved active substance of pesticides[9], and approved food additive[10]. Rules for organic products already apply throughout the value chain and include a limited list of approved chemical preservatives (EC, 2008)[11]. To go forward towards chemical pesticide- and chemical preservative-free value chains, in relation to concerns on their effects on human health and the environment, not to mention the development of resistance to these chemicals (Hamel *et al*., 2020; Maurya *et al*., 2021; Palou *et al*., 2015), a number of alternative technologies using physical control or biocontrol are being developed.

Preservatives are food-grade antimicrobial agents that have been intentionally added to food to protect them from biological deterioration (Erickson and Doyle, 2017). In conjunction with other measures (manufacturing practices, low storage temperatures, sterilization, etc.) they contribute to food product safety. Although their safety is assessed prior to their approval by EFSA, some concerns have raised over their use in food products (Carocho *et al.*, 2014; Erickson and Doyle, 2017; ANSES, 2022), leading consumers to look for products claiming 'free from' several ingredients, including preservatives. Indeed, a recent review, Roman *et al.* found out that the majority of consumers consider the naturalness of food products important, although the definition of naturalness can have different meanings and scope. It ranges from how the food has been grown (local production, organic farming) to post-harvest food processing (absence of negatively-perceived ingredients such as food preservatives, minimal processing) (Roman *et al.*, 2017).

Historically, food processing has played a key role in extending the shelf life and transportability of food, avoiding food losses and ensuring food safety (Asioli *et al*., 2017; Meneses *et al*., 2014).

Fermentation has been used for millennia, and is regaining interest. Fermentation is a naturally occurring process where biological activity of microorganisms produces a range of metabolites, which can in turn suppress the growth or survival of undesirable microorganisms in food products (Ross *et al.*, 2002). Indeed, lactic acid bacteria for example, are capable of inhibiting pathogenic bacteria and spoilage, by producing antimicrobial peptides and proteins; they are used in fermented food products such as wine, beer, bread, etc. (Ross *et al.*, 2002). The development of new techniques for characterizing microorganisms and microbial communities (for example meta-omic approaches, metagenetics and metagenomics) offers new opportunities to better know the microbiomes all across the food chain, and design new ways for naturally preserving food products, as well as improving their quality and health benefits (Yap *et al.*, 2022).

Today, industrially processed food make up 75% of world food sales with ultra-processed food dominating the food supply of high-income countries (Juul and Hemmingsson, 2015). Ultra-processed food, however, generally include a large number of chemical preservatives and raise concerns about their effects on human health (Monteiro et al., 2018).

As an alternative to ultra-processing, minimal processing is being extensively explored.

[7] Pesticides Database (v2.2) Active substance. Sodium metabisulphite https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/active-substances/?event=as.details&as_id=1152 (accessed 1.14.22).

[8] Food Additives Database. E No. 223 Sodium metabisulphite https://webgate.ec.europa.eu/foods_system/main/index.cfm?event=substance.view&identifier=67 (accessed 1.14.22).

[9] https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/start/screen/active-substances/details/455, last consulted in June 2023.

[10] https://ec.europa.eu/food/food-feed-portal/screen/food-additives/search/details/POL-FAD-IMPORT-3033, last consulted in June 2023.

[11] https://agriculture.ec.europa.eu/farming/organic-farming/organic-production-and-products_en (accessed 1.14.22).

The food industry has been working on progressively reducing or phasing out from the use of food additives, including food preservatives. According to a survey conducted by the French food observatory OQALI on more than 30 000 products, between 2008-2012 and 2010-2016, the use of additives in processed products has declined overall over the period. Among the 20 categories for which trend data are available, the number of foods without additives has increased from 13.7% to 18.3% of products since the early 2010s. Also, among the 46 food additives present in at least 2% of the products studied, only 4 food additives occurrence has been increasing, none of them being food preservatives (OQALI, 2019).

As an alternative to the use of chemical additives and especially preservatives, several technologies have been developed to preserve food, in addition to improving food safety management systems in order to prevent the spread of pathogens along the food chain. One solution used by the food industry is to substitute chemical preservatives by "natural" antimicrobial ingredients, meaning products that are not synthetized through chemical process, such as essential oils, or plant extracts (Calo *et al.,* 2015; Erickson and Doyle, 2017). For example, some manufacturers use plant extracts or vegetable broths as substitutes for nitrite additives in delicatessen. According to a very recent ANSES report, this is not "*a real alternative since these products naturally contain nitrates which, under the action of bacteria, are converted into nitrites*" (ANSES, 2022).

Technological developments also investigate novel methods of food preservation and minimal processing leveraging the food packaging. Minimal processing includes classic and more novel methods in food preservation such as fermentation, aseptic packaging, controlled/modified-atmosphere packaging, active packaging (with antimicrobial activities), bio-based and biodegradable edible films and coatings (Alzamora *et al*., 2015; Janjarasskul and Suppakul, 2018; Mari *et al*., 2016; Maurya *et al*., 2021; Nguyen Van Long *et al*., 2016; Palou *et al*., 2016, 2015; Sivakumar and Bautista-Baños, 2014; Wińska *et al*., 2019; Zhang *et al*., 2018). Palou *et al*. (2015) emphasise on the potential of antimicrobial edible coatings in controlling post-harvest decay of fresh citrus fruits. However, they conclude that their implementation is limited primarily because of the current availability of effective, convenient, and cheaper conventional fungicides.

To improve the efficiency of minimal processing methods, researchers recommend combining them in a multifaceted approach, also referred to as multiple-hurdle approach so as to slow down or prevent the growth of microorganisms, inactivate them and restrict their access to products (Alzamora *et al*., 2015; Janjarasskul and Suppakul, 2018; Palou *et al*., 2015; Zhang *et al*., 2018).

To improve the efficiency of protection methods for cereals stored in warehouses, Hamel *et al*. (2020) also discuss the interest of combining different methods such as high and low temperatures, the removal of dockages, the application of pheromones, diatomaceous earth, and natural compounds from various plants, as well as inert gases, predators, and parasites. Because some postharvest physiological losses originate in the field and others are caused by inappropriate handling or storage conditions, Palou *et al*. (2015) finally suggest to adopt an integrated pest management from farm to fork. European cereal trade associations COCERAL, EUROMAISIERS, EUROMALT and UNISTOCK published in 2018 the results of the storage insecticides survey conducted among European grain and oilseed storage operators for pest management (COCERAL *et al.*, 2018). It shows that "*in operator's own silos, the primary option to manage insect infestation is air circulation (59% of the respondents), then fumigation (52% of the respondents), followed by storage insecticides (45% of the respondents).*" The respective share of these three practices vary in other storage facilities, namely port silos storage and at farm level.

From the observation that food losses and waste occur throughout value chains, Porat *et al*. (2018) suggest to rethink the logistics of food value chains, especially that of fruits and vegetables as very perishable with relatively short postharvest storage lives, and including 'home logistics' at the consumer level. Similar to Parfitt *et al.* (2010), they point to a poor fit between purchase and sale or consumption and poor storage management that cause food waste. They also point to the lack of strategies to use suboptimal fruits and vegetables in, e.g., baking, stewing and juicing. They highlight advances in logistics, cold chain management and intelligent packaging that can make it possible to closely monitor stored products, better manage storage duration and switch from the 'first in first out' to the 'first expired first out' model as well as on-going efforts to raise consumers' awareness, including advertisement of home storage instructions.

Among levers to ensure the transition towards sustainable agri-food systems, the need to couple innovations in the production, processing, distribution, consumption and recycling of agri-food products is identified in the literature (Boulestreau *et al*., 2022; Meynard *et al.*, 2017). Examples of coupled innovations supporting crop diversification as a means to protect crops on fields are provided. Such couplings include technological, organisational and institutional innovations. Crop diversification challenges the downstream of value chains because it involves managing a diversity of products of heterogeneous quality. Among technological innovations coupled with crop diversification, are, e.g., an optical sorter purchased by a cooperative to separate crops after harvest and enhance the uptake of crop diversification on farms or a baking process to make bread with low-protein wheat grains, or even without any wheat protein at all (Meynard *et al*., 2017).

3.2.4.2. Hypotheses on technologies to sort, store, process and/or preserve food products without chemical pesticides in 2050

Management of the food microbiome (including new packaging) to preserve food products throughout food value chains

In this hypothesis, in 2050, food is preserved by monitoring closely and managing its microbiome from farm to fork.

Minimal processing combined with biological control (including new packaging)

In this hypothesis, in 2050, minimal processing is combined with biological control to preserve food while maintaining its quality and nutritional value. In this hypothesis as well, there is a better match between harvest and consumption, and thus less need to store and preserve food products. Logistics is adapted to crop diversification and to the seasonality of products.

Agile/adaptable processing to deal with heterogeneous products (in quantity and quality)

In this hypothesis, processing processes are adaptable to deal with products of heterogeneous quantity and quality as chemical pesticides are not used.

3.2.5. Microscenarios of food value chains for chemical pesticide-free agriculture in 2050

By combining the various hypotheses of change in 2050 drawn in the previous paragraphs, we built three micro-scenarios of food value chains in 2050, for chemical pesticide-free agriculture in 2050. In the following paragraphs, the various hypotheses selected for each micro-scenarios are presented (Tables 3-18, 3-19 and 3-20), together with a narrative of the micro-scenario.

3.2.5.1. Microscenario 1: Global value chains with chemical pesticide-free food as a food safety standard

Narrative of the micro-scenario 1

In 2050, consumers are willing to consume chemical pesticide-free food as they are aware and worried about the health risks associated with pesticide residues in food. Chemical pesticide-free food has thus become a food safety standard on the European food market.

Global value chains are dominant and vertically integrated. They are governed mainly by large-scale general retailers. These have expanded their power: they control the different stages of food value chains, from production and input supply (seeds, chemicals, equipment) to logistics, processing and consumption. Retailers have a monopolistic access to big data along food value chains. They use these data to optimise the allocation of production factors to what they find are most valuable uses. Information on food products is provided via retail platforms to influence food demand.

Because chemical pesticides and preservatives are disused, food products are heterogeneous in quantity and quality, and prone to losses but retailers have sufficient means to adapt their processing processes and to optimise storage conditions and stock management.

Table 3-18: Microscenario 1: Global value chains with chemical pesticide-free food as a food safety standard

Component	Hypotheses for each component in 2050				
Values associated with food choices	**Pesticide-free food as a food safety standard**	**Healthy food in a healthy diet**	**Food preserving human and environmental health (including biodiversity)**		
Organisation of activities among actors and governance of food value chains	**Partnerships between producers/cooperatives, retailers and consumers**	**Strong relationships between producers and consumers through platforms or direct contact**	**Retailers and consumers**	**Global processors and retailers (including platforms)**	
Information provided to consumers	**Third party web applications on which data on traceability of practices along food value chains are summarised**	**Evidence-based labels (e.g. "biodiversity friendly product") on the basis of actual impacts rather than stated objectives**	**Collaborative monitoring of impacts of food products by actors of food value chains or open-access statistics**	**Public campaigns or information to improve knowledge on food issues**	**Monopolistic access to data on food products by a retail platform**
Technologies to sort, store, process and/or preserve food products	**Management of the food microbiome (including new packaging) to preserve food products throughout food value chains**	**Minimal processing combined with biological control (including new packaging)** Less need to preserve food products because of a better match between harvest and consumption (logistics adapted to crop diversification and to the seasonality of products)	**Agile/adaptable processing to deal with heterogeneous products (in quantity and quality)**		
Spatial scale at which to organise food value chains	**Territorialised, diversified and short food value chains with diversified crops within diversified landscapes** (coordination and synergies)	**Regional food value chains** (states, districts, big city regions)	**Complementarity** between short and local food value chains and longer and more global food value chains	**Global food value chains**	

3.2.5.2. Microscenario 2: Local, European and global value chains marketing healthy food for a healthy diet

Narrative of the micro-scenario 2

In 2050, consumers are concerned about both consuming healthy food and achieving a healthy diet, i.e., a diversified and balanced diet. They consume chemical pesticide-free food only, avoid consuming ultra-processed food, but consume more fruit, vegetables, legumes, nuts and whole grains, and less animal-based based food, free sugars, fats and salt.

Partnerships and/or strong relationships with actors of value chains (producers and cooperatives, processors, retailers) allow building trust in food products. Moreover, public authorities and consumers' organisations empower and accompany consumers in making their choices through information campaigns on food issues and third party web applications including information on traceability of practices along value chains. Although consumers' diet is diversified, food is not necessarily produced in close geographical proximity. Food is supplied by local, national, European or global value chains.

Risks associated with the production of chemical pesticide-free food are shared along value chains. Activities are better coordinated, knowledge is shared and innovations are coupled along value chains to deal with heterogeneous food products. Food is preserved by closely monitoring and managing the food microbiome from farm to fork. Minimal processing combined with biological control is favoured. In both cases, the quality and nutritional value of food is maintained.

Table 3-19: Microscenario 2: Local, European and global value chains marketing healthy food for a healthy diet

Component	Hypotheses for each component in 2050				
Values associated with food choices	**Pesticide-free food as a food safety standard**	**Healthy food in a healthy diet**	**Food preserving human and environmental health (including biodiversity)**		
Organisation of activities among actors and governance of food value chains	**Partnerships between producers/cooperatives, retailers and consumers**	**Strong relationships between producers and consumersthrough platforms or direct contact**	**Retailers and consumers**	**Global processors and retailers (including platforms)**	
Information provided to consumers	**Third party web applications on which data on traceability of practices along food value chains are summarised**	**Evidence-based labels (e.g. "biodiversity friendly product") on the basis of actual impacts rather than stated objectives**	**Collaborative monitoring of impacts of food products by actors of food value chains or open-access statistics**	**Public campaigns or information to improve knowledge on food issues**	**Monopolistic access to data on food products by a retail platform**
Technologies to sort, store, process and/or preserve food products	**Management of the food microbiome (including new packaging) to preserve food products throughout food value chains**	**Minimal processing combined with biological control (including new packaging)** Less need to preserve food products because of a better match between harvest and consumption (logistics adapted to crop diversification and to the seasonality of products)	**Agile/adaptable processing to deal with heterogeneous products (in quantity and quality)**		
Spatial scale at which to organise food value chains	**Territorialised, diversified and short food value chains with diversified crops within diversified landscapes** (coordination and synergies)	**Regional food value chains** (states, districts, big city regions)	**Complementarity** between short and local food value chains and longer and more global food value chains	**Global food value chains**	

3.2.5.3. Microscenario 3: Territorial and regional value chains marketing food preserving human and environmental health (biodiversity included) and contributing to diversified landscape

Narrative of the micro-scenario 3

In 2050, the civil society is concerned by both human and environmental health, and in particular by biodiversity conservation. Consuming chemical pesticide-free food address these two concerns.

A diversity of value chains dealing with a diversity of crops are rooted within territories and small regions. The geographical proximity of food production and processing together with partnerships and/or strong relationships with actors of value chains (producers and cooperatives, processors, retailers) allow building trust in food products. Data on the actual impacts of food products on the environment, including biodiversity, rather than stated objectives are summarised in the form of evidence-based labels or on third party web applications so that past gaps and mistrust in labels are addressed. Moreover, consumers, environmentalists, farmers' organisations, and other actors of value chains as well as local authorities are involved in the data collection and monitoring of the impacts of food products on human and environmental health.

Risks associated with the production of chemical pesticide-free food are shared along value chains. Activities are better coordinated, knowledge is shared and innovations are coupled along value chains to deal with heterogeneous food products. Actors interact and collaborate across different levels of value chains both vertically, i.e., from producers to consumers and horizontally, e.g., producers with producers, crop value chains with livestock value chains, cereal value chains with legume value chains.

Territories and small regions produce and supply a diversity of food products locally. Logistics is adapted to crop diversification and to the seasonality of products. There is a better match of harvest and consumption and thus less need to store and preserve food products. When necessary, food is preserved by using minimal processing combined with biological control and/or by closely monitoring and managing the food microbiome from farm to fork.

Table 3-20: Microscenario 3: Territorial and regional value chains marketing food preserving human and environmental health (biodiversity included) and contributing to diversified landscape

Component	Hypotheses for each component in 2050				
Values associated with food choices	**Pesticide-free food as a food safety standard**	**Healthy food in a healthy diet**	**Food preserving human and environmental health (including biodiversity)**		
Organisation of activities among actors and governance of food value chains	**Partnerships between producers/cooperatives, retailers and consumers**	**Strong relationships between producers and consumers through platforms or direct contact**	**Retailers and consumers**	**Global processors and retailers (including platforms)**	
Information provided to consumers	**Third party web applications on which data on traceability of practices along food value chains are summarised**	**Evidence-based labels (e.g. "biodiversity friendly product") on the basis of actual impacts rather than stated objectives**	**Collaborative monitoring of impacts of food products by actors of food value chains or open-access statistics**	**Public campaigns or information to improve knowledge on food issues**	**Monopolistic access to data on food products by a retail platform**
Technologies to sort, store, process and/or preserve food products	**Management of the food microbiome (including new packaging) to preserve food products throughout food value chains**	**Minimal processing combined with biological control (including new packaging)** Less need to preserve food products because of a better match between harvest and consumption (logistics adapted to crop diversification and to the seasonality of products)	**Agile/adaptable processing to deal with heterogeneous products (in quantity and quality)**		
Spatial scale at which to organise food value chains	**Territorialised, diversified and short food value chains with diversified crops within diversified landscapes** (coordination and synergies)	**Regional food value chains** (states, districts, big city regions)	**Complementarity** between short and local food value chains and longer and more global food value chains	**Global food value chains**	

3.3. Public Policies for chemical pesticide-free agriculture: Past trends and future changes by 2050

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Table of contents

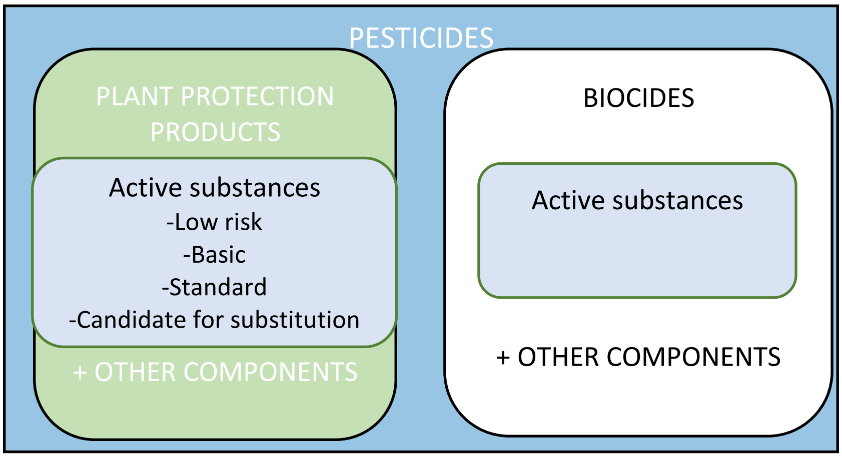
General introduction, material and method

This section covers the policies addressing the reduction of the use and risks of chemical pesticides in Europe. It includes the policies and their instruments, such as regulations, economical (taxes, incentives), informative instruments. These policies and their instruments can be of international, European, national, and territorial scope.

Since the number of policies within the scope of this retrospective analysis is very large, the analysis does not aim at being exhaustive but rather at identifying the key trends and potential future changes of public policies impacting pesticides use, in the context of achieving scenarios of chemical pesticide free agriculture in 2050.

The regulation defines pesticides as two main categories of products: plant protection products, which aim at keeping crops healthy and prevent them from being destroyed by disease and infestation, and biocides, intended for non-plant uses to control pests and disease carriers [12]. Pesticides are formulations containing at least one active substance and other components[13] (Figure 3-49). The law differentiates different types of active substances according to their risks on the environment or health (basic, low risk, candidates for substitution[14], etc.). In the section, "pesticide" is used to refer to plant protection products.

Figure 3-49: Definition of pesticides and their components according to European regulation



Method

The retrospective analysis on public policies was conducted using a four-step approach.

Step 1: Evidence review

In a first step, we conducted a literature search to gather the main public policies and regulations related to pesticides use and risks reduction in Europe. We did so by interrogating Web of Science (WOS) bibliographic tool to search for scientific publications on pesticides policies (keywords: "PESTICIDE AND POLICY AND EUROPE" limit 2010 – 2022). We also looked at grey literature through

[12] https://food.ec.europa.eu/plants/pesticides_en, last consulted in May 2023

[13] https://www.efsa.europa.eu/en/topics/topic/pesticides, last consulted in September 2022

[14] https://food.ec.europa.eu/plants/pesticides/approval-active-substances_en, last consulted in September 2023

reports from the European Commission, the European Food Safety Authority, and from non-governmental organizations and think tanks.

Step 2: Expert's interviews

We then conducted a series of semi-directed interviews with experts in pesticides policies and regulations (see Table A7 in the Appendix of the report), to gather insights on past, current trends and future evolutions of public policies related to pesticides use and risks reduction. We interviewed four experts from different European countries, from December 2021 to January 2022, in zoom interviews lasting around 3 hours each. We followed a questionnaire adapted to each expert, recorded the interviews and issued reports for each interview.

Step 3: Focused literature search

In a third step we ran focused literature searches in order to gather precise information on certain pieces of pesticides-related policies. These included targeted bibliographic searches in WOS with specific keywords.

Step 4: Expert's group

We presented the main outputs of the retrospective analysis on public policies in a meeting of the European transition expert's group, on May 30th (see Table A3 in the Appendix of the report). In this meeting, we presented the main trends we identified, and discussed them. Then, the expert's group prepared hypotheses of change, regarding how public policies may evolve by 2050 to support European scenarios of chemical pesticide-free agriculture in 2050.

Overall scope of the retrospective analysis on public policies related to pesticides use and risk reduction

There are many policies addressing the question of pesticides, through very different topics (economy, health, and environment), at different geographical scales, and through very different instruments (trainings, information, taxes, bans, etc).

First, pesticide use is a regulatory matter. As such, we studied the legislative framework for pesticides uses in Europe and its evolution during past decades.

Then, taking into consideration that many policies affect pesticide use, we studied public policies affecting pesticides use and risk reduction through the topic angle, by considering the below questions:

- How do **health** and **food policies** address the question of pesticides?
- How do **environmental policies** address the question of pesticides?
- How do **agricultural policies** address the question of pesticides?
- How do **trade policies** address the question of pesticides?
- How do **certification policies** address the question of pesticides?
- How do **territorial (intersectoral) policies** address the question of pesticides?

3.3.1. Legislative framework for regulating pesticides use on the European market

3.3.1.1. A common and harmonized legislative framework based on safety assessments and a positive list of approved products

The placing on the market of plant protection products (PPPs) is governed by the EU Regulation on Plant Protection Products[15], adopted in 2009 (Regulation (EC) n°1107/2009; European Community, 2009a), and replacing Council Directive 91/414/EEC. A similar regulatory framework exists for biocidal products under EU regulation 528/2012 (EU, 2012)[16]. It is part of a legislative framework – often referred to as "the pesticides package" - also consisting of the Directive 2009/128/EC on sustainable use of pesticides (SUD; European Community, 2009b), a Regulation related to the collection of statistics on pesticides (Regulation (EC) n°1185/2009), and a revision of the Directive related to machinery for pesticide application (directive 2009/127/EC**)**.

The main objectives of the Regulation (EC) n°1107/2009 regulation are (INIA, 2020):

1) To ensure safety for operators, workers, bystanders, residents, consumers (including vulnerable groups of consumers), non-target species and the environment;
2) To allow an efficient use of resources for risk assessment and risk management in the policy area of pesticides;
3) To shorten the time for new products to come on the market.

Its purpose is also to facilitate the free movement of plant protection products (PPPs) and plant products treated with PPPs and their availability in Member States, and to safeguard the competitiveness of EU agriculture by guaranteeing the efficacy of plant protection products.

The regulation follows the principle of positive list of approved products, based on scientific safety assessment: only active substances registered on the EU list of approved active substances, and subsequently authorized as plant protection products, can be placed on the EU market. Safety assessments are conducted by food safety authorities in Member States and by the European Food Safety Authority (EFSA), based on a dossier prepared by the company producing the active substance. For more details about the registration process please refer to Figure 3-50.

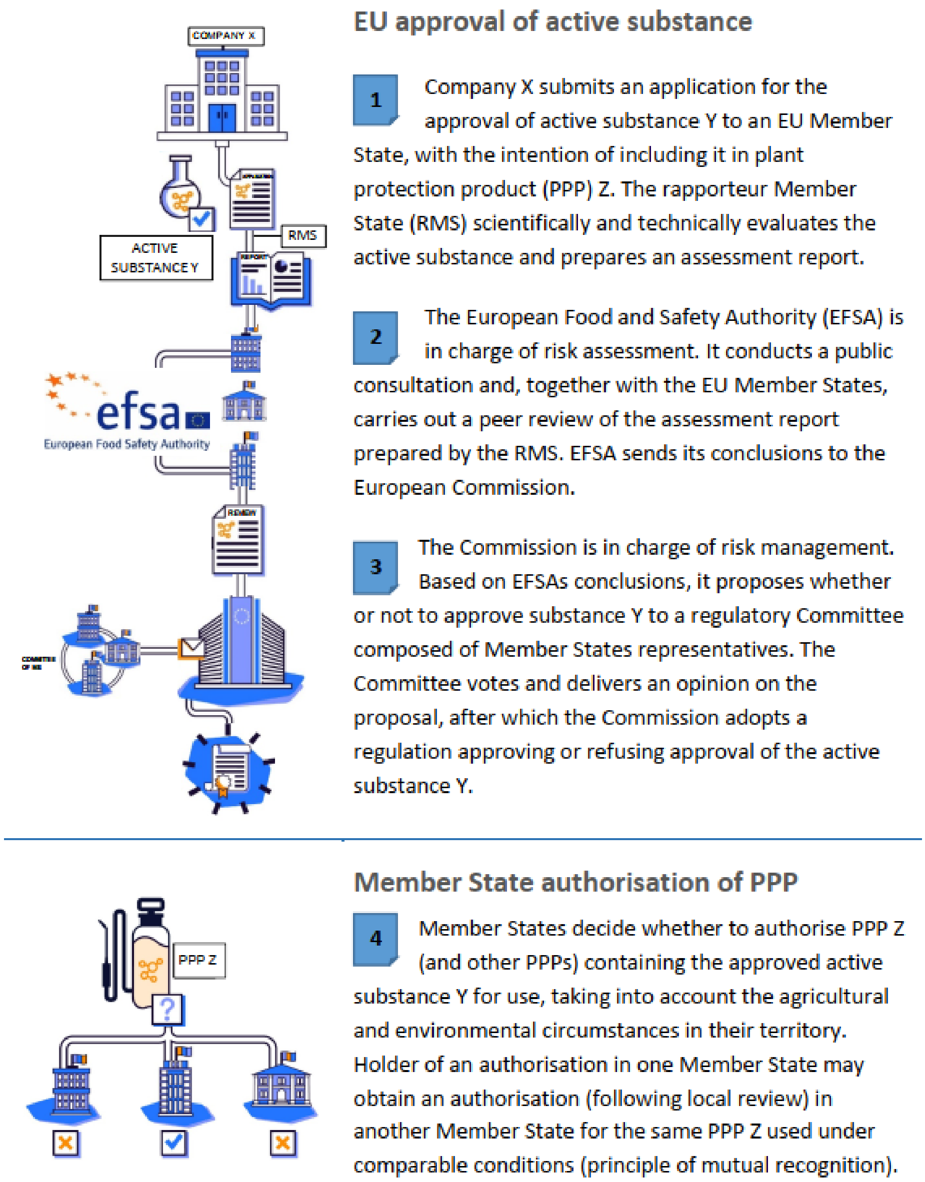
Safety assessment and regulatory approval before placing on the market is a common legislative approach applied in Europe to several chemical products (food additives, biocides, etc.) that has been in place for several decades. In the case of pesticides, the regulatory process was harmonized first in 1991 and then in 2009. Before that, each Member State had itsr own safety assessment and aproved list of pesticides.

Plant production products and biocides are subject to a dual approval process: active substances are approved at EU level and plant protection products containing these active substances are subsequently authorized by Member States.

[15] Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market, OJ L 309, 24.11.2009. See also the consolidated version.

[16] Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products, OJ L 167, 27.6.2012. See also the consolidated version.

Figure 3-50: Key steps in assessing pesticides safety in Europe (Source: ECA, 2020, based on information provided on the European commission website)



The Regulation (EC) 1107/2009 introduced some major evolutions, with the aim of further protecting human and environmental health. The Regulation (EC) 1107/2009 changed the approach related to the safety assessment of the active substances, introducing a "**hazard-risk approach**" (vs only risk assessment in the previous Directive), in order to increase the level of protection of human and animal health, and of the environment (Balderacchi and Trevisan, 2010). A hazard-based approach regulates substances on the basis of their intrinsic properties, without taking into account the exposure to the substance. Regulation (EC) 1107/2009 introduced new hazard-based "**cut-off criteria**" based on the intrinsic properties of active substances, meaning that substances meeting any of the cut-off criteria are rejected without considering the results of the risk assessment.

It defines seven criteria to assess if a substance is particularly hazardous: four toxicological cut-off criteria and three environmental cut-off criteria (see Table 3-21).

Table 3-21: Cut-off criteria for hazard assessment (Source: adapted from Bourguignon, 2017)

Criteria related to human health	Endocrine disruptor properties
	Mutagenic category 1A or 1B (either category 1A or 1B) as per the CLP regulation[17]
	Carcinogenic category 1A or 1B (either category 1A or 1B) as per the CLP regulation
	Toxic for reproduction category 1A or 1B (either category 1A or 1B) as per the CLP regulation
Criteria related to environmental health	PBT (persistent, bioaccumulative and toxic)
	vPvB (very Persistent and very Bioaccumulative)[18]
	POP (Persistent Organic Pollutant)

However, a substance reaching hazard cut-off criteria can still get approved, under certain conditions. If the exposure of humans or non-target organisms to that substance in a plant protection product, under realistic proposed conditions of use, is negligible, and if residues of the active substance concerned on food and feed do not exceed the default value of 0.01 mg/kg (LoQ – limit of quantification), a risk assessment can take place.

Mandatory comparative assessment of more hazardous substances, called candidates for substitution

The Regulation (EC) n°1107/2009 introduces a new mandatory element: the comparative assessment. This additional assessment must be conducted by Member States for all uses of plant protection products containing active substances with certain hazardous properties and a relatively high risk of environmental and human toxicity, called Candidates for Substitution (CfS).

The aim of the comparative assessment is to evaluate whether a plant protection product containing a CfS can be replaced by other adequate solution, with less hazardous properties.

As part of the review about the legislation in place on pesticides in Europe – called Regulatory Fitness and Performance or REFIT program - the European Commission asked a consultancy company (Ecorys) to conduct a study to evaluate progress made towards realizing the objectives of the legislation, and to establish whether the legislation has delivered the expected benefits at a proportionate cost (Ecorys for EC, 2018). The report provides insights about the Regulation in place and its evolutions, as well as its effectiveness, efficiency, relevance, coherence, EU added value, based on series of consultations with various stakeholders. On the question of comparative assessments, the study finds out that Member States performed 278 comparative assessments in 2015 and 2016. However, at the time of the REFIT evaluation, there had not been a case yet where a substitution had been made (Ecorys for EC, 2018).

Emergency authorisations

As already planned in Directive 91/414/EEC, Regulation (EC) n°1107/2009 allows for emergency authorisations of plant protection products containing non-approved active substances, under specific conditions. These can be, for example, unexpected situations requiring immediate action to prevent significant danger to the growth of plants. Such an emergency authorisation is limited to 120 days and should not be granted repeatedly (Ecorys for EC, 2018).

[17] Regulation (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP Regulation)

[18] Following the criteria defined in Annex II to the Regulation on plant protection products and Annex XIII to the REACH Regulation for biocidal products

3.3.1.2. Trends and hypotheses of changes

The procedure for placing plant protection products on the EU market is regarded as one of the most stringent pesticide regulation in the world (Robinson *et al.*, 2020). It has evolved over the years to reinforce its aim to achieve a high level of protection for health and environment, while facilitating the free movement of plant protection products within Europe.

However, and despite this stringent regulatory framework, it is considered by some authors and by stakeholders who conducted numerous evaluations as complex (multiple implementing regulations, guidelines, guidance, etc,) and lacking efficiency (Robinson *et al.*, 2020; Ecorys for EC, 2018 ; European Commission, 2020b). In the paragraph below, we explore recent evolution of this legislative framework. In addition, based on this trend analysis, we draw potential future evolutions of this legislative framework by 2050.

The EU harmonized legislative framework led to a reduction in the number of available substances and could further evolve to take into account new scientific knowledge about pesticides health impacts

A number of active substances were not renewed or not approved since the implementation of the harmonized EU regulation

Before the harmonization of the legislative framework in 1991, there were more than 1 000 active substances on the market[19]. In March 2022, 449 active substances are approved for use in pesticides in Europe[20]. In between, several chemical active substances were banned based on safety assessments conducted by the food safety authorities: atrazine, chlordécone, paraquat, ichloropropène, cyanamide, propisochlore, perméthrine, diméthoate, noenicotinoids, clothianidine, thiaméthoxame and imidaclopride (Bazoche *et al.*, 2022). Others were withdrawn from the market by their producers.

According to the study report supporting the REFIT (regulatory fitness and performance) evaluation of the Regulation (EC) n°1107/2009, between 2011 and 2016, out of the 31 active substances that have been non-approved or non-renewed, 23 had hazard classifications for concerns regarding human health such as genotoxic potential and long-term toxicity (carcinogenicity, reproductive toxicity and endocrine disrupting potential). Fifteen of the non-approved or non-renewed substances had environmental or potential environmental concerns (risks to groundwater, surface water, soil, aquatic organisms, honeybees, etc.) (Ecorys for EC, 2018). However, the study report also highlights that it is still not possible to verify the benefits of the cut-off criteria, because in 2018 only one active substance was non-approved due to the health cut-off criteria (Linuron).

Marchand (2022) calculated that since 2018, 53 active substances were "net lost" (balance between approvals and non-renewals, withdrawals, end of approvals), in majority chemical active substances. In a study conducted in 2017 for the European Crop Protection Association, it was estimated that 58 active substances may be subject to hazard-based non-approval in the coming years (Bryant Christie, 2017). Also, it could be that pesticide manufacturers do not proceed with submission of renewal requests for substances that qualify for the cut-off criteria, and withdraw them from the market.

[19] https://ec.europa.eu/assets/sante/food/plants/pesticides/lop/index.html#:~:text=What%20is%20a%20pesticide%3F,used%20for%20non%2Dagricultural%20purposes, last consulted in May 2023

[20] EU pesticide database https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/active-substances/index.cfm?event=search.as&s=3&a_from=&a_to=&e_from=&e_to=&additionalfilter__class_p1=&additionalfilter__class_p2=&string_tox_1=&string_tox_1=&string_tox_2=&string_tox_2=&string_tox_3=&string_tox_3=&string_tox_4=&string_tox_4=, last consulted in March 2022

An increase in the number of emergency authorisations

The number of **emergency authorisations** has significantly increased over the past years. The number of emergency authorisations in the EU rose in the period 2013-2016, and in 2016, their number was five times higher than in 2012. According to various stakeholders, this can be attributed to several causes: delays in the processing of approval dossiers requests, reduced availability of pesticides due to the increased stringency of approval criteria, ways to avoid bans and restrictions measures applicable to these pesticides (Ecorys for EC, 2018). An example of emergency authorisation are plant protection products containing neonicotinoids. Neonicotinoids, which were banned in Europe, have been authorized through the emergency authorisation process in France and other European countries for sugar beet crop protection in 2021[21] and 2022, because of the estimated damage to the sugar industry due to potential pest impacts on the crop yields (Grimonprez and Bouchema, 2021).

The criteria for the safety assessment of active substances regularly evolve to take into account developing knowledge on the impacts of pesticides on human and environmental health.

The European Food Safety Authority (EFSA) takes into account **new scientific developments on active substances** and regularly issue **additional criteria** for their assessment. For example, EFSA issued in 2018 a guidance related to the assessment of endocrine disruptive properties (ECHA and EFSA, 2018), and in 2022 a new set of criteria for micro-organisms (Mombert *et al*., 2022).

Several scientists and non-governmental organizations are asking for inclusion of additional criteria in the safety assessment of the active substances, such as **their impact on pollinating insects**. A recent development on that matter is the case of neonicotinioids, a class of active substances that were banned due to their negative effects on bee health, in particular their nervous system. In this case, results from eco-toxicological research were raised to EFSA by national research institutes, reinforced by the mobilization of beekeepers, NGOs, journalists and ultimately policy makers. All these information, coming from various sources, contributed to raising awareness and decision to ban these substances as described by Demortain (2021).

Also, the current risk assessment methodology relies on toxicological data generated on specific species. It does not take into consideration the **cumulative risks, and the actual impact of pesticides on populations of organisms, diversity within and between species** (Ecorys for EC, 2018).

Indeed, in its current set up, the regulation for placing plant protection products in the market is based on individual active substance approval. Each substance is assessed individually, whereas pesticides are sold and used as **mixtures**: one or more active substances mixed with co-formulants. The potential toxicity of mixtures is not given sufficient scrutiny prior to pesticides being placed in the market.

In addition, the potential synergistic effects (so-called "**cocktail effects**") of using different pesticides in the field is not assessed during the evaluation process of actives substances and of pesticides. Risk assessments are conducted for a single pesticide applied in a specific crop, whereas in the field several treatments can be applied sequentially. Also, animals can move within a given landscape, and therefore be exposed to several pesticides applied in different fields (Topping *et al.*, 2020). An increasing number of studies show that toxic effects can result from cumulative exposure to mixtures of different active substances (Robinson *et al.*, 2020). The European Food Safety Authority (EFSA) has started working on this matter and has developed some approaches for assessing combined exposure to multiple pesticides and contaminants in humans and multiple pesticides in bees, and issued some guidance on that matter[22]. EFSA work continues to further developing new approaches and tools for harmonising how to assess risks to humans and the environment from combined exposure to multiple chemicals in the food chain.

[21] https://www.efsa.europa.eu/fr/news/neonicotinoids-efsa-assesses-emergency-uses-sugar-beet-202021, last consulted in May 2023

[22] See for example the EFSA draft guidance document (‘MixTox 2’) for grouping chemicals across the food safety area and prioritisation of groups of chemicals for human health risk assessment launched for public consultation in May 2021.

Since 2016, EFSA has highlighted the need for developing knowledge on **pesticides metabolites** and their impacts through guidance on definition of residues[23]. Indeed, one single active substance can generate dozens of different metabolites depending on the substance itself, the soil quality, its microorganisms, the climate, the plant metabolism, etc.

These additional criteria may lead to disappearance of several active substances, especially those currently classified as Candidates for Substitution (CfS), or at least to more limitations of use for chemical pesticides. According to a report from the RISE foundation, 215 active substances were due for renewal by the end of 2021, among which only 158 had been received applications for renewal in 2018, meaning that the other 57 will certainly disappear from the market (Buckwell *et al.*, 2020).

In the future, this trend should continue and even increase as science developments progress on the knowledge of pesticides impacts on environment and human health.

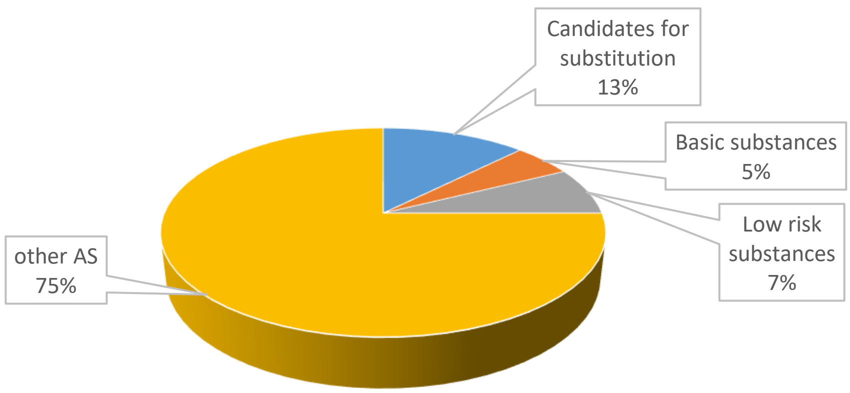
Hypothesis of change: More and more stringent safety criteria limiting the number of chemical pesticides in the market.

Growing interest in alternative solutions to chemical pesticides such as biocontrol agents or pesticides containing low-risk substances

The types of approved active substances have evolved in recent years. Indeed, one can notice a positive trend towards more and more new active substances such as micro-organisms and plant extracts being approved. According to a very recent study of the evolution of active substances in Europe, there has not been any chemical active substance approved since 2019, while approvals of biocontrol agents[24] (which include micro-organisms and plant extracts) have been quite stable each year since 2016 (Marchand, 2022). Despite this positive trend in terms of approvals, biocontrol substances are still far fewer than chemical substances. In 2018, they represented 36.8% of the total number of substances registered in Europe (Robin and Marchand, 2019).

Also, low risk and basic substances remain quite low in the total number of approved substances, as shown in Figure 3-51.

Figure 3-51: Types of active substances currently approved in Europe (February 2022)[25]



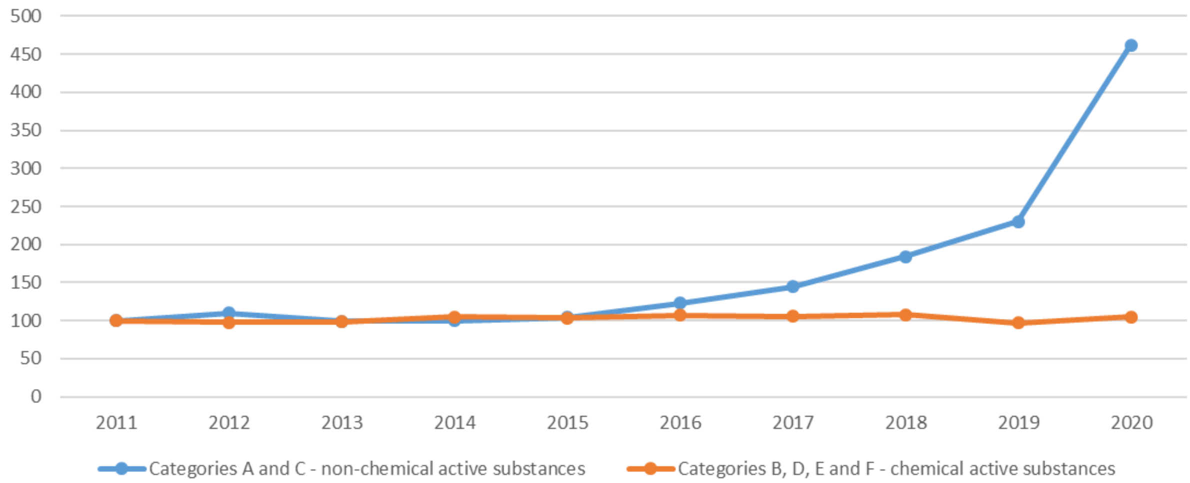
[23] EFSA Guidance on the establishment of the residue definition for dietary risk assessment published in December 2016: https://efsa.onlinelibrary.wiley.com/doi/10.2903/j.efsa.2016.4549

[24] Marchand defines active substances of biocontrol agents as microorganisms' active substances and semiochemical active substances.

[25] EU pesticide database, https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/, consulted in February 2022

In terms of market dynamics, the increased number of biocontrol substances approved in Europe has translated into increased sales of pesticides containing non-chemical active substances between 2011 and 2020, while sales of pesticides containing chemical active substances have remained stable in this period, , as shown in Figure 3-52. However, in absolute figures, sales of pesticides containing chemical active substances remain far higher than sales of pesticides containing non-chemical active substances: according to Eurostat data, in 2020, they were more than 300 times higher[26].

Figure 3-52: Pesticide sales by categorisation of active substances in European Union (index 100, from 2011 to 2020)[27]



Within the biocontrol category, the micro-organisms category is the most dynamic, and is expected to pursue its growth in the coming years (Hulot and Hiller, 2021). The European pesticide manufacturers' organization CropLife Europe[28], forecasts a 5 times increase in the global market for biopesticides between 2020 and 2031 (in value terms), which will still be 10 times smaller than the global total pesticides market (infographic published in May 2022).

From a policy standpoint, the development of biocontrol products and of pesticides containing low risk substances is encouraged[29]. Several evolutions in the regulations allow for more flexibility for these products. For example, low-risk active substances have longer approval periods than standard active substances. In France, they benefit from exemptions from the general rules applicable to pesticides: the CEPP (certificat d'économie de produits phytosanitaires) is not required for farmers using only biocontrol pesticides; also, some buffer zones, where pesticides use is forbidden, can still be treated with biocontrol products (Grimonprez, 2022). Very recently, in 2022, the European Commission issued a proposal for changing the current regulation applicable to micro-organisms[30]. The new acts follow a different approach from the current framework applicable to all active substances, mainly drawn for

[26] Eurostat data on pesticides sales by categories of active substances https://ec.europa.eu/eurostat/databrowser/view/AEI_PESTSAL_RSK__custom_6204461/default/table?lang=en, last consulted in May 2023

[27] Eurostat, last update March 2023: https://ec.europa.eu/eurostat/databrowser/view/AEI_PESTSAL_RSK/default/table?lang=en

[28] https://croplifeeurope.eu/wp-content/uploads/2022/05/CLE_Unlocking-the-Potential-of-Biopesticides_2022.pdf. Biopesticides are defined in this publication as "*pesticides of natural origin, either naturally occurring or synthetically derived*".

[29] For example, in France the Ecophyto plan states that: "[… *Le plan prévoit des mesures tendant au développement des produits de biocontrôle, qui sont des agents et produits utilisant des mécanismes naturels dans le cadre de la lutte intégrée contre les ennemis des cultures. Ils comprennent en particulier :1° Les macro-organismes ; 2° Les produits phytopharmaceutiques comprenant des micro-organismes, des médiateurs chimiques comme les phéromones et les kairomones et des substances naturelles d'origine végétale, animale ou minérale.*" (ANSES, 2021).

[30] https://food.ec.europa.eu/plants/pesticides/micro-organisms_en, last consulted in August 2022.

chemical pesticides (Bourguignon, 2017). They are based on the biology and ecology of each micro-organism and take into account the most recent scientific knowledge. This proposal, if adopted by the Parliament and the Council, should facilitate the approval of micro-organisms for use as active substances in plant protection products and the authorisation of products containing them, by applying more adapted criteria for safety assessment, streamlined application dossiers, and shorter timelines for risk assessment.

In future, rather than applying exemptions from the generic legislative framework applicable to pesticides, a dedicated framework for biocontrol and low risk substances could be set up. It would lead to a differentiated legislative framework for alternatives to chemical pesticides, covering biocontrol products, low-risk substances, basic substances, etc.

Hypothesis of change: Differentiated legislative framework for chemical pesticides and for their alternatives (biocontrol products, low risk active substances, etc.).

More transparency in safety assessments and post-market surveillance

In the current legislative framework, dossiers are prepared and submitted by petitioners, in most of the cases pesticides producers.

Several authors and stakeholders call for more transparency in the safety risks assessments conducted on pesticides and their active substances (Robinson *et al.*, 2020; Möhring *et al.*, 2020b; Ecorys for EC, 2018; Storck *et al.*, 2017). For example, Möhring *et al.* suggest that independent and anonymous laboratories could run studies in addition to industry-provided data, to increase credibility and trustworthiness whilst reducing conflicts of interest (Möhring *et al.*, 2020b). This transparency issue has been recently addressed in Europe, with the publication of a new regulation (EU, 2019). C**itizens now have access to the scientific studies and information submitted by the industry**. Also, **public consultations are systematic in the process of assessing authorisation applications for pesticides. The industry must also communicate to EFSA all the studies that they commission. Finally,** the European Commission now has the **power to ask EFSA to commission further studies** to verify the evidence used in its risk assessment process[31].

The European Environment Agency (EEA) in its report "late lessons from early warnings" discusses case studies of health hazards identified on chemical substances and technical innovations, and how they have been addressed by public policies (EEA, 2013). Several case studies related to pesticides – dibromochloropropane (DBCP) and male infertility, seed-treatment of insecticides and honeybees - are described together with lessons learned from these experiences. EEA makes some recommendations on how to better take into account these 'early warnings'. These include "*reduce delays between early warnings and actions*", and "*foster collaboration between business, government and citizens*".

Topping *et al.* (2020) discuss several improvements to the current environmental risk assessment of pesticides. They call for a post-market "pesticidovigilance" system, in which several stakeholders would be involved, including farmers, and would provide information on their pesticide use, agronomic and environmental data. In turn, farmers would get information from risk assessors on the pesticides they use.

In future, the legislative framework for pesticides could be revised to include a warning system for sharing information related to pesticides health impacts, accessible to multiple stakeholders.

Hypothesis of change: Dynamic regulatory framework enabling the rapid reporting of warnings related to pesticides uses and health impacts, open to multiple stakeholders.

31 https://www.anses.fr/en/content/european-transparency-regulation-new-framework-risk-assessment-and-food-safety consulted in August 2022

3.3.1.3. Summary of the hypotheses of changes for the legislative framework related to pesticide use in Europe

The Table 3-22 below summarises the three main hypotheses identified for the evolution of the legislative framework for pesticides use in Europe.

Table 3-22: Hypotheses of changes of the legislative framework related to pesticide use in Europe up to 2050

Hypothesis 1	Hypothesis 2	Hypothesis 3
Additional safety criteria based on new scientific developments, leading to less and less chemical substances available	Differentiated legislative framework for chemical pesticides and biocontrol / micro-organisms products	Dynamic regulatory framework enabling the rapid reporting of warnings related to pesticides uses and health impacts, open to multiple stakeholders

3.3.2. Policies aiming at reducing the uses and/or risks of chemical pesticides

Since the years 2000, several policies have been developed across Europe to address the issue of reducing the use and/or risks of pesticides. Development of these policies were triggered by the increased knowledge about the health and environmental impacts of pesticides, as well as citizens increased awareness and concerns about these issues. In 2002, the European Parliament and the Council adopted the 6th environment action programme (6th EAP), in which they acknowledged that the impacts of pesticides on human and environmental health must be further reduced. The European Commission published a pesticides thematic strategy in 2006, describing five specific objectives:

a) *"to minimize the hazards and risks to health and environment from the use of pesticides;*
b) *to improve controls on the use and distribution of pesticides;*
c) *to reduce the levels of harmful active substances including through substituting the most dangerous with safer (including non-chemical) alternatives;*
d) *to encourage low-input or pesticide-free cultivation, among others through raising users' awareness, promoting the use of codes of good practices and promoting consideration of the possible application of financial instruments;*
e) *to establish a transparent system for reporting and monitoring progress made in the fulfilling of the objectives of the strategy, including the development of suitable indicators."* (European Commission, 2006).

In the strategy document, the European Commission also proposed measures, some that could be included in existing policy instruments (for example reinforcement of monitoring, comparative assessments for candidates for substitution), others that could not and would be part of a Directive (EC Directive 2009/168, (SUD)).

The measures that have been developed since the 2000's include various policy instruments of regulatory (command and control), economical and informational types. They can be set at European levels, and directly applicable to all Member States, or set overall objectives at European level and leave Members States with the implementation of adequate action plants and targets.

As part of this retrospective analysis it was not possible to draw an exhaustive list of all policies and instruments in place in every Member State; instead, we will focus on the major policies addressing the reduction of pesticide use and/or risks, their trends and hypotheses of changes.

3.3.2.1. Water policies set clear limits of pesticides residues, to ensure protection of waters

One of the first European policy to address pesticides-risk reduction was related to water quality protection. Adopted in 2000, the Water Framework Directive (WFD) (European Community, 2000), is the EU policy requiring Member States to protect their surface waters. Specific directives dealing with ground waters and marine waters have completed this directive[32]. According to the WFD, to have a good status, a surface water must exhibit both a **good chemical and a good ecological status**. This includes limiting the pollution of waters with chemical pesticides, since 23 pesticides (out of 45 priority substances (PS) or substance groups) are listed in the WFD and must be monitored regularly. As part of the ecological classification, each EU Member State is also obliged to identify pollutants of regional or local importance, the river basin-specific pollutants (RBSP), and this list may include pesticides. Both PS and RBSP are assigned legally binding environmental quality standards (EQS) reflecting concentration levels below which it is assumed that the aquatic environment and human health are protected (Weisner *et al.*, 2022).

The specificities of this Directive are that it introduces a **management of the water status in each river watershed**, corresponding to a natural geographical and hydrological unit, instead of relying on administrative or political boundaries. Also, these **plans involve local stakeholders in a collective and participatory process** (elected representatives, administration representatives, users of water including industries, farmers, citizens, associations). The goals, management plan and set of measures taken are **reviewed and updated every six years** (2009-2015, 2015-2021, 2021-2027).

The Directive's original aim of achieving at least good ecological status for all surface water bodies by 2015 has not been achieved and is currently extended until 2027. According to the European Environment Agency[33], in 2018, only around 40% of surface waters were in good ecological status or potential, and only 38% were in good chemical status. Hydromorphological pressures (40%) and diffuse pollution from agriculture (38%) are the two most significant causes of failure in surface water bodies (Bieroza *et al.*, 2021).

Pesticides are broadly represented in the WFD list of substances to be monitored. According to monitoring data from the second river basin management plan, in the period running from 2010 to 2015, only 0.4 % of water bodies were affected by pesticides, and 15 % of the groundwater body area (Mohaupt *et al.*, 2020). According to Weisner *et al.*, the protocol for monitoring pesticides as currently described in the WFD is insufficient to measure the actual pollution risk, and **therefore the contribution of pesticides to the chemical and ecological status of waters may be underestimated** (Weisner *et al.*, 2022). The European Environment Agency (EEA) confirmed this in a recent publication of a new indicator that tracks findings of pesticides in Europe lakes, rivers, and groundwaters. This new indicator shows that **levels of pesticides exceeding thresholds were measured in a quarter of all reported monitoring sites in European surface waters** in 2019. From 2013 to 2019, this share varied between 13% and 30% (Figure 3-53). The share for **groundwater** with exceedances was considerably lower, between 3% and 7% (EEA, 2021).

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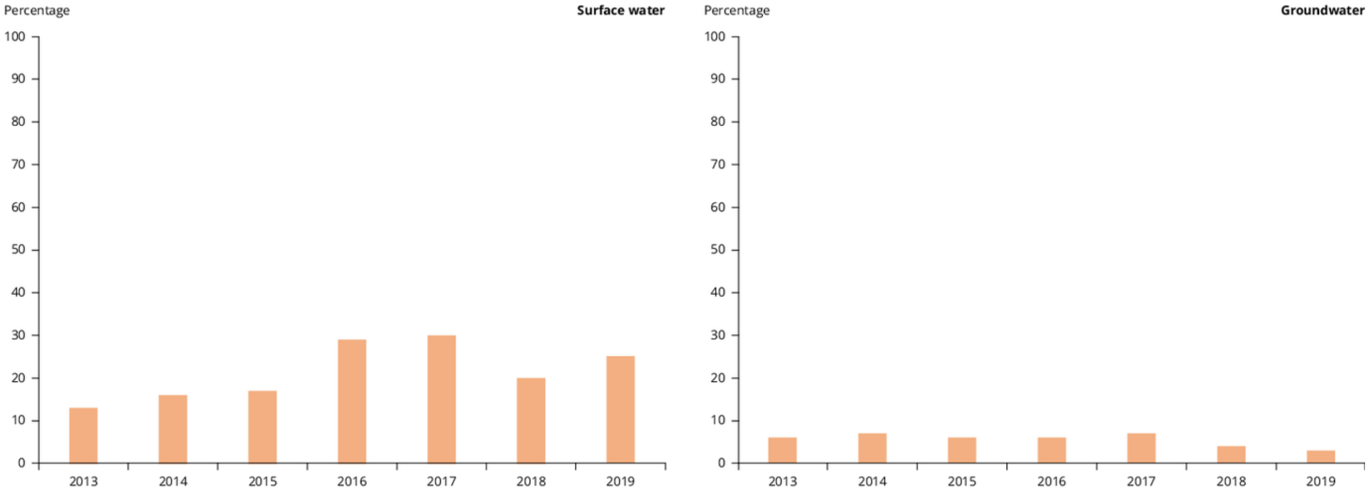
[32] Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration

[33] https://www.eea.europa.eu/ims/ecological-status-of-surface-waters, consulted on April 1st, 2022.

Figure 3-53: Percentage of reported monitoring sites with pesticides exceeding thresholds in surface waters (left) and groundwater (right) in Europe weighted by country area (Source: EEA, 2021)



After two management cycles – 2009-2015 and 2015-2021 - several authors have analyzed the impacts of the Water Framework Directive and reasons for failing to achieve the objectives set to reach good chemical and ecological status.

In particular, Van Kats *et al.* (2022) have reviewed the available literature and interviewed regional water authorities. They found out that the legislation is generally perceived as flexible, which is positive but also makes it ambiguous and open for interpretation. It is also described as ambitious and stringent, and the short time frame available to attain the objectives is seen as a challenge. A lack of political will is described as a common issue, but the "river basin approach" is a good design as it requires efficient collaboration between different stakeholders.

Another water policy covers drinking water quality: the **drinking water Directive**. It was initially adopted in 1998 (European Community, 1998) and recasted in 2020 (EU, 2020). It intends to "*protect human health from the adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean*". It applies to all water distribution systems including tap water, bottled water (excluding natural mineral waters) and water used in the food-processing industries**. It sets maximum levels for several substances and parameters in drinking water, including for pesticides**[34]. It also sets monitoring plans to control the quality of drinking water, and reporting to the European Commission on the water quality. This Directive has been recasted at the end of 2020, to introduce new elements. These include a risk-based approach for Member States to prioritize pollution prevention, the obligation for Member States to improve or maintain access to water for all, in particular for vulnerable and marginalized groups. Also, the general public will get more information on the water quality, price, volume consumed. A watch list of pollutants of emerging concern, together with guidance values, has been created, with the obligation for Member States to monitor and take relevant actions if necessary (EU, 2020).

Water laws, in their set up, remain an interesting lever for reducing the use of pesticides, because it creates a necessary coordination between actors within the river watershed, and also because the very clear objective of achieving good chemical and ecological status and drinking water quality justifies the implementation of measures through various instruments including on pesticides (Grimonprez, 2021).

[34] For pesticides, the maximum allowable concentration (MAC) is 0.1 µg/L for any individual active substance (a 0.03 µg/L standard applies to four exceptions: aldrin, dieldrin, heptachlor, and heptachlor epoxide) and 0.5 µg/L for the total pesticide concentration (Dolan *et al.*, 2013).

Several initiatives illustrate this:

- In Deux-Sèvres, Vienne, in France, has decided collectively to make access to water conditional on agroecological commitments by irrigators. To be able to continue to take water, they must obtain results, especially in terms of pesticide use (Grimonprez, 2021).
- In Munich area, in the Mangfall Valley which supplies 80% of the drinking water in Munich, a voluntary payment scheme was offered by the municipal water provider to farmers in the area, to support their conversion into organic farming. The scheme was more environmentally-effective and cost-effective than upgrading water treatment to remove nutrients and pesticides (Sud, 2020).

Barataud *et al.* analyse different initiatives implemented in France and in Germany to protect water catchment areas. They identify three critical points or conditions for successful solutions implementation. The first one is sharing the knowledge of the territory, of the sources of the pollution, and of the diversity of cropping systems in place. The second is building long-term and large-scale (beyond the water catchment area) Solutions. Thirdly, successful solutions require conceiving different models of technical solutions, at different scales (relocalisation of agricultural productions, internal strategy changes within the farms, new production modes such as organic farming), taking into account different types of relations between the actors involved (Barataud *et al.*, 2016).

3.3.2.2. Reducing the risks and impacts of pesticides use: The Sustainable Use Directive and its national action plans

The Sustainable Use Directive (Directive 2009/128/EC, SUD) is often quoted in the literature as a central piece of legislation with regards to pesticides use reduction. It sets the framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment, promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to chemical pesticides (European Community, 2009b). The Sustainable Use Directive required the Member States to draw up National Action Plans (NAPs) to implement the Directive by November 2012. Each NAP needs to propose measurable goals, targets to decrease the potential and proved effects of pesticide use on humans and the environment, and indicators for monitoring. It also needs to stimulate the expansion of Integrated Pest Management (IPM) and alternative approaches or methods to reduce reliance on pesticides (Helepciuc and Todor, 2021). A proposal for the revision of SUD is currently being discussed by the European Parliament and by Member States in the Council (see more details about the proposed revision in paragraph 3.3.2.6).

SUD does not set quantitative objectives for risk reduction of pesticide use, which responsibilities are given to Member States through their national action plans (NAPs). The Directive however identifies specific actions that EU countries are required to include in their plans for proper implementation.

One of the key element of SUD is the provision for Member States to promote Integrated Pest Management (IPM) for all EU farmers from 2014, so as to reduce dependency on pesticides. IPM is defined in SUD as "*the careful consideration of all available plant protection methods and subsequent integration into appropriate measures that discourage the development of populations of harmful organisms and keep the use of PPPs (Plant Protection Products) and other forms of intervention to levels that are economically and ecologically justified and reduce or minimize risks to human health and environment*". SUD lists the eight principles of IPM. In a review of IPM developments over the past six decades, Deguine *et al.* identify some weaknesses that may have limited its implementation, notably in the EU. The authors explain that, although application of IPM principles was made compulsory in the SUD Directive, for all EU farmers, and as of 2014, the Directive does not explicitly describe practices that have to be adopted, and how they are to be applied in practice on the fields. Also, it does not rank these principles according to priorities. Finally, some principles relate to agrochemical protection efficiency, contributing to legitimizing and facilitating their use even more (Deguine *et al.*, 2021).

Other important measures promoted in SUD are the minimized or prohibited use of pesticides in specific areas (article 12), and the establishment of buffer zones to protect non-target aquatic organisms and to protect surface and groundwater from pollution (article 11).

Other actions relate to the training of users, advisors and distributors, the inspection of pesticide application equipment, the prohibition of aerial spraying, the information and awareness raising about pesticide risks, and the development of systems for gathering information on pesticide acute poisoning incidents, as well as chronic poisoning developments, where available.

After the adoption of the SUD in 2009, Member States have developed and implemented their national action plans. These include various policy instruments mixes. Most of them have evolved over time. In France, several National Action Plans have been implemented: called "Ecophyto", then "Ecophyto II" in 2015, and since 2018 "Ecophyto II+".

The European Commission assessed the implementation of the SUD Directive through the national plans, and published two reports, in 2017 and in 2020 (European Commission, 2020a). Both reports highlighted that implementation of SUD was lacking especially on the promotion of alternatives to chemical pesticides and implementation of IPM.

Several authors have also analysed the efficacy and impacts of SUD and in particular of the NAPs. From these evaluations, it is worth noticing that, first of all, the level of ambition with regards to pesticide risk reduction varies a lot between Member States. Indeed, a very limited number of Member States (5) identified high-level measurable targets in their national NAPs, related to either risk reduction or use reduction[35], of which four relate to risk reduction (Belgium, Denmark, Greece and Germany) and one to use reduction (France) (Sud, 2020). Other Member States have set objectives based on compliance or actions. For example, the UK pesticides strategy sets six separate action plan groups on biodiversity, water, availability of products and techniques, amenity use, amateur use and health, each with its own indicators, desired strategic outcome and headline and core indicators (Barzman and Dachbrodt-Saaydeh, 2011).

Also, and although IPM is a key element of the Directive, the European Commission acknowledges that: "***the assessment of the implementation of IPM continues to be the most widespread weakness in the application of the SUD****. Consequently, Member States have failed to exploit the significant potential for greater adoption of IPM, including the more widespread adoption of non-chemical pest control techniques*" (European Commission, 2020a).

Member States have used a broad diversity of policy instruments to achieve the objectives or targets set in their national action plans. According to the European Commission 2020 report, the majority of Member States have implemented **training and certification systems**, **ban** of aerial spraying (even though derogations can be granted under strict conditions) and have established measures to protect the aquatic environment and to ensure that pesticides are stored and handled safely. Some Member states have introduced **economical instruments** – taxes, incentives – to support adoption of practices using less pesticide. Few countries have introduced pesticide taxes, with different set up, rates, and impacts. Many Member States have leveraged the opportunity of agro-environmental measures within the Common Agriculture Policy (CAP) to compensate for the costs associated with reducing the use of chemical pesticides, and to promote IPM adoption. These are further developed in the paragraph 3.3.3.

[35] Examples of reduction targets set by some Members States: Germany: -30% in potential risk to the environment by 2023 vs baseline average 1996-2005; Denmark: -40% in pesticide load indicator and -40% in the load from Substance of Very High Concern (SVHC) by end 2015, vs 2011; France: -25% use of plant protection products by 2020, and -50% by 2025, vs 2015, without having a negative impact on farm incomes.

Another type of policy instruments used by some Member States is the **restriction of use of pesticides in certain areas** to protect sensitive areas and/or populations (zoning), etc. The Figure 3-54 below illustrates the major initiatives taken by the French government on that topic. It shows an increase over years in the measures taken to restrict the use of pesticides and protect vulnerable populations and areas.

Figure 3-54: Examples of measures taken by the French government to reduce the risks of pesticides applications on vulnerable population and areas (adapted from Grimonprez and Bouchema, 2020)[36]

2015	2017	2020	2022
Ban or minimal distance for pesticide application in places hosting vulnerable populations (children schools and day care, hospitals, etc.) *Law 2014-110, Code rural et de la pêche maritime article L253-7-1*	Non-treatment and minimal treatment zone (buffer zone) close to water areas *Arr. 4/05/2017, modified by Arr. 27/12/2019* -- Ban of pesticides applications in all public green spaces *Law 2014-110*	Application of pesticides conditioned to the protection of residents through a departmental collective charter *Law n°2018-938, code rural L253-8*	Ban of pesticides application in all houses, hotels, cemeteries, public parks, sports areas *Arr. 15/01/21* -- Re-inforcement of non-treatment and buffer zones *Arr. 25/01/22*

NB: biocontrol products and products containing only basic or low risk substances are excluded from the restrictions.

3.3.2.3. Health and nutrition policies to reduce exposure risks for consumers

Presence of residues of pesticides in food can pose some issues for human health, and animal health in the case of residues in feed products.

To manage these risks, and ensure a high level of consumers' protection, the pesticide legislative framework **regulates the quantities of pesticides residues that are allowed in food and feed**. This framework has been harmonized in all Europe and for all food and feed crops in the 90's. Maximum Residue Levels (MRLs) are set in these regulations, for couples of active substance and agricultural product. Before, and since the 70's, these levels of residues were set at national levels, resulting in different norms in the European countries, raising potentially food safety questions and trade barriers

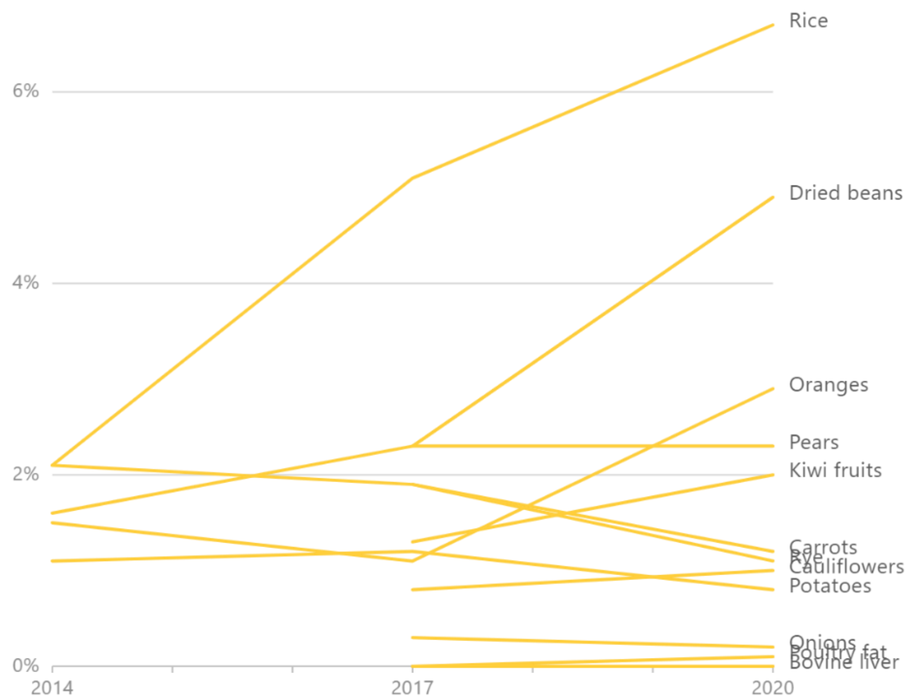
[36] References of the legal texts quoted in the table: *Loi n° 2014-110 du 6 février 2014 visant à mieux encadrer l'utilisation des produits phytosanitaires sur le territoire national ; Code rural et de la pêche maritime, Article L253-7-1 ; Arrêté du 15 janvier 2021 relatif aux mesures de protection des personnes lors de l'utilisation de produits phytopharmaceutiques dans les propriétés privées, les lieux fréquentés par le public et dans les lieux à usage collectif et modifiant l'arrêté du 4 mai 2017 relatif à la mise sur le marché et à l'utilisation des produits phytopharmaceutiques et de leurs adjuvants visés à l'article L. 253-1 du code rural et de la pêche maritime ; loi n°2018-938 du 30 octobre 2018, Article L. 253-8 du code rural et de la pêche maritime ; décret n°2019-1500 et arrêté du 27 décembre 2019 relatif aux mesures de protection des personnes lors de l'utilisation de produits phytopharmaceutiques. Arrêté du 25 janvier 2022 relatif aux mesures de protection des personnes lors de l'utilisation des produits phytopharmaceutiques et modifiant l'arrêté du 4 mai 2017 relatif à la mise sur le marché et à l'utilisation des produits phytopharmaceutiques et de leurs adjuvants visés à l'article L. 253-1 du code rural et de la pêche maritime.*

(Ecorys for EC, 2018). Currently, the EU regulation 396/2005 (European Community, 2005) contains all European MRLs applicable to food crops. Specific MRLs are set in Directives 2006/125/EC (European Community, 2006a) and 2006/141/EC (European Community, 2006b) for food intended for infants and young children. These MRLs apply to any food crop entering the European market, including imported products from non-European countries. A general default MRL of 0.01 mg/kg applies where a pesticide is not specifically mentioned (not used in EU or not approved). The European regulation however provides that some maximum residue limits be set for substances not approved in Europe, at the request of the importing country, and following a risk assessment (import tolerances).

The compliance of agricultural products with this regulation is checked through monitoring programs at EU and national levels. Every year, the European Food Safety Authority (EFSA) reports on the quality of food regarding pesticides residues, based on data provided by Member States (EFSA, 2022). EFSA's 2022 report on pesticide residues in food covers more than 88,000 food samples collected in the European Union in 2020. Analysis of the results shows that **94.9% of samples fell within legally permitted levels** (96.1% in 2019). **MRLs were exceeded in 5.1% of the samples**, a slight increase compared with 2019 (3.9%) and 2018 (4.5%). For some food crops, the rate of exceedances progressed between 2014 and 2020, as shown in Figure 3-55. In addition, compared to conventionally produced food, the MRL exceedance rate trends are generally lower in organic food. Most of the exceedances found in organic production were coming from persistent organic pollutants, which are no longer approved.

Samples of products imported from third countries showed higher MRL exceedances (3.3%) and non-compliance (2.6%) rates compared with food produced within EU. When analysing certain foods subject to increased frequency of controls at border, EFSA found some rather high levels of non-compliance for some combinations of food commodity and country of origin, for example: grape leaves and similar species from Turkey (55.6%), chili peppers from Vietnam (50%), pomegranates from Turkey (38%), chili peppers from India (33%), oranges from Turkey (27%).

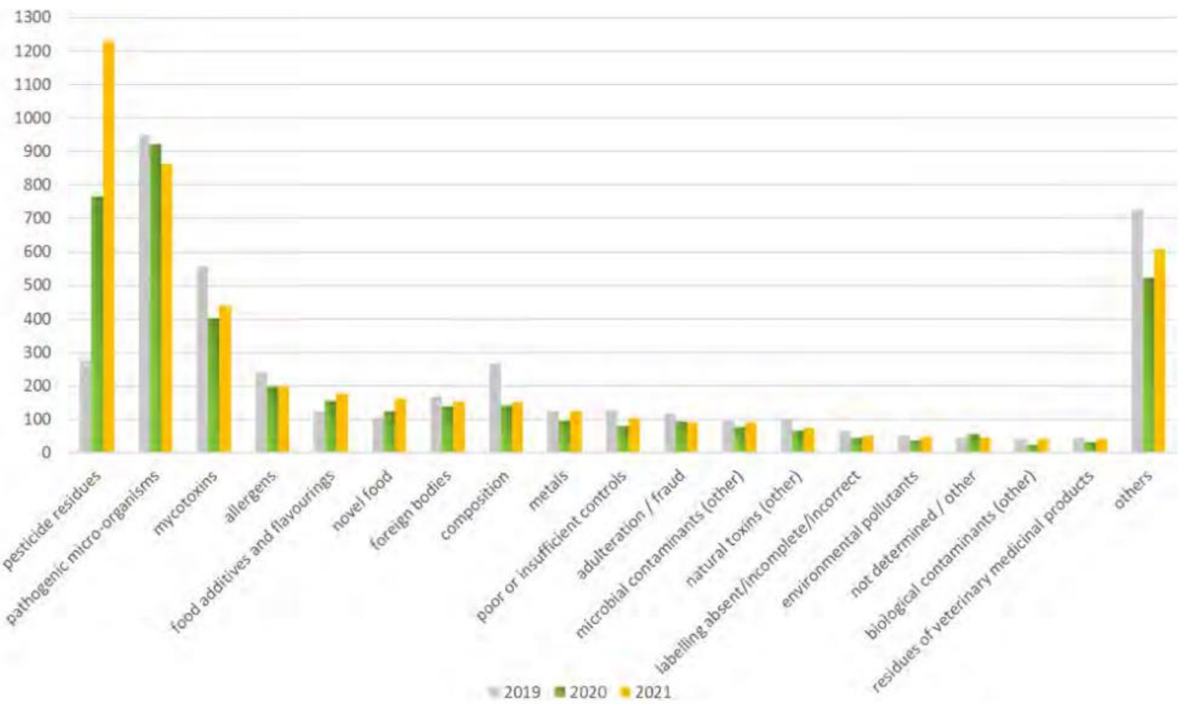
Figure 3-55: MRL Exceedances rate comparison (2014, 2017, 2020) for some food crops (Source: EFSA, 2022)



Overall, EFSA concludes that in 2020, the MRLs were exceeded in 5.1% of the samples, an increase compared with 2019 (3.9%). According to EFSA, for most of the samples analysed, the dietary exposure to pesticides is unlikely to pose a risk to EU consumer health. The higher level of residues found in products coming from non-EU countries raises the question of border controls, and of alignment of international legislations on pesticides. This is discussed in the paragraph 3.3.4.

In addition, Europe has put in place since 1979 a Rapid Alert System for Food and Feed (RASFF), a common platform communicating food safety alerts arising from any country in Europe. This platform is also available to consumers since 1994. It allows Member States and food business operators to take appropriate actions such as product recalls from the market, in order to protect consumer's safety. According to the 2021 Annual report from the European Commission on the Alert and Cooperation Network: "***in 2021, pesticide residues were the most reported issue in RASFF and this for the first time in its history:*** *1231 notifications, representing an increase by 61% in comparison with 2020 and more than quadruplicated in comparison with 2019*" (Figure 3-56) (European Commission, 2022f).

Figure 3-56: RASFF notifications by food hazard category (2019 – 2021) (European Commission, 2022f)



Nutrition policies are also addressing the topic of pesticides and issuing in **their dietary guidelines recommendations to consumers to limit their exposure**. This is the case of the French national nutrition program (PNNS) whose nutritional objectives are set by the Haut Comité de Santé Publique (HCSP). HCSP issued in January 2022 an opinion on the revision of dietary guidelines for pregnant and lactating women (HCSP, 2022). In this opinion, HCSP recommends the consumption of vegetables, cereals and pulses products coming from **production modes that reduce the exposure to pesticides**. It adds that organic production is a way to reduce exposure to pesticides from plant-based products. However, organic consumption is a complementary element to the main dietary guidelines – such as, for fruit and vegetables, a minimum of five portions per day (HCSP, 2022).

These nutritional recommendations translate into **communication campaigns** for the population (see example of the PNNS guidelines for pregnant women[37]).

[37] https://www.mangerbouger.fr/manger-mieux/a-tout-age-et-a-chaque-etape-de-la-vie/les-recommandations-et-conseils-avant-pendant-et-apres-la-grossesse/manger-equilibre-avant-pendant-et-apres-la-grossesse, consulted in August 2022

They can also translate into policy instruments to **support and develop organic products consumption in public procurement**. In France, since January 1st 2022, collective catering facilities (including schools, universities, kinder gardens, public administration canteens) must provide a "*minimum of 50% of quality and sustainable food products, including 20% of organic food products*" (République française, 2018). Also, in Rome, the 'Tutto per la Qualita' school feeding program focuses on purchasing local and organic food for school canteens (Place *et al.*, 2022).

Green Public procurement policies, aiming at increasing public sector purchases of organic food, can positively impact the share of organic farmland in the country. This was demonstrated in the case of the Swedish government policy on organic food public procurement implemented in 2006, that led to a significant increase in organic farmland from 2003 to 2016 (Lindström *et al.*, 2020).

3.3.2.4. Protecting the health of users of pesticides

Operators, applicators and farm workers can be directly exposed to pesticides and their health impacts (occupational exposure), in acute and chronic ways. Most occupational exposure to pesticides occurs through the dermal and inhalation routes, during mixing and loading and application from splashes and spray, including spray drift or by contact during re-entry into treated crops or areas or contaminated surfaces, equipment and materials (FAO and WHO, 2020b).

In Europe, the SUD directive for sustainable use of pesticides includes several recommendations for Member States to act, through their National Action plans, on minimizing the risks for farmers when applying chemical pesticides on their fields (European Community, 2009b). The actions implemented by the Member Stated include several measures to protect users of pesticides, among which the training of users, advisors and distributors, the inspection of pesticide application equipment, information and awareness raising about pesticide risks for example on plant protection products labels, etc.[38]

Public authorities officially acknowledge that several diseases are linked to professional exposure to pesticides. In France, these include prostate cancer, lymphomas, Parkinson disease, cognitive disorders. Since 2020, a pesticides fund has been created to compensate victims, financed partly by the professional accident insurance, and by the revenues of the pesticides tax (République française, 2019). In its first year, the fund received 226 requests for compensation, and gave 166 approvals. 93% of the requests came from farm workers, of which 67% were agricultural holders (FIVP, 2021).

3.3.2.5. Biodiversity laws to protect wildlife from the impacts of pesticides

Over the past years, the European Union and its Member States have made commitments and set clear goals to halt biodiversity loss. This translated into European regulations such as the Birds and Habitats Directive (so-called "Nature Directive"), the Biodiversity strategy 2020, which led to the creation of the Natura 2000 network of Protected Areas[39]. The EU has also adopted international convention and agreements such as the Convention on Biological Diversity. More recently, the Biodiversity strategy for 2030 was adopted (European Commission, 2020d). In the latter, the aim is to "*Bring nature back into our lives*", in line with the Green Deal objectives. In particular, the **Biodiversity Strategy for 2030 will establish protected areas for at least 30% of European lands and 30% of seas**. It will also restore degraded ecosystems by notably **increasing organic farming**, halting and reversing the decline of pollinators, **reducing the use and risks of pesticides by 50% by 2030**. The strategy also addresses urban

[38] https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/main-actions_en, last consulted in May 2023

[39] https://ec.europa.eu/environment/nature/legislation/index_en.htm, last consulted in May 2023

areas with the objective of "Greening urban and peri-urban areas" in European cities of at least 20,000 inhabitants. These urban greening plans should include measures to favour biodiversity in green areas in cities, including the elimination of the use of pesticides.

This Biodiversity strategy has yet to be translated into a legislative framework, and the Commission adopted in June 2022 a proposal for Nature Restoration law, to repair the 80% of European habitats that are in poor condition, and to bring back nature to all ecosystems, from forest and agricultural land to marine, freshwater and urban ecosystems (European Commission, 2022b). In particular, the law proposal plans on reversing the decline of pollinator populations by 2030 and increasing their populations from there on, increasing biodiversity in agricultural ecosystems, etc.

According to Hermoso *et al.* (2022), the success of the Biodiversity strategy relies on better coordination of restoration efforts among Member States, to avoid asymmetric implementation, and on the set up of management plans. It also requires the integration of conservation objectives into other policies such as the Common Agricultural Policy, to ensure the coherence between policies and optimal efficiency. It also requires multilevel multisector governance including participation of individuals, and adequate funding.

At national level, France adopted at the end of 2021 an Arrêté that restricts the use of pesticides on crops during certain hours in the blooming season, in order to protect bees and other pollinator's insects. Also, pesticides must carry an information on labels providing information about the effect of the product on bees and pollinators: "*dangerous for bees. During blooming, do not apply in foraging zones*", or "*can be dangerous for bees. During blooming, only apply in the 2 hours before or 3 hours after sunset*" (République française, 2021b).

3.3.2.6. Trends and hypotheses of changes

An important development of policies and instruments, with limited impact in reducing the use and risks of pesticides

As shown in the previous paragraphs, since 2000, there has been a substantial increase in public policies, mainly set at European level and then implemented nationally, to reduce the impacts, risks and uses of pesticides. Available evaluations of these policies suggest weak effects on reducing pesticides use and risks across Europe (see for example Möhring *et al.*, 2020b; ECA, 2020; Jacquet *et al.*, 2022).

This is reflected in the Harmonized risk indicators monitored by the European Commission, which show a limited reduction in use and risks of pesticides (-21% between 2011-2013 and 2019 for Harmonized risk indicator 1; Figure 3-57) and an important increase in the number of emergency authorisations (+55% over the same time period; Figure 3-58) (European Commission, 2021a). In the meantime, it seems that pesticides sales have remained stable (ECA, 2020). Also, surface water contamination with pesticides regularly exceeds legal thresholds (EEA, 2021).

Harmonized risks indicators: the Commission has developed two harmonized risk indicators to monitor the evolution of pesticide use and risks. Harmonized risk indicator 1 (HRI1) and Harmonized risk Indicator 2 (HRI2) were established under Commission Directive 2019/782[40], so 10 years after the publication of SUD. HRI1 measures the quantities of active substances in plant protection products sold in each Member State, weighted to reflect the intrinsic hazardous properties of the active substances. HRI1 shows a reduction by 21% in the risk to human health and the environment from pesticides in the European Union in the period from baseline (average 2011, 2012, 2013) to 2019, and

[40] Commission Directive (EU) 2019/782 of 15 May 2019 amending Directive 2009/128/EC of the European Parliament and of the Council as regards the establishment of harmonised risk indicators https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:32019L0782&from=EN.

a 4% decline compared to 2018. In the meantime, overall use of plant protection products remained pretty much constant. This suggests a shift towards the more widespread use of less-hazardous substances (European Commission, 2021a).

HRI2 measures the number of emergency authorisations of Plant Protection Products weighted by the hazardous properties of the active substances in the PPP. Harmonised Risk Indicator 2 for the European Union shows a 55% increase from the baseline period (average of 2011, 2012, 2013) to 2019, but a 5% decrease compared to 2018. Several reasons for these emergency authorisations can be given: emerging plant health issues, alternative techniques to prevent pest outbreaks not yet available or not applied, delays in authorisations of new active substances, failure to implement the SUD directive, etc.

Figure 3-57: Evolution of the EU harmonized risk indicator 1 from 2011 to 2019 (Source: European Commission, 2021a)

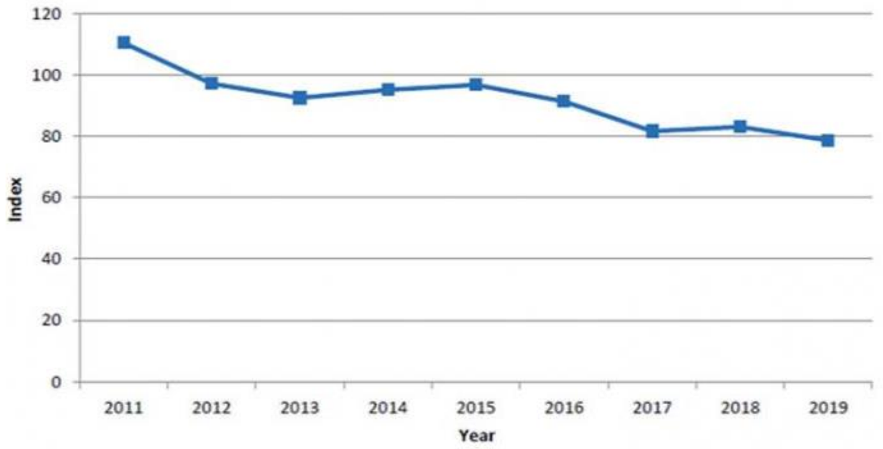
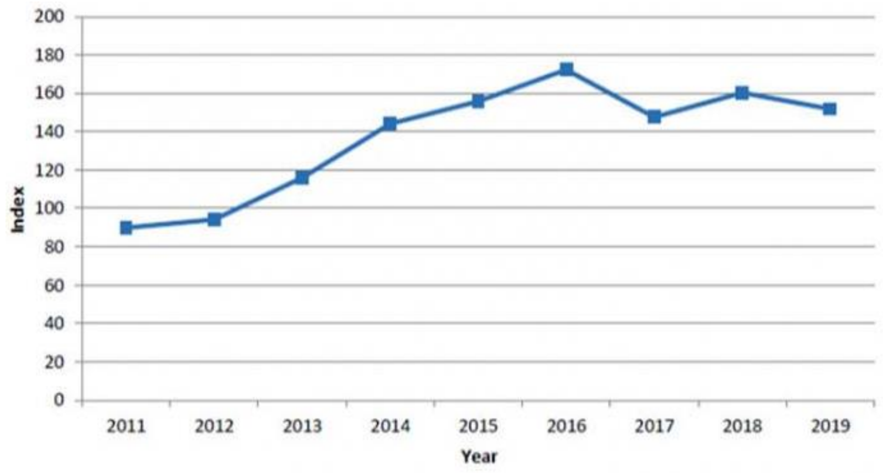


Figure 3-58: Evolution of the EU harmonized risk indicator 2 from 2011 to 2019 (Source: European Commission, 2021a)



According to some authors, these indicators can be improved in their set up, to take into account new data sources, country specific priorities, and better measure the evolution of the risks associated with the use of pesticides (European Commission, 2020a; Möhring *et al.*, 2020b). According to the report from the European Court of Auditors, the usefulness of these harmonized risk indicators is limited; they do not include information about how, where and when the pesticides are used, the weighting factors used for calculating the risks can be questioned (ECA, 2020).

The European Commission has launched since 2020 a revision process of the SUD, to address the key problems of its limited effectiveness in reducing pesticide use and risks to human health and the environment across Member States. On June 22nd 2022, the European Commission made a proposal for a new Regulation on the Sustainable Use of Plant Protection Products, in line with Farm to Fork and Biodiversity strategies (European Commission, 2022a). In this proposal, the European Commission plans to set **legally binding targets at EU level to reduce by 50% the use and the risk of chemical pesticides as well as the use of the more hazardous pesticides by 2030.** Also, these new measures will ensure that all farmers and other professional pesticide users practice Integrated Pest Management (IPM), and use chemical pesticides as a last resort. Finally, pesticides will be banned in sensitive areas such as urban green areas, protected areas in accordance with Natura 2000, and any ecologically sensitive area to be preserved for threatened pollinators. The proposal still needs to be approved by Member States in the Council, and by the European Parliament[41].

In the future, if this proposal is adopted, and fully implemented across Member States, it could be a significant step in the reduction of the use and risks of chemical pesticides. It could then be followed by a new version of the Regulation - version 2 – setting further reduction objectives.

Hypothesis of change: Iterative reduction objectives set in European regulation, with Member States empowered to set relevant plans for achieving the EU targets and to report annually on pesticides uses.

A partitioned set of policies and measures to reduce use and risks of pesticides, not articulated with each other and with other policies

As shown above, policies and measures targeting directly or indirectly the reduction of use and risks of chemical pesticides have developed and multiplied over the past years. However, these initiatives have been created independently of other policies affecting farmers and their activities. Therefore, the incentive signals sent out by public policies targeting reductions in pesticide use are not the only policies at play, nor are they necessarily the ones to which a farmer gives the highest priority.

For example, the first pillar of the Common Agricultural Policy and its conditionality provisions takes little account of the issue of pesticide use (Lamichhane *et al.*, 2019) (see also paragraph 3.3.3 analysing the CAP).

Another example is the EU biofuels policy which produced various Directives aiming at promoting the development of energy from renewable sources. It created demand for food crops for the production of biofuels in Europe. Notably, due to the increased demand for biodiesel fuel, the area of cultivated oilseed rape grew significantly across Europe between 2003 and 2010, with a simultaneous rise in insect pest populations and therefore the need for the use of synthetic insecticides (Ortega-Ramos *et al.*, 2022).

Many other examples can be found, illustrating the issues arising from policies – especially environmental and agri-food policies – being designed independently of each other (Jacquet *et al.*, 2022; Galli *et al.*, 2020; Möhring *et al.*, 2020b).

To address this, in the future, several authors and organizations have been calling for the implementation of a Common and holistic Food systems Policy in Europe. This would change the way policies are designed towards: coherence around common objectives, avoidance of trade-offs, involvement of all actors of the food chain, etc. This holistic approach is core to the Green Deal, adopted in 2019 by the European Union, as a global EU deal for achieving a sustainable and carbon-neutral economy by 2050 (European Commission, 2019). The Green Deal goes well beyond pesticides

[41] https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides_en, consulted in August 2022

issues, by considering all environmental, health, food, agricultural dimensions and proposing a new sustainable growth for the EU. To that end, the Green Deal defines a roadmap under the form of ten key actions, detailed within different strategies (see Figure 3-59).

Figure 3-59: Ten strategies of the Green Deal (European Commission, 2019) – strategies where pesticides issues are addressed are circled in black

Within this framework, the "Farm to Fork Strategy" (F2FS), and the Biodiversity strategy for 2030 are setting goals regarding pesticides reduction, in particular (Table 3-23):

- Reduce by 50% the use and risk of chemical pesticides by 2030
- Reduce by 50% the use of more hazardous pesticides by 2030
- Achieve 25% of total farmland under organic farming by 2030.

The Farm to Fork strategy sets two new indicators regarding pesticides use and risks. In comparison with previous harmonized risk indicators followed as part of the SUD, the second indicator has changed (no more monitoring of exceptional authorisations given by Member States), and the years of reference have changed (2015-2017 instead of 2011-2013, to reflect the first years where the Farm to Fork strategy was discussed).

Table 3-23: Main objectives of the Farm to Fork and Biodiversity 2030 strategies (in green are objectives related to pesticides use)

Farm to Fork	Biodiversity 2030
Reduce by 50% the use and risk of chemical pesticides by 2030 **Reduce by 50%** the use of more hazardous pesticides by 2030	Legally protect a minimum of 30% of the EU land area and 30% of the EU sea areas, and integrate ecological corridors as part of a true "Trans-European Nature Network"
Reduce nutrient losses by at least 50%, while ensuring no deterioration on soil fertility **Reduce fertilizer use by at least 20%** by 2030	Strictly protect at least one-third of the EU's protected areas, including all remaining EU primary and old growth forests
Reduce by 50% the sales of antimicrobials for farmed animals and in aquaculture by 2030	Effectively manage all protected areas, by defining clear conservation objectives and measures, and monitoring them appropriately
Achieve **25% of total farmland under organic farming by 2030**	Define legally binding EU nature restoration targets to be proposed in 2021, subject to an impact assessment: by 2030, significant areas of degraded and rich-carbon ecosystems should be restored; habitats and species should show no deterioration in conservation trends and status; and at least 30% should reach favorable conservation status or at least show a positive trend
Propose mandatory harmonised front-of-pack nutrition labelling and develop a **sustainable food labelling framework** that covers the nutritional, climate, environmental and social aspects of food products	Reverse the decline in pollinators
Propose legally binding **targets** to reduce food waste across the EU by 2023	Reduce the use and risk of chemical pesticides by 50% in 2030, as well as the use of more hazardous pesticides by 50% in 2030
	Dedicate at least 10% of agricultural area to high-diversity landscape features
	Devote at least 25% of agricultural land under organic farming management by 2030, and significantly increase the uptake of agro-ecological practices
	Diminish the loss of nutrients from fertilizers by 50% in 2030, resulting in the reduction of the overall use of fertilizers by at least 20%
	No chemical pesticides are used in sensitive areas such as EU urban green areas

Sources: European Commission, 2020c; European Commission, 2020d and Guyomard, Bureau *et al.*, 2020

According to the latest release of the European Commission (based on 2020 pesticides data provided by Member States), the use and risk of chemical pesticides show a decrease of 14% from the baseline period of 2015-2017, and a 1% decline compared to 2019 (Figure 3-60). The use of more hazardous pesticides shows a decrease of 26% from the baseline period of 2015-2017, and a 9% decline compared to 2019 (Figure 3-61). The results show a continued reduction in the use and risk of chemical pesticides. The Commission concludes that: "*while progress is steady and continuous, overall, the results show that Member States need to do more to reduce the use and risk of chemical pesticides as foreseen under the Farm to Fork strategy*".

Figure 3-60: Evolution of Farm to Fork pesticide indicator "use and risk of chemical pesticides"

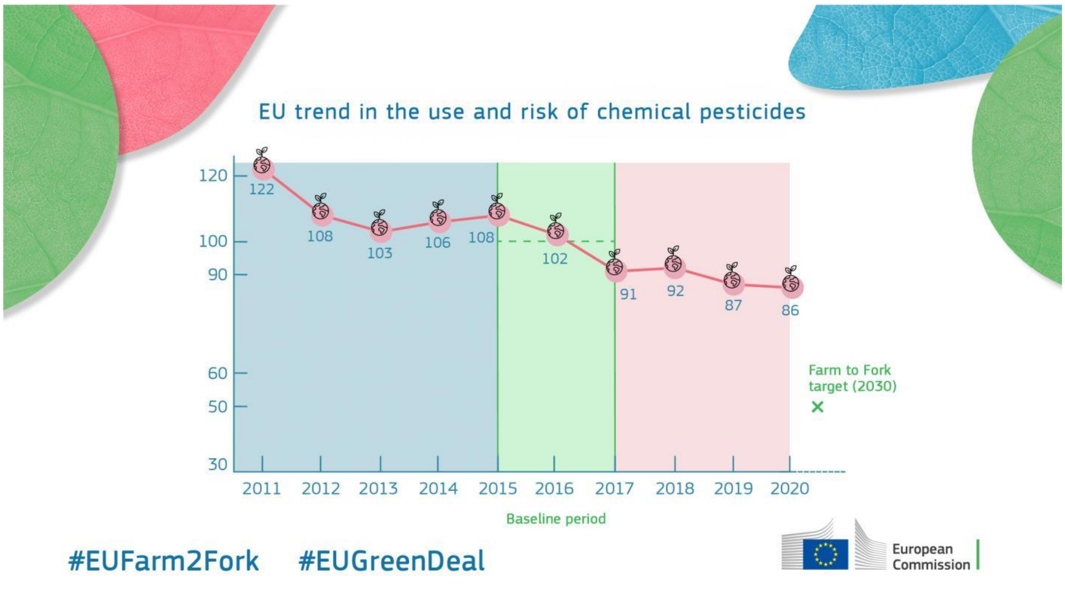
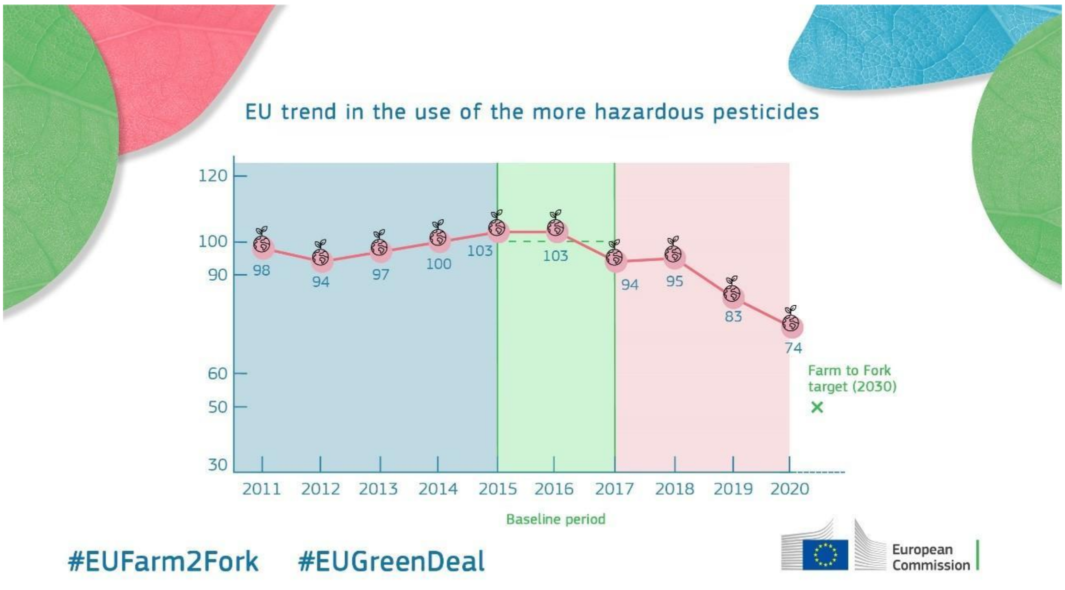


Figure 3-61: Evolution of Farm to Fork pesticide indicator "use of the more hazardous pesticides"



Source: European Commission, 2022, available at https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/farm-fork-targets-progress/eu-trends_en, consulted in June 2022

As part of the Farm to Fork strategy, it is foreseen that the **European Commission will publish a legislative proposal for a framework for a sustainable food system by the end of 2023**. Indeed, the European Commission recognizes that the EU food system is characterised by different approaches and analyses at Union, national and sectoral levels vis-à-vis sustainability aspects, lacking a common approach and resulting in divergences, inconsistencies and even some gaps. A harmonized transformational change is needed at EU level to address the comprehensive challenges the food system is facing and achieve the climate and environmental objectives of the European Green Deal. The European Commission launched a public consultation on this initiative, with four policy options being considered including a comprehensive framework legislation on the sustainability of the Union food system (European Commission, 2021d).

The European Commission is also currently consulting on the idea of a soil Health law, a potential proposal for a European Directive to specify the conditions for a healthy soil, determine options for monitoring soil and, lay out rules conducive to sustainable soil use and restoration[42].

In the future, if the framework for a sustainable food system is adopted, as well as other legislative initiatives, this could lead to an **integrated food policy**, covering all food system aspects. Integrated food policy can be defined as "*the joining up of goals and policies related to food systems – horizontally across governments, vertically between government levels, or between inside and outside government actors – to better align these efforts, reduce incoherence between them, and tackle food systems challenges more effectively*" (Parsons, 2019). Parsons further describes the various dimensions of a food policy integration: the areas (agriculture, production, health, etc.), the spatial scale (national, regional, territorial, global), the goals (sustainability, nutrition, etc.), and the actors of the food value chain (farmers, food manufacturers, etc.).

In 2019, the Food International panel of experts on sustainable food systems (IPES-Food) issued a report making the case for a Common Food Policy for the European Union (IPES-Food, 2019), reforming European food systems under one common food policy covering the whole food system (food production, processing, distribution and consumption). The report describes the content of this Food Policy, articulated over five objectives: ensuring access to land, water and healthy soils, rebuilding climate resilient, healthy agro-ecosystems, promoting sufficient, healthy and sustainable diets for all, building fairer, shorter and cleaner supply chains, and putting trade in the service of sustainable development.

In the foresight exercise "*An agroecological Europe in 2050: multifunctional agriculture for healthy eating Findings from the Ten Years For Agroecology (TYFA) modelling exercise*", the authors identify the **need for a common food policy addressing five public policy sectors together to achieve the transition: trade and intra-EU competition, agricultural policy, food policy, and environmental and health policy (**Roux and Aubert, 2018).

Möhring *et al.*, in reviewing pathways for advancing pesticides policies, call for their integration into a **holistic food policy framework** that would "*overcome conflicting goals between food production, environmental protection, biodiversity and human health*" (Möhring *et al.*, 2020b).

Hypothesis of change: A holistic food system policy, where pesticides reduction measures are embedded in a single Food Systems Policy framework with clear long-term policy goals for all actors in the value chain.

Development of territorial policies addressing the reduction of risks linked to the exposure to pesticides

Territorial initiatives to address pesticides have developed over the past decade. These are triggered by increased societal concerns about the impacts of pesticides used in agricultural production and in urban amenities areas. The negative effects of pesticides are increasingly present in the public debate, and gather more and more interest from citizens, as demonstrated for example by petitions to ban pesticides. One of the latest example is the European Citizen Initiative "save bees and farmers", signed by 1.2 million citizens in 2022, and that was officially validated in October 2022[43].).

Since the early 2000s, local level actions by residents have successfully influenced the establishment of municipal, territorial, or regional policies regarding pesticide uses that go beyond the national regulatory framework (Zollet and Maharjan, 2021).

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[42] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13350-Soil-health-protecting-sustainably-managing-and-restoring-EU-soils_en, last consulted in November 2022

[43] https://europa.eu/citizens-initiative/initiatives/details/2019/000016_en, last consulted in May 2023

These initiatives can take very diverse forms in terms of topics, governance, objectives, means, etc. They are generally implemented faster than policies at national level, and involve civil society in reforming local agri-food policies.

In some cases, local authorities do not have the legal right to regulate pesticides. In France, a group of French mayors has taken action to ban pesticides on their territory. Administrative courts have contested these municipal legislative initiatives, considering that pesticides are the remit of the agricultural ministry. However, in its most recent ruling in July 2021, the French "Conseil d'Etat" instructed the government to revise the current laws applicable to pesticides, in order to better protect inhabitants (revision of the minimum distance for pesticide spraying, and of the information process) (Conseil d'Etat, 2021).

Local or territorial actions on pesticides are very often anchored in broader policies. An important lever to take territorial action on pesticides is water quality preservation (see example of the Mangfall valley in the region of Munich described in paragraph 3.3.2.1). Indeed, the set-up of the Water Framework Directive allows for management at the level of river watershed, and measures to be taken locally to protect watercourses and drinking water catchment areas (Grimonprez and Bouchema, 2021).

Another lever to take actions on pesticides is the mobilization through the development of initiatives within territorial agri-food systems (Lamine *et al.*, 2019). In these initiatives, as studied by Lamine *et al.* (2019), there is a strong articulation of a diversity of initiatives, taken by various actors (civil society, private actors such as farmers, food processors, etc.), supported by territorial public policies, and collective action in general.

Several examples of initiatives illustrate the strategies used to mobilize the local population and policy makers around pesticides issues. These strategies do not always rely on public policies but are rather collective initiatives taken by groups of local actors.

Belluno province (Italy) – described in Zollet and Maharjan, 2021

In this province in the North East of Italy, an anti-pesticide mobilisation started back in 2008 as a consequence of the development of intensive apple orchard and vineyards in the area. This development generated concern among residents about the negative health and environmental consequences of pesticide use and groundwater pollution. The first mobilisation were organised by municipal resident groups, together with organic farmers whose land bordered the new apple orchard. Then, a protest movement – Terra Bellunese – was created in 2014, for advocating against intensive farming and increased use of pesticides. The movement proposed a revision of the law to ban hazardous pesticides in the municipalities of the province, on the basis that in the Italian legislation mayors have jurisdiction over public health matters within the municipal territory and can intervene according to the precautionary principle in case of possible threats to public health. This proposal for revising the law was accompanied by a public campaign to educate residents about the impacts of pesticides, and a petition to give more weight and legitimate the action. Fourteen municipalities between 2016 and 2018 adopted the law proposal, covering half of the population.

Key points to notice from this example are:

- The possibility for mayors in Italy to intervene and regulate on public health matters;
- The mobilisation of the civil society to run the advocacy campaign;
- The importance of citizens's strong attachment to their territory and pride, leading the public opinion to reject the development of new practices not in line with the territory;
- Food democracy.

VitiREV program in Nouvelle Aquitaine (France)[44]

In Nouvelle-Aquitaine the wine production is very important, representing 29% of French total vine surfaces, and a very important economic driver for the region, as well as for its "patrimoine". In this region, vineyards are located close to cities and to resident's houses. In recent years, residents' concerns increased over the risks of pesticide use in vineyards, triggering a collective mobilization from regional actors. The vitiREV program was created in 2018 by the region Nouvelle Aquitaine, to support the transition to agroecology for the wine sector. It gathers several actors involved in this topic: winemakers, researchers, extension services, authorities, etc. especially through a network of LITs (Laboratoires d'innovation territorial, "living labs"), places for experimentation and innovation in real conditions, and at a local level. Specific targets are set within the program such as reaching by 2030, 85% of winemakers certified on environmental practices (organic, HVE, or ISO 14001), less than 1% use of carcinogenic, mutagenic and repro-toxic (CMR) plant protection products and 80% use of biocontrol products, etc.

Munich water quality preservation through conversion to organic farming (described in Barataud et al., 2014)

In 1992, the city of Munich created a large-scale program of organic farming conversion for farmers located in the Mangfall Valley, next to the water catchment areas. This program was renewed and extended until 2026 given its success. Farmers are financially supported for converting into organic production and maintaining it, through European subsidies and an additional fund from the federal state of Bavaria. This program was highly successful, resulting in a very large increase in the number of farms converted to organic farming: from 23 in 1993 to 150 in 2010. The Mangfall area thus became the largest single farming area under organic agriculture in Germany.

Reasons for the success of this territorial policy include:

- The Munich municipality chose to heavily support conversion to organic farming leveraging a favourable context in the area with existing organic farming already, supply chain available to sell farmers' organic products;
- Highly attractive forms of remuneration;
- Policy based on water quality preservation, to provide access to good quality water to residents.

Eco-regions (described in Zanasi et al., 2020)

The International Network of Eco-Regions (IN.N.E.R) defines an Eco-Region as "*an area where farmers, citizens, touristic operators, associations, and public actors established an alliance for the sustainable management of local resources based on the principles and model of organic farming in order to boost the economic and socio-cultural development of their territory*". Eco-regions are fairly developed in Italy (in 2020, more than 40 Eco-Regions are operating in Italy) and in other Mediterranean countries. They focus on developing and valorising the local organic production within the territory, its typical products (terroir) and natural resources. Yet, they remain voluntary approaches.

Zanasi *et al.* (2020) describe the supply-chain in the bio-district "Cilento", the first bio-district launched in Italy in 2009. It now gathers 30 municipalities, 400 companies, 20 restaurants and 10 tourist establishments that sell locally produced organic food[45].

Projets Alimentaires Territoriaux (PAT) in France

Since the 2000's, there has been an important development of local food policies in the French territory. These address the topic of food in various dimensions, such as food equity, environmental impact, urban agriculture, local food procurement, food consumption, etc. In these programs, actors

[44] https://agriculture.gouv.fr/vitirev-un-projet-regional-pour-reduire-les-pesticides-en-viticulture, last consulted in May 2023

[45] https://www.ideassonline.org/innovations/brochureView.php?id=91, last consulted in May 2023

develop various policies promoting local economic development, food safety, public health, social integration, etc. They aim at transforming food and also agriculture within the territory, although their effects on agriculture are limited (Pahun, 2020). Among these initiatives, the "Projets Alimentaires Territoriaux" (Territorial Food Projects, PAT) gather groups of individuals, local authorities and organizations who share the same diagnosis about local food, and define together an action plan. These PAT are defined in French national law since 2014. In 2022, the French ministry of Agriculture registered 370 PAT[46]. The impacts of these local food policies, including the PAT, on the reduction of use of pesticides within the territories, remain to be studied.

Territorial coordination of actors can enable the development of innovative solutions for pesticide use reductions, and facilitate collective action (Bazoche *et al.*, 2022). Development of management plans at local level have proven to be better targeted towards local specificities and issues (Galli *et al.*, 2020). These initiatives are considered by several authors as highly promising for reducing the environmental impacts, but also to reclaim value for small-scale farmers and food businesses, and to reconnect food system actors and ultimately consumers trust in food systems (IPES-food, 2019).

In the future, pesticide use reduction policies could be managed at the territorial level, by local stakeholders working together to define the most appropriate plans according to local conditions and stakes. This could allow more flexibility in the actions implemented to take into account local specificities, more coordination within actors, more transparency and dialogue with residents. This would require in most instances decentralization of states to empower local authorities to develop local policies related to pesticides

Hypothesis of change: Territorial / local and cross-sectoral policies managing sustainable food system policies including pesticides policies (but also covering land use, landscape design, water & soil protection, production, value chain and market), led by local authorities and local actors.

3.3.2.7. Summary of the hypotheses of changes for the policies to reduce use and risks of chemical pesticides

The Table 3-24 below summarises the three main hypotheses identified for the evolution of the legislative framework for reducing the use and risks of chemical pesticides in Europe.

Table 3-24: Summary of hypotheses of changes for policies to reduce use and risks of chemical pesticides

Hypothesis 1	Hypothesis 2	Hypothesis 3
Territorial and cross-sectoral policies (food policy councils) that organize the land use, landscape, water & soil protection, production, value chain and market (inc trade)	EU regulation set progressive and iterative reduction targets (SUR version 1, SUR version 2, etc.)	Holistic food systems policy covering water, soil, agriculture practices, food, nutrition and health

[46] https://agriculture.gouv.fr/plus-de-370-projets-alimentaires-territoriaux-reconnus-par-le-ministere, last consulted in May 2023

3.3.3. Agricultural policy and economic instruments to support the adoption of alternatives to chemical pesticides

Economical, agricultural policies and their instruments (taxes, subsidies directly or indirectly influencing pesticides use, etc.) can influence or support the adoption of new practices, by making them more financially attractive than the current solutions.

3.3.3.1. A progressive "greening" of the Common Agricultural Policy (CAP)

The European Union's Common Agricultural Policy (CAP) was established back in 1962 to ensure food security and to create a 'European Agricultural Welfare' with a high level of protection of farmers and consumers in a market economy (Galli *et al.*, 2020). Its overarching objectives have remained unchanged since its launch. Initially aimed at increasing the agricultural output through market price support, the CAP developed towards providing direct income support for famers since the 1990s. It has then progressively evolved in the past decades, to introduce economical instruments that address the environmental impacts of agricultural practices (Heyl *et al.*, 2020).

The CAP has progressively introduced in its successive reforms measures aimed at reducing the environmental and health impacts of agriculture (Figure 3-62), although the assessments made at EU and national levels converge on the fact that their real effects remain disappointing (Tibi *et al.*, 2022).

In 1992, the European Commission introduced the agri-environmental measures (then renamed agri-environmental-climate measures - AECM) as part of the establishment of a pillar 2 focusing on rural development. Agri-environmental schemes are the only schemes in the rural development policy that are mandatory for Member States to apply, but with individual measures being proposed by Member States. They are multi-annual (usually for five years), must go beyond regulatory requirements, and are voluntary for farmers, meaning that farmers receive financial support if they participate to these programs. In most cases, the financial support received covers the additional costs associated with the adoption of the new practices (Bazoche *et al.*, 2022). For example, AECMs support organic conversion and maintenance and water quality preservation.

Figure 3-62: Historical development of the CAP and its environmental measures

1990	1999	2003	2013	post-2020
1992 REFORM (Mac Sharry) **Direct income support** for farmers Agro-environmental measures	**Agenda 2000** Deepening the reform process Creation of Pillar 2 - Rural development	**REFORM 2003** Decoupling Cross compliance Environmental enlargement	**REFORM 2013** Green direct payments: -ecological focus area -crop diversification -maintenance of permanent grassland	**REFORM 2023** Enhanced conditionality Eco-schemes

(Sources: Matthews *et al.*, 2017; CAP'eye website: https://capeye.fr/pac-environnement/; European Council website: https://www.consilium.europa.eu/en/policies/cap-introduction/timeline-history/)

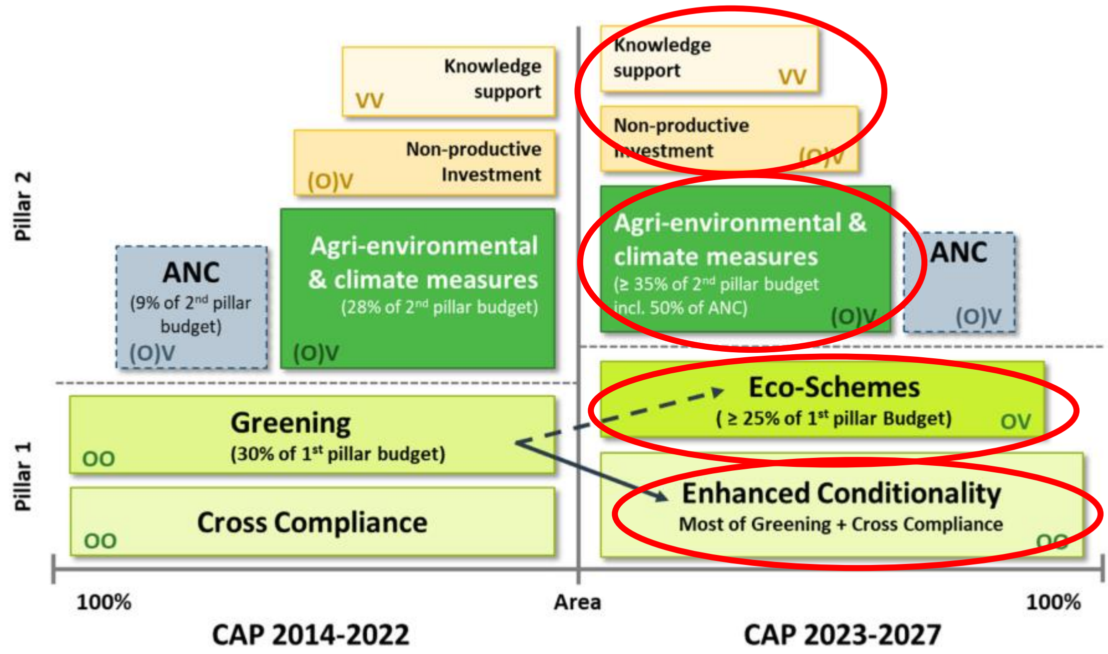
Since 2003, the direct payments within pillar 1 are subject to compliance with European laws on environment, animal health and welfare, in the forms of Statutory Management Requirements (SMR) and of standards for Good Agricultural and Environmental Conditions (GAEC). The SMR include compliance with the Pesticide European Regulation 1107/2009 and part of its article 55.

In the 2014-2020 CAP reform, so-called "greening" measures were introduced as part of pillar 1; these include diversification of crops, maintenance of permanent grassland, securing of ecological focus areas. (Heyl *et al.*, 2020; Guyomard, Bureau *et al.*, 2020).

In December 2021, after four years of discussions, the reform of the common agricultural policy (CAP) was formally adopted. The new legislation, which came into force in January 2023, paves the way for a fairer, greener and more performance-based CAP. According to the European Commission, it aims at being a key tool in reaching the ambitions of the Farm to Fork and biodiversity strategies[47].

The 2023-2027 CAP proposes a new ‘’Green Architecture’’ around three environmental instruments: ‘’**enhanced conditionality’’**; **AECM** in Pillar 2; and new ‘’**Eco-schemes**’’ in Pillar 1 (Figure 3-63). The new CAP also reinforces the budget allocated to this "green architecture": Member States are required to invest at least 20% of Pillar 1 payments in eco-schemes in 2023–2024 and at least 25% after 2025. Also, the minimum share of Pillar 2 payments for environmental instruments increases from 30% currently to 35% after 2023 (Pe’er *et al.*, 2022).

Figure 3-63: Evolution of environmental measures in the CAP between 2014-2022 and 2023-2027 (Source: from Pe’er *et al.*, 2022)



ANC = Areas facing natural or other constraints. OO = implementation obligatory for Member States, obligatory for farmers; OV = implementation obligatory for Member States, voluntary for farmers; VV: implementation voluntary for Member States, voluntary for farmers; (O)V = implementation Member states must ascertain a minimum implementation over several interventions, voluntary for farmers. Boxes circled in red can be used to support pesticide reduction initiatives.

[47] https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/new-cap-2023-27_en, consulted in August 2022

"**Enhanced conditionality**" gathers cross compliance and most of the previous greening measures. The cross-compliance rules include requirement related to pesticides. CAP payments are conditioned to compliance with EU laws: part of article 55 of the EU Regulation on plant protection products[48] and, in future, part of the sustainable use of pesticides directive[49].

"**Eco-schemes**" provide an opportunity for Member States to support voluntary practices by farmers that are more ambitious than the legal baseline. Eco-schemes are mandatory for Member States to develop and propose, but voluntary for farmers to adopt. At least 25% of the budget for direct payments is allocated to eco-schemes, providing stronger incentives for climate-and environment-friendly farming practices and approaches (such as organic farming, agro-ecology, carbon farming, etc.). Member States set eco-schemes in their CAP strategic plans, and the European Commission assesses and approves them as key tools for the CAP to deliver on the Green Deal targets. The European Commission has published a list of examples of measures that could be supported by "eco-schemes"[50], some of which related to pesticide use reduction (ie. Precision crop farming to reduce inputs -fertilisers, water, plant protection products-, buffer strips without pesticides, Conversion and maintenance of organic farming, etc.) *(*European Commission, 2021b*).* It is up to Member States to decide and prioritize the measures they want to promote through the eco-schemes in their national strategic plans.

3.3.3.2. Trends and hypotheses of changes for the CAP in relation to pesticides

Despite the growing integration of environmental aspects into the various CAP reforms and their instruments, several authors have questioned their environmental outcomes, including their effects on pesticide use reduction. They call for the Common Agricultural Policy to be re-designed, and other policies implemented (Wezel *et al.*, 2018 ; Guyomard, Bureau *et al.*, 2020 ; Heyl *et al.*, 2020 ; Bazoche *et al.*, 2022 ; Pe'er *et al.*, 2022; Tibi *et al.*, 2022).

Cross compliance and greening under pillar 1 of the CAP are not restrictive enough to have an impact on pesticide use beyond compliance with regulations

Within Pillar 1, **cross-compliance so far covers minimum regulatory requirements**. The 'greening' measures go beyond these regulatory requirements by including diversification of crops, maintenance of permanent grassland, securing of ecological focus areas. However, they have been considered environmentally weak, because many farmers are exempted from the measure, and the requirements of ecological focus areas allow for a large range of areas to be considered (Heyl *et al.*, 2020).

In the future, the enhanced conditionality in pillar 1 could be even re-inforced with regards to cross-compliance with future pesticides policies (such as the revised Sustainable Use of pesticides Regulation – see paragraph 3.3.2.6). CAP pillar 1 payments of future CAP reforms after 2027 could be conditioned to compliance with the revision of the Sustainable Use Directive, the adoption of IPM and any other pesticide policies, making a direct link between direct payments and changes in farming practices.

Hypothesis of change: The conditionality of CAP payments is re-inforced to include compliance with reduction of chemical pesticide use.

[48] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009R1107

[49] https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides_en ; https://ec.europa.eu/info/food-farming-fisheries/sustainability/environmental-sustainability/low-input-farming/pesticides_en, consulted on March 31st, 2022.

[50] https://agriculture.ec.europa.eu/news/commission-publishes-list-potential-eco-schemes-2021-01-14_en, consulted in July 2022.

Agri-environmental-climate measures are effective if well designed, and could be further developed

Within Pillar 2, agri-environmental-climate measures (AECM) have shown positive results if well designed. For example, during the 2007–2014 CAP programming period, agri-environmental schemes (AESs) have been used in France to fulfil the objectives of the European Union water framework directive. Therefore, AESs have been implemented to reduce contamination by pesticides in catchment areas where water quality improvement has been identified as a priority. Farmers participating in these AESs commit to reduce their use of pesticides for five years in exchange for a predefined annual payment. Kuhfuss and Subervie (2018) showed that these AESs can be effective in reducing the use of herbicides in vineyards in South of France.

Also, AECM have shown efficient in supporting farmers' conversion and maintenance to organic farming (Jaime *et al.*, 2016).

Kleijn *et al.* (2006) analysed agri-environmental schemes implemented in five different European countries and their impact on biodiversity. They showed that in all countries these schemes had marginal to moderate positive effects on biodiversity, measured by species density (plants, bees, orthoptera, spiders and birds). In three out of five countries, the implemented schemes significantly reduced the fertilizers and pesticides applications (measured as frequency of pesticide applications per year) compared to conventionally managed fields (Kleijn *et al.*, 2006).

Agri-environmental schemes can have positive results but also have some limitations by design. First, they are voluntary schemes, and in most cases are implemented by individuals and even on individual fields. This can result in limited implementation in number and also in a scattered spatial distribution, all of which may reduce their effectiveness (Kleijn *et al.*, 2006). Second, they are multi-annual but still limited in time (5 years in general, sometimes more), whereas more time may be needed for effective implementation of environmental practices such as restoration of biodiversity (Kleijn *et al.*, 2006). They also have been challenged for their costs in comparison with their environmental effectiveness (Place *et al.*, 2022; Bazoche *et al.*, 2022). In addition, they represent a limited incentive since they are supposed to compensate for the extra costs linked to the adoption of environmental-friendly practices. Between 2014-2020, they represented 2.4% of the total CAP budget (pillar 1 and 2) (Bazoche *et al.*, 2022).

Analysing French agri-environmental schemes implemented as part of the CAP between 2007 and 2013, Thoyer *et al.* (2017) have identified ways to improve their impact on farmers' adoption of practices less intensive in pesticides. These are, for example, the inclusion of a collective component in the payment (collective bonus), the use of auctions, and of nudging techniques.

The CAP reform that came into force in 2023 contains some opportunities to support environmental initiatives, including those potentially targeting pesticide use reduction and/or suppression. The European Commission reviewed the national strategic plans proposed by the Member States, and provided some observations in June 2022 (European Commission, 2022e). The Commission noted that eco-schemes proposed vary significantly in their level of environmental ambition – whether at the level of individual practices supported, or at the level of how options work together in multi-option schemes. Within rural development support, agri-environmental climate commitments proposed by Member States vary hugely: some proposals are designed as broad schemes covering several environmental needs, other are very targeted and cover smaller areas, some propose support to 'green' investments such as biogas, or restoring habitats and landscapes, some include support for exchanges and co-operation. Eleven Member States address the issue of Integrated Pest Management and/or Pesticide management in their proposed eco-schemes. Overall, the Commission calculated that the intended uptake of funded CAP interventions related to sustainable and reduced use of pesticides covers from 1.3% to 56% of the total utilised agricultural area of each Member State. In the case of support to organic farming, the vast majority of plans forecast to at least increase by 25% (in proportional terms) the area receiving CAP support for organic farming by 2027 in comparison with the level in 2018 (European Commission, 2022c).

In the scientific literature, authors have identified some critical areas for ensuring the success of the future CAP in terms of environmental impact, which can be interesting insights to identify hypothesis of future change. First, most of the environmental measures remain voluntary, so it is rather difficult to anticipate the level of interest and therefore adoption by farmers. Different types of instruments could be further implemented in order to encourage the adoption of alternative practices to chemical pesticides. These are described by Bazoche *et al.*, and consist in: more flexible measures (in time of commitment, in the possibility to disengage), encouraging coordination between farmers (bonus for collective actions), promoting peers effects among farmers with similar preferences, and setting up environmental auctions where farmers propose a price for delivering a given environmental service (Bazoche *et al.*, 2022).

Also, current agri-environmental measures mostly cover the additional costs linked to the adoption of a new practice that aims at improving environmental conditions. In future, they could evolve towards **payments of ecosystem services** (PES). PES are tools that financially reward farmers (and other actors) for actions contributing to restoring or maintaining ecosystems with benefits for the society (Duval *et al.*, 2019)[51]. PES are an application of the "Provider-Gets" principle (PGP), in opposition to the "Polluter Pays" principle (PPP), in the sense that they offer additional remuneration to farmers, based on its provision of environmental services[52] (Guyomard, Bureau *et al.*, 2020). Studies show that schemes that are **result-oriented**, such as **payments for a valued ecosystem service**, attain better environmental outcomes than schemes that are action-oriented (e.g. payment for adoption of a practice). Several authors support this evolution towards rewarding the achievements of environmental outcomes (Buckwell *et al.*, 2020), in more particularly the public goods produced by pesticide-free agriculture (e.g., increased biodiversity) (Jacquet *et al.*, 2022).

Wezel *et al.* report on the outcomes of a participatory exercise carried out with 310 european stakeholders to identify the major challenges for the development of sustainable agriculture and food systems, and more specifically the amplification of agroecology in Europe. They highlight the need for policy changes, in particular a redesign of the Common Agricultural Policy (CAP), and other policies implemented including payment schemes for farmers providing ecosystem services (Wezel *et al.*, 2018).

In the IPES-Food report for a Common Food Policy for the European Union, authors also recommend that future CAP reforms focus on changing the rationale for CAP payments towards rewarding public goods. They propose a progressive increase on the baseline for conditionality of payments in terms of sustainability requirements, to ultimately achieve that "*all CAP income support payments should be phased out*", in order to "*refocus all CAP payments on public goods provision under a single pillar*" (IPES-Food, 2019).

These ecosystem services payments could be delivered within territories. This will encourage collective action and coordination of efforts. This will also fit with the spatial scale of ecosystems: ecological responses are governed by landscape and ecosystem properties, whereas current financial supports, subsidizing individual initiatives, limit the reach and success of measures (Pe'er *et al.*, 2022).

Hypothesis of change: Farmers and all actors in the territory receive payments for ecosystem services provided locally.

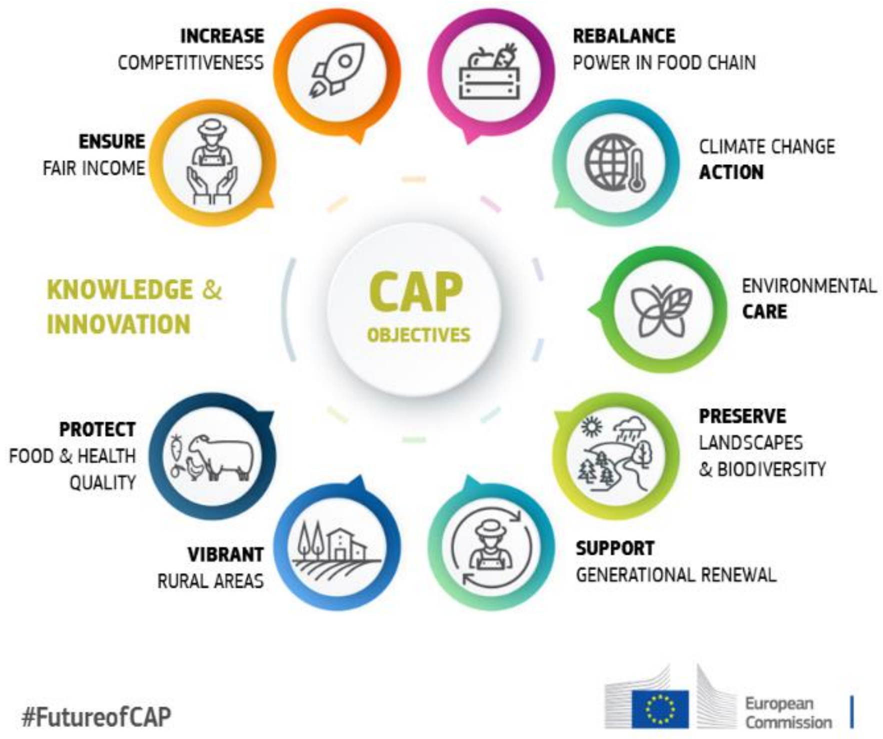
[51] IPBES definition: PES is a market-based instrument that is increasingly used to finance nature conservation. Payment of ecosystem services programs allow for the translation of the ecosystem services that ecosystems provide for free into financial incentives for their conservation, targeted at the local actors who own or manage the natural resources. https://ipbes.net/policy-support/tools-instruments/payment-ecosystem-services

[52] Eco-schemes and AECM can also be viewed as an application of the Provider Gets Principle (PGP) principle, but in these cases the application of the PGP is weak since subsidies can only compensate the extra costs (Guyomard, Bureau *et al.*, 2020).

The CAP and its articulation with other Agri and Food systems Policy

The Common Agricultural Policy 2023-2027 has nine objectives, among which to "*protect food and health quality*", "*environmental care*", "*preserve landscapes and biodiversity*" (Figure 3-64). These objectives require actions that go far beyond the scope of agriculture, for example at the food industry and food consumption levels. Yet, so far, the common agriculture policy has never included – or very poorly – nutrition and consumers' health components (Guyomard, Bureau *et al.*, 2020; Recanati *et al.*, 2019). Several academics and organizations have recently published reports calling for an evolution of the agricultural policy towards an integrated agricultural and food policy.

Figure 3-64: The nine objectives of the 2023-2027 CAP (Source: European Commission[53])



Recanati *et al.* (2019) reviewed 165 scientific publications analysing how the CAP is and how it could in future address challenges related to environment, nutrition and rural living altogether. They conclude on "*the importance of a revised approach to policy-making able to draw together social, environmental, food and agricultural policies to create 'whole-food system' impacts*". According to the review outcomes, policy integration should take into account all the food system actors, from the environment to the EU citizens. For example, a nutrition focus CAP could encourage more diverse, plant-based consumption patterns to support healthy diets, by subsidizing fruit and vegetables productions (Recanati *et al.*, 2019).

Similarly, Jacquet *et al.* (2022) argue that the Common Agricultural Policy does not address food issues and does not involve actors in the entire food chain. They recommend to increase knowledge on how to combine policies including food policies more effectively.

Galli *et al.* (2020) have discussed policy processes that contribute to sustainable food systems in Europe, by analysing the European food-related policies, their past evolution and gaps. They highlight some incoherence between various food-related policies, such as the 'fruit and milk in schools' scheme

[53] https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27/key-policy-objectives-cap-2023-27_en, last consulted in July 2023

that is subsidized by the CAP. They call for reviewing existing tools to identify incoherencies, gaps and potential synergies, in order to reorganize and introduce new and coherent policy tools in a food system perspective, involving new actors such as the food industry and municipalities.

Hypothesis of change: The Common Agricultural Policy is built in coherence with food and health policies.

3.3.3.3. Taxes on chemical pesticides and their impact on pesticides use reduction

Among economic instruments, pesticides taxes can be an interesting tool for policy makers to support pesticides use reduction. Several countries across Europe have implemented taxes on pesticides, with very different design, scope, rate, etc. Pesticide taxation is an economical instrument that reduces the profitability of using the taxed pesticides, and therefore, if well designed, should encourage the adoption of alternatives practices limiting pesticides use (Bazoche *et al.*, 2022).

Almost all European countries apply Value Added Taxes (VAT) on pesticides, though with very different rates: some countries apply reduced VAT rates for pesticides (i.e. Cyprus, Poland, Portugal, etc.), other regular VAT (i.e. 27% in Hungary). France used to have reduced VAT rates for pesticides, and, since 2011, implemented two categories of VAT on pesticides: reduced VAT for pesticides that are allowed in organic farming, and regular VAT (20%) for other pesticides (Böcker and Finger, 2016). Farmers pay these taxes when buying plant protection products.

In addition, registration fees are in place in some European countries, to cover for the administrative costs of pesticides evaluation dossiers. Petitioners (companies producing the pesticides) pay for these fees.

Finally, a number of countries have implemented specific pesticide taxes to encourage reduction in their use. Table 3-25 summarises the pesticides fiscal instruments in place in the main European countries that have implemented them.

The Danish tax is considered the highest pesticide tax ever implemented in the world (Pedersen *et al.*, 2020). The country implemented a pesticide fee back in 1972, completed with a pesticide tax in 1982 (only covering use by households in private gardens). These evolved at the end of the 90's to become a general *ad valorem* tax covering all types of pesticide use (including agricultural), and differentiated by pesticides categories: for insecticides the tax rate was 35%, and for herbicides, fungicides an growth regulators the tax rate was 25% (Pedersen, 2016). In 2013, because the scheme was considered unsuccessful in reducing treatment frequency and pesticide load, the tax scheme was changed again into a more differentiated one, where each single pesticide product receives a specific tax rate according to its load. The tax level is calculated on a combination of a pesticide use and a pesticide risk indicators (risk comprises three factors: environmental toxicity, environmental fate and behaviour load, human health load). The tax introduction was accompanied with compensation measures for farmers. Moreover, tax revenues were used to support organic farming, agricultural support and environmental purposes. In 2013, the revenues generated from the tax were ca 88.4 € million (Böcker and Finger, 2016). Bocker and Finger estimated on a selection of different pesticides, that on average the taxation is 5 to 10 times higher in Denmark vs France (Böcker and Finger, 2016).

The Danish tax was assessed on its impact on pesticide load reduction. From 2011 to 2017, the data indicate that a substantial reduction in load has been reached within the range of 12-27 percent (depending on baseline year).The ex-ante evaluations had estimated a 40 to 50 percent reduction prior to the introduction of the tax (Pedersen *et al.*, 2020).

Table 3-25: Summary of specific pesticides taxes in some countries aimed at reducing pesticides uses and risks (adapted from Böcker and Finger, 2016, with information from Sud, 2020; Lefebvre *et al.*, 2015; Pedersen, 2016; Bazoche *et al.*, 2022)

Country	Date created	Revision date(s)	Tax base (for current scheme)	Tax rate (for current scheme)	Point of taxation	Tax revenues	Use of revenues	Pesticide use reduction since implementation of the tax[54]
France	1999	2006 2019	Plant Protection Products 3 categories according to human and environmental risks	3 rates depending on risks: 0,9 €/kg active substance (AS); 2 €/kg AS; 9 €/kg AS. In 2017, tax represents on average 5-6% of the sale price of pesticides.	Farmers at the retail level	60 million euros in 2013	Water utility and sewage treatment Ecophyto plan	No significant reduction in pesticides use since 2006.
Denmark	1996	1998 2013	Each pesticide has a specific tax rate based on PLI (pesticide load indicator*) and amount of active substance. **based on human health, environmental fate and environmental toxicity.* Tax accompanied with measures to compensate farmers.	30 to up to 54% of the retail price	Manufacturers wholesalers and importers of pesticides	DDK 600 M in 2015 (ca. 80 million euros)	Agriculture fund to support the sector, green growth measures and administrative purposes.	The treatment frequency index stayed flat. Reduction of the pesticide load indicator by 40%.
Norway	1988	1999	Base rate and additional rate 7 categories of pesticides according to human and environmental health risks		Producer and importer	NOK 50 M in 2015 (ca. 5,8 million euros)		Sold quantities remained constant after 1999. Small to medium reduction in human and environmental health risks indicators
Sweden	1984	2015	Fixed amount on every kg of active substance	3,64 EUR per kg active substance (= 5-8% tax rate on retail price)	Manufacturers wholesalers and importers of pesticides	70 M SEK in 2015 (ca. 7,5 million euros)	States budget	Human health risk decreased and then stabilized at 20% to 40% of values from 1988. Environmental health risk levels between 50% and 80%.

[54] Since various policy instruments were introduced at the same time, it is difficult to assess the isolated impact of the pesticides taxes.

Evaluating taxes and comparing taxation schemes is very difficult, because taxes can have different goals (generating revenues, polluter pays principle, reduction in pesticide use, reduction in pesticide load, etc.) (Böcker and Finger, 2016). Also, pesticides taxes have often been implemented simultaneously with other measures, and therefore their impact cannot be isolated from the impact of other instruments. Several authors have evaluated the impact of taxes on pesticides (Sud, 2020; Böcker and Finger, 2016; Bazoche *et al.*, 2022; Lefebvre *et al.*, 2015), based on several criteria: their efficiency, their feasibility, their acceptability among stakeholders, their economic consequences for farmers, etc. These assessments provide interesting insights regarding their past evolutions and potential future trends.

Overall, these evaluations show that pesticides taxes are effective when applied proportionally to the pollution induced by the pesticides. However, they can be very difficult to implement because it requires to be able to measure the pollution induced by each substance applied. That's why the majority of pesticides taxes in place are calculated based on the quantity of substance applied. Actually, among different taxes designs, the literature shows that **taxes with differentiated rates according to the environmental risk of the pesticides, can be more economically efficient** than a flat tax applied on all pesticides (Sud, 2020). Differentiated pesticide taxes create an incentive for farmers to switch to less risky pesticides or to alternative plant protection practices, whereas non-differentiated taxes can lead to substitution towards more risky pesticides (Finger *et al.*, 2017). Several European countries have implemented differentiated taxation schemes (Denmark, France), some after having experienced non-differentiated taxes (Norway). In Denmark, in the current tax scheme, each plant protection product has its specific tax rate according to its risk (measured though the pesticide load indicator) and use (measured by the quantity of active substance).

Due to the lack of availability or knowledge about alternatives, and the common view that pesticides are risk-reducing inputs, **demand elasticity for pesticides seems to be fairly low, at least in the short term**, meaning that pesticides use is very limitedly impacted by pesticides price increase (Skevas *et al.*, 2013; Bazoche *et al.*, 2022). Therefore, high rates of taxes seem to be necessary to achieve reductions in use (Sud, 2020; Böcker and Finger, 2016). According to some economic models, achieving a 20% pesticide use reduction while keeping the same production process (cereals/oilseed crops) would require a price increase of at least 700%, if the tax is not differentiated according to pesticides risk for example. This suggests that pesticides taxes alone cannot be sufficient to reach ambitious pesticides reduction objectives (Ayouba and Vigeant, 2020). However, this low elasticity of demand may not be true in the long term, when farmers can adopt alternative crop protection practices and therefore reduce the risks associated with pesticides use (Finger *et al.*, 2017).

The need for a high level of pesticides tax rate in order to impact the pesticides use level raises the issue of **farmers' revenues and competitiveness of their products, if the tax revenues are not redistributed to them.** Therefore, they are poorly accepted in the agricultural sector and by policy makers, which can limit their use by countries and their rates (Bazoche *et al.*, 2022). Finger *et al.* (2017) propose that the revenues of the pesticides tax be re-distributed to the agricultural sector, in order to finance measures to reduce pesticides risks. These can be for example financial support to organic conversion or pesticide-free crop protection, financial support for equipment acquisition related to pesticide use (ibid.).

3.3.3.4. Combinations of instruments to support adoption of new practices

Countries developing pesticide policies usually implement various instruments. Several authors have looked at the impacts of these combinations of instruments in reducing the use and risks of pesticides. They have studied the various instrument mixes implemented across Europe since the 90's and mostly after 2009 (date of publication of the sustainable use Directive), and the experience gained from them, to identify combination of instruments and conditions for their effectiveness. The paragraphs below present the main combinations described in the literature.

On the other hand, some instruments seem to be less efficient and even can be counter-productive tools. For example, risk insurance can be an interesting tool to cover for crop risks linked to a change of practice, but it can also lead farmers to take more risks, and therefore to increase the use of pesticides (Möhring *et al.*, 2020a ; Grimonprez and Bouchema, 2021). Another example is the regulatory instrument to ban of substances. Financial support for adoption of alternative practices is useful to accompany the transition, if there is a clear perspective on the ban (Grimonprez and Bouchema, 2021).

Taxes on pesticides and subsidies on alternatives

In this policy instrument mix, the revenues of the pesticide tax are re- distributed to farmers, to support adoption of pesticide-free crop protection strategies (Finger *et al.*, 2017; Möhring *et al.*, 2020b). This, in addition to contributing to reducing pesticides uses and risks, can increase the political acceptability of pesticide taxes (Sud, 2020).

Covenants (private or public agreements between parties) and subsidies for transition

In this policy instrument mix, the agreement from farmers to adopt pesticide-free practices, or reduced use of pesticides is rewarded by subsidies, to compensate for the costs induced (Lee *et al.*, 2019). This is the principle behind Agri-Environmental and Climate Measures (AECM) in Pillar 2 of the CAP. These measures have shown to be effective in favouring the adoption of farming practices with less pesticides, even more when farmers are collectively encouraged and supported financially (Kuhfuss *et al.*, 2016).

Another example is the IP SUISSE pesticide-free wheat private production standard implemented in Switzerland in the 2018/2019 campaign [55]. It comes after a first program ("Extenso"), where participants were neither allowed to use insecticides, fungicides, nor growth regulators in a specific crop of the crop rotation (e.g., wheat production), which evolved into a "pesticide-free" production program, which restrict farmers from using conventional pesticides in one part of the crop rotation, e.g. wheat production (Möhring et Finger, 2022). This program is supported by the largest Swiss retailer Migros that plans on selling only bread made from "pesticide-free wheat" from 2023 on. The adoption of pesticide-free wheat production is supported financially by both public and private financial mechanisms. The Swiss government subsidises with additional direct payments farmers not using specific (or all) pesticides. Farmers are also remunerated with a market-based price premium (Finger, 2021). The IP-SUISSE logo is applied on food products made with the "pesticide-free wheat" program.

Certification and subsidies for transition

In this policy instrument mix, the adoption of a certification scheme related to reduced use of pesticides, or chemical pesticide-free practices, is supported financially by subsidies. This is the case of organic conversion and maintenance, supported by CAP payments under Pillar 2 (rural development measures) (Figure 3-63). In addition, organic farming certification is associated with an organic logo on food products. This organic label is probably the most well-known label among European consumers. In an experiment conducted in four European countries, consumers gave the highest Willingness To Pay after information on pesticide use to organic apples, before apples produced using IPM methods, and before conventional production methods (Bazoche *et al.*, 2014).

Over the past years, there has been a multiplication of labels communicating on the reduction or absence of pesticides in food products. They vary in their claims: "pesticide-free", "pesticide residue-

[55] https://www.ipsuisse.ch/fr/, last consulted in May 2023

free", "cultivated without pesticide", etc. They also vary in their forms: logos, and more recently eco-scores including criteria related to pesticide use. The only label that is currently regulated at European level is the organic label (Figure 3-65). However, as part of the Farm to Fork strategy the European Commission plans to examine ways to harmonize voluntary green claims and to create a sustainable labelling framework that covers, in synergy with other relevant initiatives, the nutritional, climate, environmental and social aspects of food products (European Commission, 2020c).

Figure 3-65: European leaf - Organic label

Subsidies for transition and regulation (ban) in the long term

In this policy instrument mix, a ban or a restriction in pesticide use is accompanied with financial support for adoption of alternative practices. For example, in Denmark, mandatory measures regarding crop protection and adoption of Integated Pest Management (IPM) is supported financially: the government covers up to 80% of the costs incurred by farmers for advisory support on integrated pest management (Barzman and Dachbrodt-Saaydeh, 2011). Also in Denmark, subsidies are provided to farmers for maintaining pesticide-free buffer zones and for the use of alternative to chemical pesticides, and a dedicated funding program supports the costs of authorising non-chemical pesticides under which applicants can receive up to 100 % of the total costs associated with gaining authorisation for a new pesticide (Sud, 2020).

Subsidies (consumers' behaviours) and certification (products without pesticides)

In this policy instrument mix, instead of an intervention on agricultural production, **food products are subsidised** in order to influence consumers' choices towards healthier diets. In this instrument mix, consumer's subsidies are accompanied with certifications or labels so that consumers can identify healthier products.

Fiscal policies to improve diet have been implemented in several countries around the world, including in European countries[56]. According to a report published by the World Health Organisation (WHO) in 2015, appropriately designed taxes on sugar sweetened beverages can result in reductions in consumptions, when prices is raised by minimum 20%. Similarly, subsidies for fresh fruit and vegetables that reduce prices by 10-30% increase their consumption. The WHO report also adds that greater effects may be accomplished by combining subsidies and taxation (WHO, 2015).

In a very recent meta-analysis and systematic review analysing the impacts of food taxes and subsidies on diets (Andreyeva *et al.*, 2022), the authors found that fruit and vegetable subsidies are

[56] Denmark, Finland, France, Hungary have implemented taxes aiming at influencing food consumption. For an overview of the schemes in place see the WHO Europe report : https://www.euro.who.int/__data/assets/pdf_file/0008/273662/Using-price-policies-to-promote-healthier-diets.pdf

associated with a significant increase in fruit and vegetable sales. Data on consumption outcomes of subsidies for fruits and vegetables were inconclusive, due to limited number of studies of mostly low quality. The authors found convincing evidence that food taxes were associated with higher prices and reduced sales of taxed products.

The Green deal and Farm to Fork strategy (European Commission, 2019) also refer to tax incentives as instruments that should drive the transition to a sustainable food system and encourage consumers to choose sustainable and healthy diets.

Insurances covering risks conditioned to the adoption of new practices

Several insurances mechanisms can be used by farmers to manage the risks associated with their activity: individual insurance contracts, mutualisation funds that can be partly publically funded, or national compensation schemes for extreme, "catastrophic" events. Some studies have shown that insurance mechanisms alone may not be efficient in reducing pesticide use: indeed, empirical results indicate a positive and significant relation between crop insurance and pesticide use (Möhring *et al.*, 2020a). Puel and Grimonprez explore different measures to address this issue: they propose to condition the insurance mechanisms to the adoption of prophylactic measures in terms of pest management (for example crop diversification, mechanical weeding, use of biocontrol, etc.). Also, they discuss the possibility to reduce the thresholds of crop losses to get financial compensation (20 to 30% crop losses). However, these thresholds are set in accordance with WTO rules and may not be easily reduced, unless through a national scheme (Puel and Grimonprez, 2022). Such mechanism has been in place in some regions in Italy ("Fondo Risemina Mais") since 2014: producers can get access to a mutualisation fund covering for crop losses due to climatic and phytosanitary events. Conditions to get access to this fund are to pay a contribution per hectare and to commit to adopt IPM measures (Grimonprez and Jacquez, 2022).

3.3.3.5. Summary of the hypotheses of changes for the agricultural policy and economical instruments

The Table 3-26 below summarises the main hypotheses identified for the evolution of the agricultural policy and economical instruments in Europe.

Table 3-26: Summary of hypotheses of changes for the agricultural policy and economical instruments

	Hypothesis 1	Hypothesis 2	Hypothesis 3	Hypothesis 4
Evolution of the CAP	EU policy including payments for ecosystem services	CAP payments conditioned to compliance with pesticides reduction goals	CAP coherent with food and health policies	
Combination of instruments	Taxes for chemical pesticides uses and subsidies for adoption of pesticide-free practices	Covenants, certification and/or sustainability label and subsidies for transition	Subsidies to consumers on healthy products	Insurances covering risks conditioned to adoption of new practices

3.3.4. International trade policies and pesticides

Note: We do not cover in this paragraph the international trade of chemical pesticides. We cover international trade of products produced with the use of chemical pesticides.

The EU is the world's biggest exporter and the third biggest importer of agri-food products, including aquaculture (European Commission, 2021c). As an important player on international food markets, the EU can significantly impact the development of regulations and standards of global significance.

There is no single international regulation regarding pesticides, but a set of international standards, agreements and guidance documents have been developed since the 90's, covering the ban of certain substances that are harmful to human health and/or the environment, consumer's protection, testing standards.

3.3.4.1. WTO sets common rules regarding phytosanitary measures, recognizing countries sovereignty on safety matters

Globally, The World Trade Organization (WTO) sets a framework for health standards including pesticides residues, through the Sanitary and Phytosanitary measures (SPS) agreement[57]. It dates back from the creation of WTO in 1995. The principle of this agreement is to favor a non-discriminatory framework for trade of products across the globe, while recognizing the sovereignty of countries (or regions) to set their own standards on products. This agreement allows countries to set their own standards, but also states that these must be based on science. They should be applied only to the extent necessary to protect human, animal or plant life or health, and they should not arbitrarily or unjustifiably discriminate between countries where identical or similar conditions prevail. Governments are required to notify other countries of any new or changed sanitary and phytosanitary requirements that affect trade, and to set up offices to respond to requests for more information on new or existing measures (WTO, 1998). Countries can complain and submit concerns or trade disputes regarding a sanitary or phytosanitary measure that they believe does not fulfill SPS agreement criteria, using the WTO dispute settlement procedures. There are currently 69 concerns related to pesticides raised by countries on the WTO trade concerns database, over 548 concerns raised on Sanitary and Phytosanitary topics[58].

Other WTO agreements can be of relevance to pesticides and to environmental protection. These include the General Agreement on Tariffs and Trade (GATT) and its article XX that allows for countries to set measures necessary to protect human, animal or plant life or health, under certain conditions (European Commission, 2022d). Also, under the Uruguay round agreement on agriculture, there are sets of rules and commitments related to market access, domestic support and export subsidies, which can have an impact on the possibilities for states aid related to reduction in pesticides use[59]. For example, WTO classifies domestic support to agriculture into three boxes, the "green box" relating to supports to research programs, environmental program payments, disaster assistance, direct payments to farmers that are not contingent on production. Although these "green box" supports are exempted from reduction objectives, the agreement specifies that direct payments to producers such as those related to natural disaster relief (including pest infestations) or to state contribution to crop insurance programs, can only be applied if there is a production loss exceeding 30% of the average production in the preceding three-year period. Also, payments under environmental programmes, must be limited to the extra costs or loss of income involved in complying with the government programme (WTO, 1994).

[57] https://www.wto.org/english/tratop_e/sps_e/spsund_e.htm, last consulted in August 2022

[58] https://tradeconcerns.wto.org/en/stcs?searchTerm=pesticide, last consulted in August 2022.

[59] https://www.wto.org/english/thewto_e/whatis_e/tif_e/agrm3_e.htm, last consulted in November 2022

3.3.4.2. European maximum residue limits apply to imported agri-food products, with possibility of import tolerances

Europe applies the same health and sanitary standards for domestic and imported food products from third countries. For pesticides, this means that food products entering the European market must comply with the European maximum residue limits set for food and feed products in the European Regulation 2005/396. The compliance of animals, plants or products entering the EU from third countries with relevant EU standards and requirements is verified through control systems implemented by the competent authorities in EU Member States, in cooperation with national customs authorities. In practice, and given the huge number of agri-food products exchanged, these border controls can be quite challenging and costly (Place *et al.*, 2022). As shown in paragraph 3.3.2.3, EFSA monitoring results show a trend towards less compliance of imported products than domestic ones in terms of maximum residues limits. Very recently, contamination of food products with Ethylene oxide, an unauthorised substance in Europe used as a fumigant in various products such as sesame seeds, locust bean gum, spices (etc.) triggered the withdrawals and recalls of thousands of products in many EU Member States (European Commission, 2022e).

This requirement on compliance with maximum residue limits applies to the products entering the European market. Requirements on the way these products are produced, such as the use of pesticides, are not imposed to imported products (European Commission, 2022d). This means that an agricultural product can be produced in a non-European country with the use of a pesticide not allowed in Europe, and still enter the European market if it does not contain more than the maximum residue level allowed for this pesticide.

Also, the European Regulation provides that exporting countries can ask for specific tolerances – so-called "import tolerances". Within this process, exporting countries can request a change in the European maximum residue limits of pesticides applicable to their products, for example for pesticides that are no longer approved in Europe, or for crops that are not produced there. These requests are assessed by EFSA only on the basis of good agricultural practices and consumers' protection. Recently, a request was submitted for clothianidine in potatoes from North America, requesting a 10-fold increase in the MRL for this neonicotinoid. EFSA gave a positive opinion to the request but the European Parliament rejected it (Baldone *et al.*, 2021).

According to the European Commission in its recent report on the application of EU health and environmental standards to imported agricultural and agri-food products (European Commission, 2022d), regulations related to the production practices – such as the use of pesticides - to limit the environmental impact "*are not linked to the end product itself, but to the production of that product. Therefore, if such standards apply to imports,* ***they de facto 'regulate' the production process abroad****, to the extent the products concerned are intended to be sold on the market of the regulating country*". Nonetheless, there are some examples of production practices that are imposed by Europe to imported products, on animal welfare (protection of animals at the time of killing, protection of animals during transportation). Similarly, the United States of America impose environmental measures regarding fish and seafood (ban of imported tuna that does not demonstrate the protection of dolphins during fishing (Beyers, 1992).

3.3.4.3. International standards have been created to set common guidelines on pesticides

In the absence of international regulation covering pesticides and their use, several international standards were adopted over the past years. These standards are compiled in the FAO and WHO guidance on pesticide legislation, as part of their International Code of Conduct on Pesticide Management (FAO and WHO, 2020a).

Started in 1988 and reaching universal ratification in 2009, the **Vienna Convention for the Protection of the Ozone Layer**[60] has reduced usage of hazardous pesticides by replacing methyl bromide with less hazardous alternatives (European Parliament, 2021).

The **Stockholm Convention on Persistent Organic Pollutants** (POPs) has been ratified by 184 parties as of 2020 and restricts 12 initial and 16 newly added POPs deemed harmful for human health and the ecosystem (UNEP, 2017).

The **Rotterdam Convention on the Prior Informed Consent** (PIC), adopted in 1998 and entered into force in 2004, fosters information sharing between states about hazardous chemicals including pesticides entering international trade. The Convention covers pesticides and industrial chemicals that have been banned or severely restricted for health or environmental reasons by member countries. The Convention promotes the exchange of information about these hazardous chemicals. Member countries are required to inform the other countries of each national ban or severe restriction of a chemical. There are currently a total of 52 chemicals listed in Annex III of the convention, listing the chemicals that have been banned or severely restricted for health or environmental reasons by two or more Parties and which the Conference of the Parties has decided to subject to the PIC procedure. Among them, there are 35 pesticides (including three severely hazardous pesticide formulations), 16 industrial chemicals, and one chemical in both the pesticide and the industrial chemical categories[61]. A major drawback with the PIC procedure is that there is no obligatory mechanism for compliance (Handford *et al.*, 2015).

Joint WHO/FAO codex alimentarius: the Codex Alimentarius Commission that is a joint body of FAO (Food and Agriculture Organization) and of WHO (World Health Organization), elaborates harmonized maximum residue limits (MRLs) for pesticides in food. These food standards are recognized by the WTO through the Agreement on the Application of Sanitary and Phytosanitary Measures. The updated list of MRLs is available on the FAO website and is regularly updated[62]. Up to 2016 the Codex Alimentarius Commission has adopted **4844 MRLs** for different pairs of pesticide and food commodities. Some governments have adopted Codex MRLs as legally binding standards, other (like EU, USA for example) have set their own MRLs.

Since 1992, **OECD** (the Organisation for Economic Co-operation and Development) has launched a **pesticide program** to harmonise the pesticide registration procedures. OECD has developed harmonised test methods for assessing pesticide safety, as well as good laboratory practices. Tests conducted following these OECD protocols are recognised by all OECD members, avoiding duplication of experiments for the same substance[63].

3.3.4.4. Trends and hypothesis of future changes

Towards a global and harmonized regulation on pesticides?

Despite the multiplication of international standards, agreements, conventions, there remains significant differences in pesticides regulations worldwide. These global differences can be explained by different needs for pest management, different practices (application rates, etc.) across regions. These differences can act as a technical barrier to trade especially for developing countries, which may still be using hazardous pesticides that are not allowed anymore in other countries. Indeed, producers

[60] https://ozone.unep.org/treaties/vienna-convention?q=fr/treaties/convention-de-vienne, last consulted in august 2022.

[61] http://www.pic.int/TheConvention/Chemicals/AnnexIIIChemicals/tabid/1132/language/en-US/Default.aspx, last consulted in august 2022.

[62] https://www.fao.org/fao-who-codexalimentarius/codex-texts/dbs/pestres/en/, last consulted in august 2022.

[63] https://www.oecd-ilibrary.org/environment/oecd-guidelines-for-the-testing-of-chemicals_72d77764-en, consulted in August 2020.

exporting to several countries must manage different maximum residue limits, generating complexity, additional costs. Importing countries with more stringent regulations can limit trade for exporting countries, encountering bigger difficulties to comply with the standards (Handford *et al.*, 2015).

Several attempts for global harmonization have been made by international parties such as FAO/WHO Codex (harmonized MRLs), the OECD (harmonized testing protocols and mutual data recognition). Also, several collaborations have been developed between countries regarding pesticide regulatory programs. For example in East Africa, the Treaty for the establishment of the East African Community signed in 1999 by three countries harmonizes policies and legislation enforcement of pest and disease control (Handford *et al.*, 2015). Also, the Association of the South-East Asian Nations has developed voluntary Good Agricultural Practices (GAP) to enhance the standards for the production, harvesting and post-harvest handling of agricultural products, including harmonized maximum residue limit of pesticides for 61 pesticides (European Parliament, 2021).

Private initiatives have developed to propose international agricultural production standards. One of the most important one is GLOBALG.A.P., created in 1997 by several major north-european retailers (Bernard de Raymond and Bonnaud, 2014). It now covers more than 700 certified products and over 200,000 certified producers, in more than 135 countries[64]. GLOBALG.A.P. standard is based on holistic approach to cover various topics linked to agriculture production such as food safety and traceability, environment (including biodiversity), workers' health, **integrated crop management, integrated pest control**, Hazard Analysis and Critical Control Points (HACCP). This private and voluntary standard can complement the existing laws and regulations by setting additional requirements or criteria on certain topics. It can also ensure, through audit by a certification body, compliance with requirements that may not be properly monitored by authority's controls and analyses (Bernard de Raymond and Bonnaud, 2014).

In the future, we could foresee an increase of the initiatives towards global harmonization of pesticide regulations. This would be beneficial to parties involved – consumers (increased level of protection), manufacturers of pesticides, producers, and regulators (Don Wauchope, 2008). Obstacles could be the time necessary to align all countries in all regions, the incompatibility of global standards with local situations and needs, and also the change in governance required to establish these global regulations.

Introduction of mirror or reciprocity clauses addressing the question of pesticides

Recently, the possibility to introduce reciprocity clauses (or "mirror clauses") between Europe and its trade partners has been debated. Mirror clauses aim at guaranteeing that imported products are produced under the exact same sanitary, phytosanitary, welfare and environmental standards as those imposed on domestic products within the European Union (Rees, 2022).

Mirror clauses usually pursue three main objectives. First, they allow to extend the protection of health and environment (including animal welfare) to countries outside Europe. They also promote or contribute to the adoption of good agricultural practices. Finally, they allow to reduce the risks of unfair competition between European farmers and farmers from other regions (Dehut and Pouch, 2021).

As part of the Farm to Fork strategy, the European Commission specifies that "*trade policy will be used to support and be part of the EU's ecological transition*", and that "*the EU will seek to ensure that there is an ambitious sustainability chapter in all EU bilateral trade agreements. EU trade policy should contribute to enhance cooperation with and to obtain ambitious commitments from third countries in key areas such as animal welfare, **the use of pesticides** and the fight against antimicrobial resistance*" (European Commission, 2020c).

Regarding pesticides, the question is whether Europe could extend the current regulation for imported products (compliance with maximum residue limits), by banning the use of pesticides not approved in

[64] https://www.globalgap.org/uk_en/index.html , last consulted in May 2023

the EU for producing food and feed products entering the European market. The rationale for such ban would be health and environment protections, including on pollinator insects. According to a report issued by several NGOs (Baldone *et al.*, 2021), this proposal could be compatible with WTO trade agreements, provided that emergency authorisations are not allowed anymore within Europe, as well as the production, storage and transport of substances banned in Europe.

Actually, France has already set up this principle of mirror clauses applicable to pesticides in the "EGALIM" law (article L236-1A du code rural et de la pêche maritime), but has not enforced it yet. The article says: *"It is forbidden to offer for sale or to distribute free of charge for human or animal consumption foodstuffs or agricultural products for which phytopharmaceutical or veterinary products or animal feedstuffs not authorized by European regulations or not complying with the identification and traceability requirements imposed by these same regulations have been used[65]".*

In this context, the European Parliament and the Council asked the European Commission to study the possibility, including legally in conformity with WTO rules, to apply EU health and environmental rules to imported agri-food products. After a full legal analysis of applicable rules, especially within WTO, the European Commission concludes that it is possible, in compliance with WTO rules, to set health and environmental requirements to imported agri-food products related to their process and production methods. The Commission calls for a case by case analysis of each potential measure (European Commission, 2022d).

The Commission also lists arenas where Europe can influence international trade discussions towards the inclusion of environmental measures. These include (European Commission, 2022d):

- "*Reforming WTO rules towards more consideration of environmental challenges and responses to them;*
- *Adopting sustainability criteria within Codex Alimentarius norms;*
- *Including sustainable criteria into the bilateral trade agreements (which represent currently almost 50% of agri-food imports in Europe) covering topics such as reduction in chemical pesticides use;*
- *Applying unilateral autonomous measures to products entering the European market. For example, the EU will from now on also consider environmental impact of pesticides when examining import tolerances requests for pesticides*".

3.3.4.5. Summary of the hypotheses of changes for international trade policies

The Table 3-27 below summarises the main hypotheses identified for the evolution of the international trade policies related to pesticides.

Table 3-27: Hypotheses of changes for trade policies and pesticides

Hypothesis 1	Hypothesis 2
Global harmonized regulation on pesticides through Codex alimentarius and the WTO	Bilateral trade agreements including mirror or reciprocity clauses related to pesticides use

[65] « Il est interdit de proposer à la vente ou de distribuer à titre gratuit en vue de la consommation humaine ou animale des denrées alimentaires ou produits agricoles pour lesquels il a été fait usage de produits phytopharmaceutiques ou vétérinaires ou d'aliments pour animaux non autorisés par la règlementation européenne ou ne respectant pas les exigences d'identification et de traçabilité imposés par cette même règlementation".

3.4. Changes in the remaining dimensions of the food systems: Diets, agricultural equipment and digital technologies, education and agricultural knowledge and innovation systems

Authors: Olivier Mora, Claire Meunier

Table of contents

Introduction

In this section we cover recent and future changes in European diets, agricultural equipment and digital technologies, and in education and agricultural knowledge and innovation systems (AKIS). For these components, a lighter retrospective analysis has been performed, mainly based on recent publications such as meta-analysis, reviews, and foresight studies. Experts' workshops have been organised to generate hypotheses of changes on agricultural equipment and digital technologies, and education and AKIS (see Table A2 ("Agricultural equipment and digital technologies" group) and Table A3 in the Appendix of the report).

3.4.1. Changes in European diets

Diet is a very important component of food systems in general, and as such it is important to consider future dietary changes when we think about chemical pesticide-free agriculture in 2050. Indeed, food demand drives agricultural production needs in diversity, quantity and quality and therefore, the evolution of food diets and their composition will influence the transition towards chemical pesticide-free agriculture by 2050.

This paragraph examines past and current trends in European diets, and draw hypotheses of change in 2050 to support scenarios of chemical pesticide-free agriculture. It is based on scientific articles and on reports published on this topic by organisations such as the World Health Organisation (WHO), the Food and Agriculture Organisation (FAO), the Organisation for Economic Co-operation and Development (OECD). In these reports and articles, it is important to note that Europe corresponds to different geographical areas, such as countries forming the European Union, countries belonging to the WHO Europe geographical zone (comprising 53 countries), Europe and Central Asia, etc.

3.4.1.1. Past and current trends in European diets

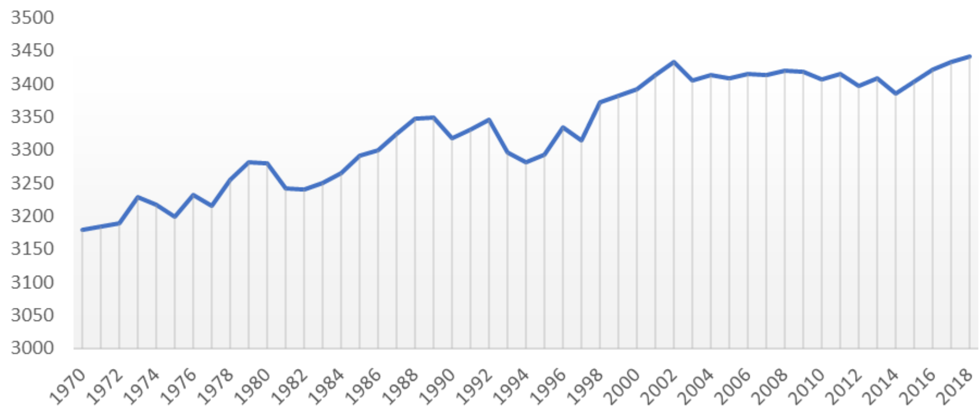
The nutrition transition of European diets

Overall, in Europe, there has been a **nutritional transition** over the past decades, favoured by increased incomes, the urbanisation and the changes in food value chains allowing the supply of cheap, industrially-processed foods (WHO Europe, 2022). The transformation of the food value chain, that promoted the development of ultra-processed, energy-dense manufactured foods and sugar-sweetened beverages, is further described in section 3.2 (food value chains for chemical pesticide-free agriculture).

It is possible to follow the evolution of food consumption across Europe, both quantitatively (quantities consumed) and qualitatively (food products consumed). The Food and Agriculture Organization (FAO) produces food balance sheets worldwide, that allow to measure the evolution in the availability of food calories across regions of the globe. These food balance sheets do not reflect actual food consumption, but are very often used as proxy in scientific studies.

Overall in Europe, **the total available energy has importantly increased between the 1970's and the 2000's, moving from around 3 150 kcal per capita and per day to up to around 3 440 kcal in 2018**. Since the 2000's, this increase seems to have stabilized (Figure 3-66).

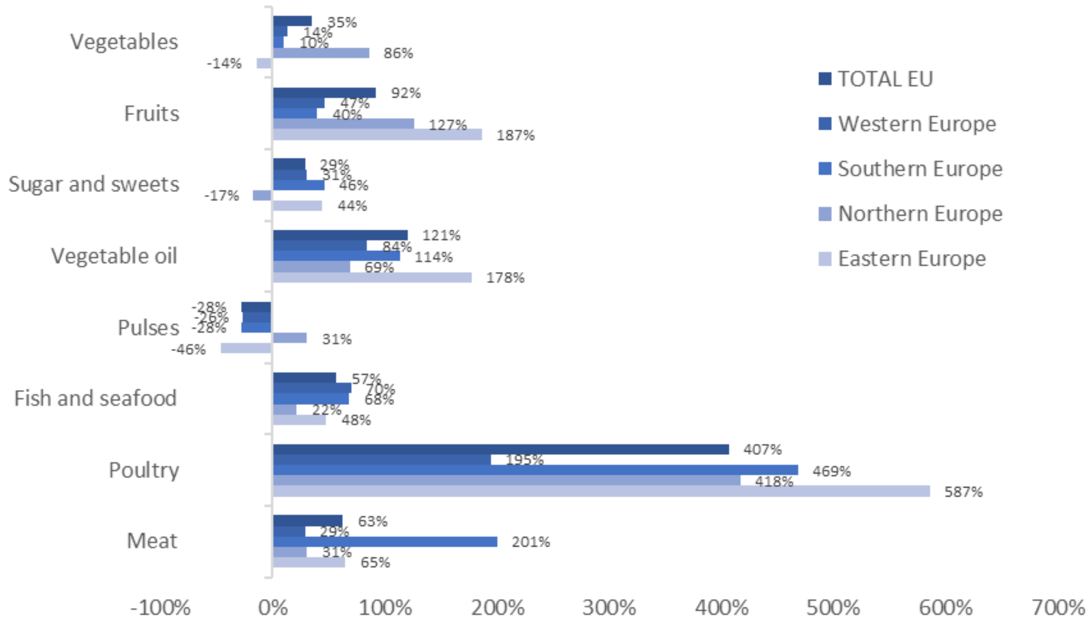
Figure 3-66: Evolution of the average number of calories available per person and per day (kcal) in the European Union between 1970 and 2018 (Source: FAO balance sheet)



In terms of macronutrients, the percentage **energy from fat available has increased**, while the percentage **energy from carbohydrates has fallen** and that of **proteins has remained almost constant** (Balanza *et al.*, 2007).

Beyond this observed increase in calories and evolution of macronutrients availabilities, there has also been a **shift in the composition of the foods available for consumption in Europe.** Between 1961 and 2013, there has been a **very important increase in the quantities of meat** (especially poultry), **vegetable oils, fish and fruits** available for consumption in Europe and all European regions. There has also been an **increase in the availability of sugars and vegetables**, although not in all European regions. On the contrary, the **availability of pulses has decreased** in total Europe and in all European regions except Northern Europe (Birt *et al.*, 2017, based on FAOSTAT; Figure 3-67).

Figure 3-67: Evolution of the availability of various food product categories (in % kg/cap/year) in Europe and European regions between 1961 and 2013 (Source: data from Birt *et al.*, 2017, based on FAOSTAT)



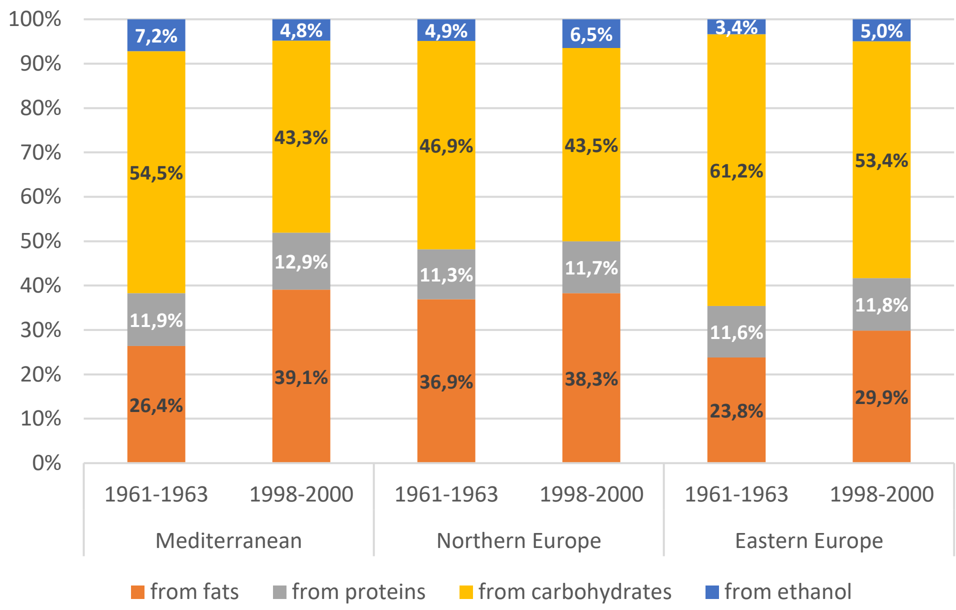
The same trends in the evolution of the categories of food consumed are observed when looking at caloric intakes, as calculated by Dave *et al.* (2016). Between 1961 and 2011, there has been a significant growth in caloric intakes from vegetable oils, meat, fruits and vegetables, alcohol (only in Western Europe – WE), fish (WE) and eggs (Eastern Europe and Central Asia). On the other hand, starches (WE) and cereals caloric intakes significantly decreased within the same period (Dave *et al.*, 2016).

If we look at more recent trends, **in the past decade, only minor changes in European dietary patterns have occurred, mostly confirming past trends**, as described in Riccardi *et al.* (2020): fruits and vegetable consumption slowly declined, fat consumption showed a small decline as well as salt, although still far above recommendations. Intakes of free sugars continued to increase, driven by consumption of manufactured foods, and exceed World Health Organisation (WHO) recommendations. Wholegrain consumption remained low, except in Northern countries.

There are obviously differences across European regions and countries, although they tend to be less and less visible. For example, Balanza *et al.* (2007) show that, between 1960 and 2000, food habits in the Mediterranean countries have deviated a lot from the traditional pattern generally considered to represent the Mediterranean diet, with a fall in the availability of carbohydrates and an increase in the availability of fats (Figure 3-68). The food habits in the Mediterranean region have tended to move closer the food pattern typical of the northern countries (ibid.).

In addition to data from FAO food balance sheets, dietary surveys, conducted among European consumers, can provide information about individual food consumption, by using for example 24-hour dietary recall questionnaires.

Figure 3-68: Percentage energy (in % kJ per capita per day) availability from fats, proteins, carbohydrates and alcohol in three European regions, between 1960's and 2000's (produced from Balanza *et al.*, 2007, based on FAO food balance sheet data)



The EPIC study (European Prospective Investigation into Cancer and Nutrition) is a multi-centre cohort study that aimed at investigating the association between diet, cancer and other chronic diseases across 10 European countries: Denmark, France, Germany, Greece, Italy, the Netherlands, Norway, Spain, Sweden and the United Kingdom. Data from more than 36 000 participants were gathered between 1995 and 2000, and provide interesting information about the energy intakes of Europeans, and contribution of the various food groups. Energy intakes range from 2 196 to 2 877 kcal/person/day in men, and from 1 659 to 2 070 kcal/person/day in women (Ocké *et al.*, 2009). In all studied areas except Greece and some Spanish centres, **carbohydrates are the main source of energy in European diets** (contribution of carbohydrates to total energy intakes ranging from 35 to 50%), **followed by fat**. **Mean protein takes ranged between 13 and 21% of total energy.**

An increasing share of ultra-processed foods in the European diets and its impacts on diet quality

Dietary patterns evolution in Europe is also characterised by an **increased availability and consumption of ultra-processed food** (FAO, 2022). Ultra-processed food category has been developed by the NOVA classification in order to study the relationship between food processing and health. The NOVA classification consists of four food groups, defined according to their degree of processing: unprocessed or minimally processed foods, processed culinary ingredients, processed foods, and ultra-processed foods (UPFs) (Monteiro *et al.*, 2019). FAO defines ultra-processed food and drinks (UPFDs) as "*'formulation of ingredients, mostly of exclusive industrial use, typically created by series of industrial techniques and processes (hence 'ultra-processed').*" (ibid.). Ultraprocessed foods "*are made up of snacks, drinks, ready meals and many other product types formulated mostly or entirely from substances extracted from foods or derived from food constituents*" (ibid.). These products are usually energy-dense, high in salt, sugar and fat.

UPFs are linked to the development of several non-communicable chronic diseases (NCD). The increasing consumption of UPFs is correlated with high risk to develop obesity (Swinburn *et al.*, 2011; Costa el al., 2018) and other diet-related NCD (Lim *et al.*, 2012; Global Panel on Agriculture and Food Systems for Nutrition, 2016; Rauber *et al.,* 2018) such as type 2 diabetes (Conklin *et al.*, 2016), cardiovascular diseases (Mozaffarian *et al.,* 2016, Bonaccio *et al.*, 2021), certain cancers (Fiolet *et al.*, 2018).

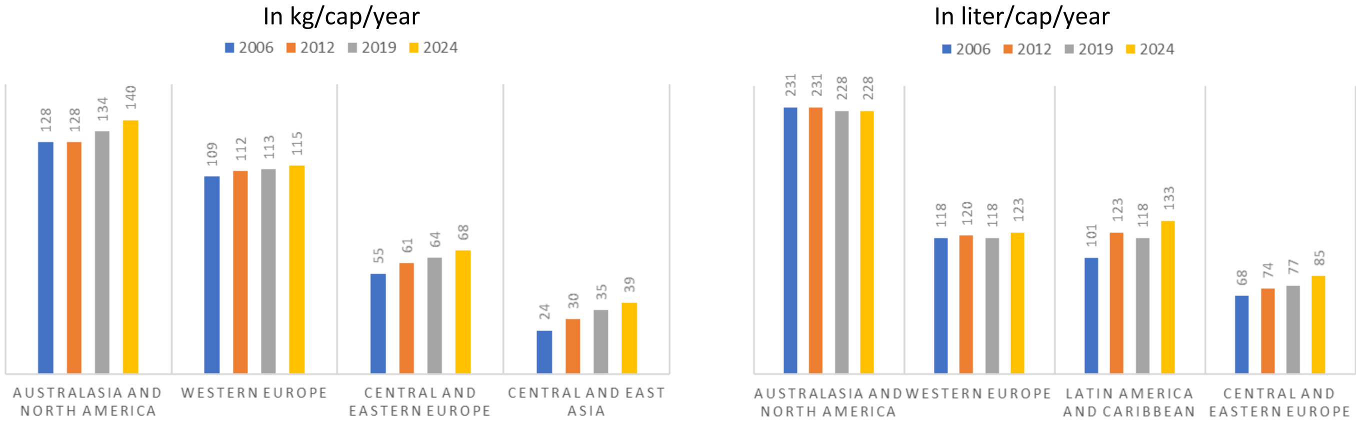
A recent study aimed at characterizing European food consumption patterns in terms of their consumption of ultra-processed food across Europe (Mertens *et al.*, 2022). It showed that, overall, **ultra-processed food currently contributes to between 14 to 44% of total daily energy intakes**, with very important variations between countries (lowest share in Italy and Romania, highest share in the UK and Sweden). In another recent study (Lauria *et al.*, 2021) based on a cohort from eight European countries, the average household availability of ultraprocessed foods has a quite homogeneous pattern, and correspond to 50 % of the usual daily calories for children and adolescents, and 40 % for adults.

Baker *et al.* (2020) analysed trends in sales of ultra-processed foods and beverages globally, and forecasted evolutions towards 2024. They show that, **globally, sales of ultra-processed foods and beverages have strongly increased since 2006**, with Australasia, North America and Western Europe having the highest per capita sales in 2019. In Western Europe however, sales of ultra-processed foods seems to have only slightly increased between 20012 and 2019, and sales of ultra-processed beverages remained stagnant (Baker *et al.*, 2020; Figure 3-69).

Studies show that an increased consumption of UPFs is accompanied by a reduction in diet quality. Diets with a high share of UPFs exhibit higher intakes in sugar, saturated and trans fats and refined cereals, and lower intakes in fruit, vegetables, legumes and seafood. They also provide lower protein, fibre and micronutrient contents than other diets and lead to unbalanced diets (Moubarac *et al.*, 2017; Martinez Steele *et al.,* 2017).

In Europe, several studies in France, UK, Portugal, and at the EU level showed similar results. Diets with a high share of UPFs show a high usual daily intake of total fats, saturated fats, and carbohydrates (Mertens *et al.*, 2019a; Monteiro *et al.*, 2018; Julia *et al.*, 2018; Rauber *et al.*, 2018; de Miranda *et al.*, 2021). Another recent study on a specific cohort from eight European countries confirmed that an increase in the consumption of UPFs is associated with unhealthy dietary patterns characterized by high consumption of sugars and low consumption of protein and fiber (Lauria *et al.*, 2021).

Figure 3-69: Evolution of ultra-processed foods sales (kg/cap/year) and beverages (liter/cap/year) in the top 4 regions, 2006–2019 with projections to 2024 (Source: adapted from Baker *et al.*, 2020)



Trying to identify if the impact of UPFs on diet quality comes from nutrient composition of foods or their ultra-processed nature, a recent study conducted by Julia *et al.* (2023) showed that nutritional quality and ultra-processing should be considered as resulting from the two correlated dimensions of the diet, explaining jointly its overall quality.

Evolutions of the food practices

In addition to the evolution of food consumption patterns, the way European people eat has evolved over the past decades. Indeed, there are some major trends identified in terms of food consumption modes across Europe, potentially impacting quality of diets.

For example, **average time spent on cooking has decreased**, although this trend seems to have been reversed during the covd-19 pandemic due to lockdown measures (Sarda *et al.*, 2022).

Also, there has been an **increase in the out-of-home consumption**, with an increased share of food consumed from vending machines, from take-away outlets, at restaurants, at work or ‘on the go’ (Lachat *et al.*, 2012).

Another trend is the **reduction in the frequency of family meals**, the latter being associated with better nutritional children health (Dallacker *et al.*, 2018).

Nutritional status of the European population

As a result of the evolution of food consumption across Europe, currently, and compared to other world regions, dietary patterns in Europe (EU-27) are characterised by high level of calorie intake, excessive intake of saturated fats, trans fats, sugar, salt, and processed meat, and low intakes of vegetables, fruits and whole grains (FAO, 2022). The current **European food consumption patterns are unsustainable from both health and environmental points of view** (European Commission, 2020a).

The EAT-Lancet Commission on healthy diets from sustainable food systems have calculated reference intakes for various food groups to ensure human health, based on available knowledge (Willett *et al.*, 2019). The authors highlight the food groups whose consumption exceed and, on the other hand, is below these reference intakes for healthy diets. For Europe and central Asia, in 2016, average intakes of red meat (and all processed meat) and starchy vegetables such as potatoes represented more than 400% the reference intakes, and dairy, poultry, and eggs more than 100%. Consumption of fruits, vegetables, fish were insufficient, and whole-grain cereals, fruit and vegetables, legumes and nuts consumption represented less than 25% of reference dietary intakes (Willett *et al.*, 2019).

Similarly, the Global Burden of Disease study 2017 published a review of the consumption of 15 dietary factors worldwide, and their overall impact of diet on mortality and diseases. They showed that in Europe, **intakes of nearly all food groups associated with healthy diets were lower than optimal, especially nuts and seeds, legumes, milk and whole grains** (GBD 2017 Diet Collaborators, 2019). On the other hand, consumption levels of food groups associated with unhealthy diets were **higher than optimal, especially for sugar-sweetened beverages, processed and red meat** (ibid.).

Also, and despite very significant progresses made over the past decades, **food security and affordability remain an issue in EU with 33 million of people who cannot afford a quality meal every second day**, and requiring food assistance (European Commission, 2020a). In some countries such as Bulgaria and Slovakia, respectively 3 and 6.1% of the population in undernourished (European Commission, 2020a).

In parallel, **physical activity levels have overall decreased over the past decades**, triggered by increasing urbanisation, rapid economic development, rise of digital technologies, all of which leading to reductions in domestic and occupational physical activity. In 2016, **more than 35% of adults in the high-income Western countries were insufficiently active, which was 5 points higher than in 2001** (Guthold *et al.*, 2018). This is confirmed by the latest Eurobarometer on sport and physical activity published by the European Commission in 2022, where 45% of the respondents report that they never exercise or play sport. Conversely, 38% declare that they practice sport or physical activity at least once a week, and 6% five times a week or more (European Commission, 2022).

In conclusion, there is a big diversity in terms of diets across Europe, going together with a diversity of countries development levels, food culture and traditions, although this diversity is progressively decreasing. However, and despite these differences, European countries face similar challenges related to unhealthy diets, mainly: energy imbalance and excessive intakes of trans fats, sugars and salt, consumption of highly processed, energy-dense manufactured foods and beverages, and insufficient consumption of vegetables, fruits and whole grains (Breda *et al.*, 2020).

Consequences of diets on human health and on the environment

As a result of the above-described evolutions in dietary habits in Europe, together with lifestyle changes, over-nutrition has developed in Europe, with consequences on increased overweight, obesity and diet-related non-communicable diseases (Mora, 2018).

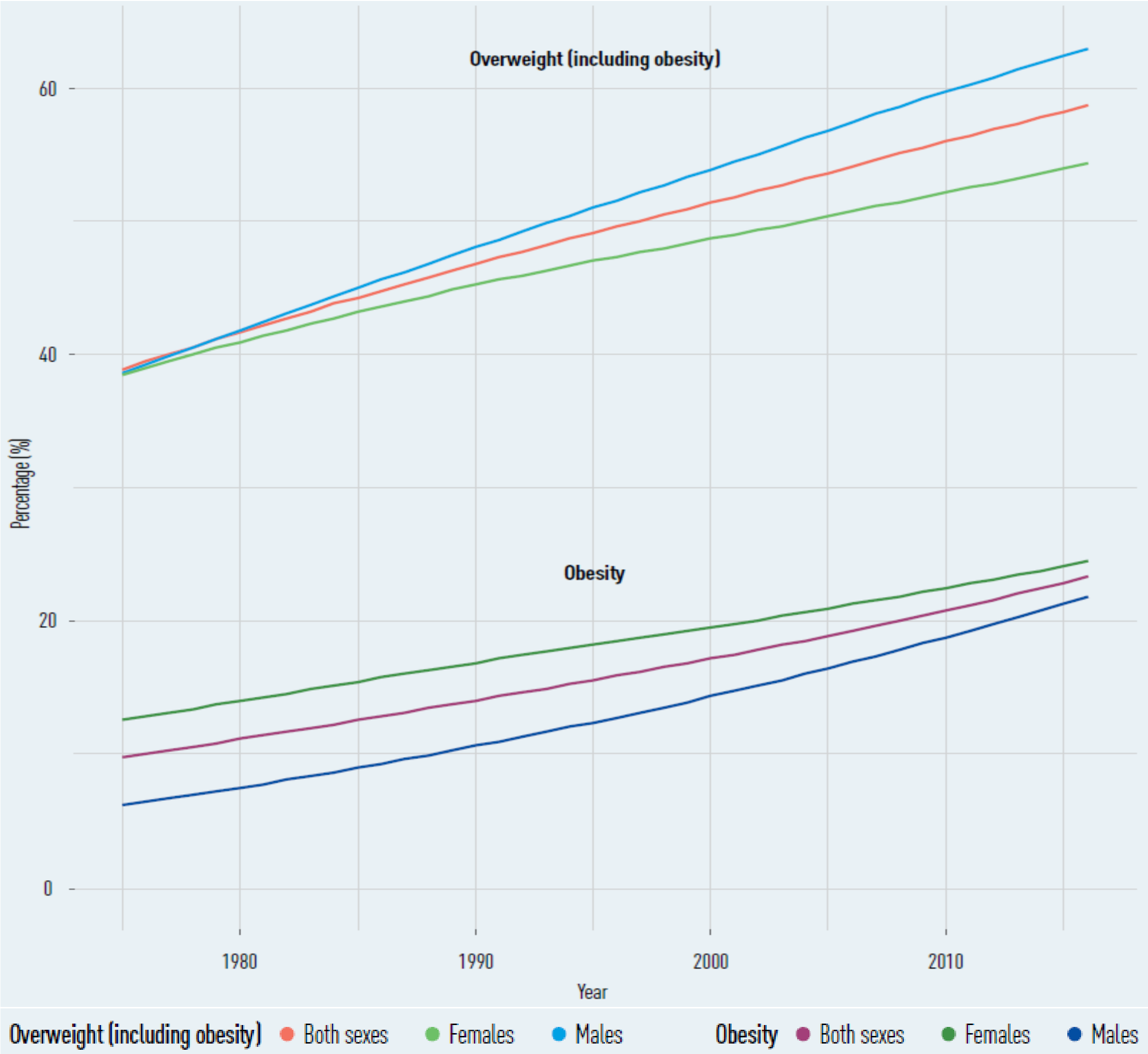
Increasing rate of overweight and obesity among European adults and children

In adults, overweight is defined as a body mass index (BMI) above 25 kg/m^2, and obesity as a BMI of more than 30 kg/m^2 (WHO Europe, 2022). **Over the last 40 years, obesity has increased threefold in several European countries.** Diets, with caloric intakes exceeding recommended amounts, at least partly account for the rise in BMI and obesity (Doytch *et al.*, 2016).

According to OECD latest health barometer, in 2019, **53 % of the adult population were overweight (including obesity**). In most EU countries, more than half of adults are overweight or obese, and between 2014 and 2019, overweight rates increased in virtually all countries, except France and Luxembourg where they remained stable. Austria, Croatia, Finland, Hungary, Slovak Republic saw the largest increases (OECD/European Union, 2022).

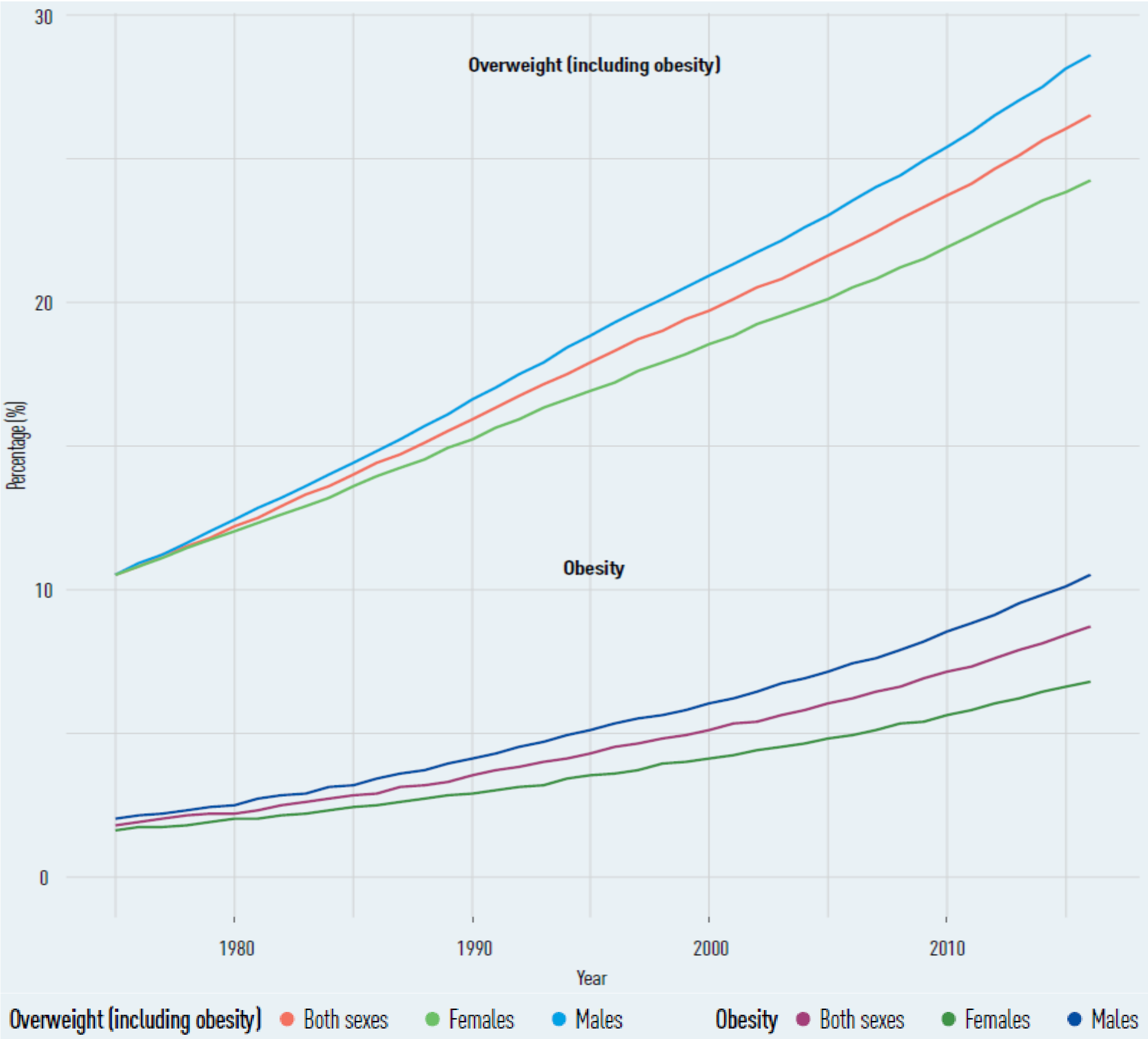
According to WHO Europe, the rapid increase in the levels of overweight and obesity among adults is of great concern. Indeed, in the WHO European Region, recent prevalence estimates for obesity rose by 21% in the 10 years before 2016 and by 138% since 1975; and for overweight (including obesity), by 8% in the 10 years before 2016 and by 51% since 1975 (WHO Europe, 2022; Figure 3-70). This rapid development of overweight and obesity in Europe is a consequence of environmental changes, described as "obesogenic" since the 1990s. This term, according to WHO Europe relates to "*the sum of influences that promote obesity, recognized as the net result of biological, behavioural and* *environmental impacts that act through the mediators of energy intake and expenditure*". These environmental changes include the increased availability of cheaper, more energy-dense and less nutritionally beneficial foods, with the increased consumption of UPFs, and also increased urbanization, associated with less opportunities for physical activity.

Figure 3-70: Prevalence of overweight and obesity among adult men and women, from 1975 to 2016 (Source: WHO Europe, 2022)



Overweight and obesity are also prevalent and increasing among children. In the joint UNICEF/WHO/World Bank estimates, in Europe, in 2020, **overweight, including obesity, affected 3.2 million children under 5 years of age, representing 8.3% of children in this age group** (UNICEF/WHO/ World bank, 2021). The WHO Global Health Observatory shows that in the age group 5–9 years, in 2016, **nearly 30% children are living with overweight including obesity**. Regarding trends, the same set of data show a strong increase in the prevalence of overweight and obesity among children between 1975 and 2016, especially in the last decade (from 2006 to 2016) where the prevalence of obesity increased by 40%; and of overweight including obesity by 20% (WHO Europe, 2022; Figure 3-71).

Figure 3-71: Prevalence of overweight and obesity in children aged 5 to 19 years in WHO Europe countries, between 1976 and 2016 (Source: WHO Europe, 2022)



Increase prevalence of non-communicable diseases (NCDs)

Unhealthy diets are acknowledged as a leading risk factor of diet-related non-communicable diseases, especially **cardiovascular diseases, diabetes and some cancers**. It is estimated that **in the EU in 2017 over 950,000 deaths (20%) and over 16 million lost healthy life years were attributable to unhealthy diets, mainly cardiovascular diseases and cancers** (GBD 2017 Diet Collaborators, 2019).

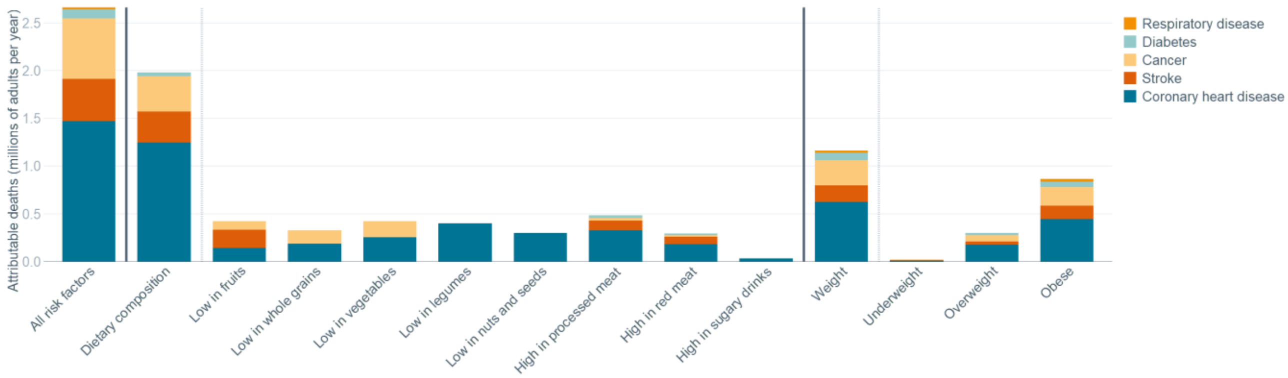
Obesity is considered as both a disease and a risk factor for many other diseases that affect multiple body systems, such as musculoskeletal complications and increased cardiovascular risk, as well as the effects on mental health and metabolic effects; for example, type 2 diabetes mellitus (WHO Europe, 2022).

The global nutrition report[66] provides state of the art data on progresses related to the nutritional status globally and in different regions, on items such as overweight and obesity prevalence, breastfeeding, diabetes, and diet-related non-communicable diseases. It models the Deaths (in millions) attributable to dietary risk factors by cause of death for risks related to dietary composition and weight levels, based on food intakes, risk-diseases relationships found in the literature, and

[66] https://globalnutritionreport.org/resources/nutrition-profiles/europe/, last consulted in August 2023

mortality and population estimates. For Europe, in 2023, the Figure 3-72 taken from the global nutrition report shows that almost 2 million deaths can be attributed to the composition of the diet (global nutrition report, 2023).

Figure 3-72: Mortality attributable to dietary composition and weight in Europe (Source: global nutrition report, 2023)



Note provided by the global nutrition report: deaths (in millions) attributable to dietary risk factors by cause of death, for risks related to dietary composition and weight levels. The combined risk is less than the sum of individual risks because individuals can be exposed to multiple risks, but mortality is ascribed to one risk and cause. 'All risk factors' includes all deaths associated with dietary composition (i.e. diets low in fruits, diets low in vegetables, diets low in wholegrains, diets high in processed meat, diets high in red meat, and diets high in sugary drinks) and all deaths associated with weight levels (i.e. underweight, overweight, obese). PATH authorises the use of this material subject to the terms and conditions on the Global Nutrition Report website.

Since 1990, the Global Burden of Disease approach endeavors to measure disability and death from a multitude of causes worldwide. The Global Burden and Disease study collects data, including on diets, across countries worldwide, and estimates the effect of each risk factor, including dietary factor, on NCDs mortality. The latest data comes from the 2019 study (Murray *et al.*, 2020). Figure 3-73 shows the evolution of the contribution of several dietary risk factors to total deaths in Western and Central Europe, between 1990 and 2019. A trend towards an overall slight reduction in the percentage of deaths attributable to dietary risk factors is visible, especially in Western Europe.

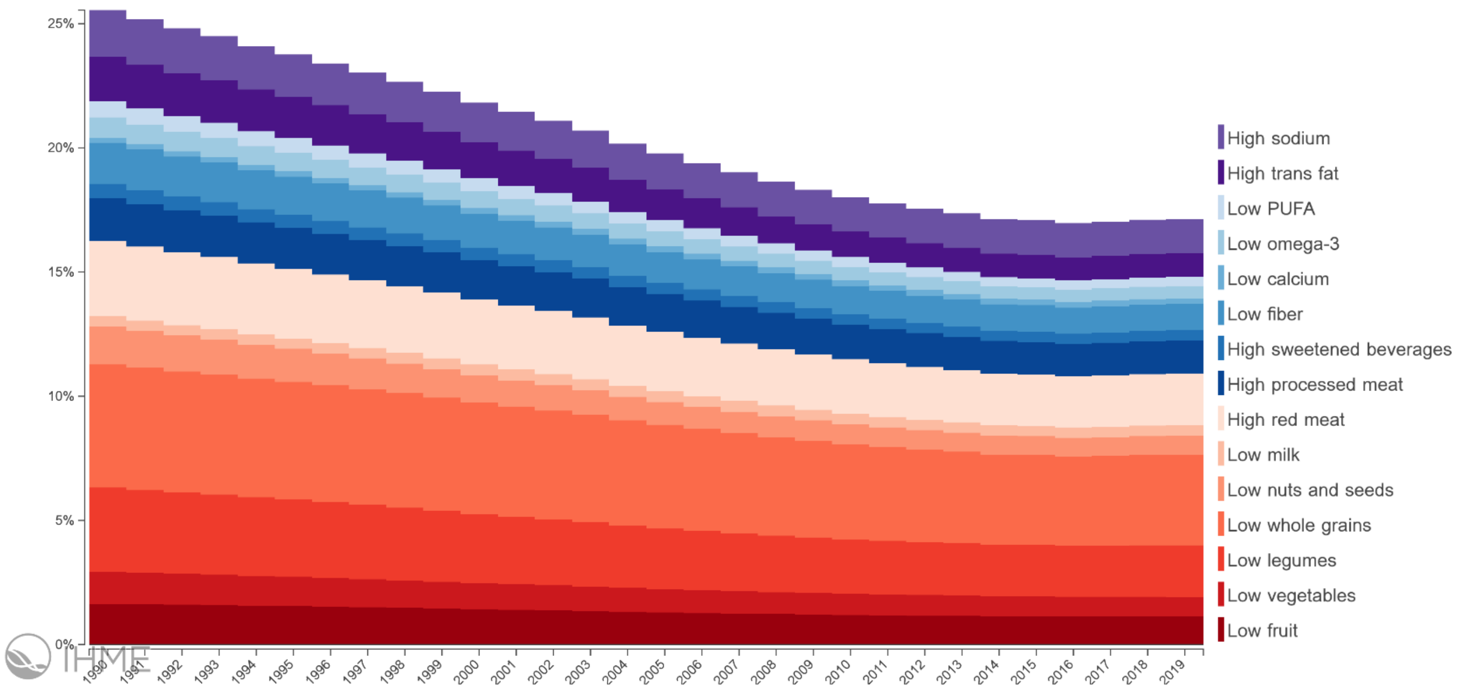
As **cardiovascular diseases** (CVD) remain the leading cause of death in the EU, **dietary risks are responsible for 49% of all the years lost to cardiovascular death or disability** (men and women combined) in the European Union, followed by other behavioural risks such as low physical activity, smoking and alcohol consumption. According to the Global Burden of Disease database, in 2015 dietary risks[67] accounted for 476 000 CVD deaths among men in the European Union, and for 458 000 deaths among women. These dietary risk factors account for 50.4% of male CVD deaths in 2015 in the EU, and for 41.5% of such deaths for women (Wilkins *et al.*, 2017).

Type 2 diabetes: According to the International Diabetes Federation estimates (IDF, 2021), in 2021 59 million adults are living with diabetes in the European region (covering 59 countries), which represents close to 9% of the region population for this age group. This prevalence has increased over the past years. Importantly, an important part of the population are undiagnosed. IDF foresees that this prevalence could increase by 13% by 2045.

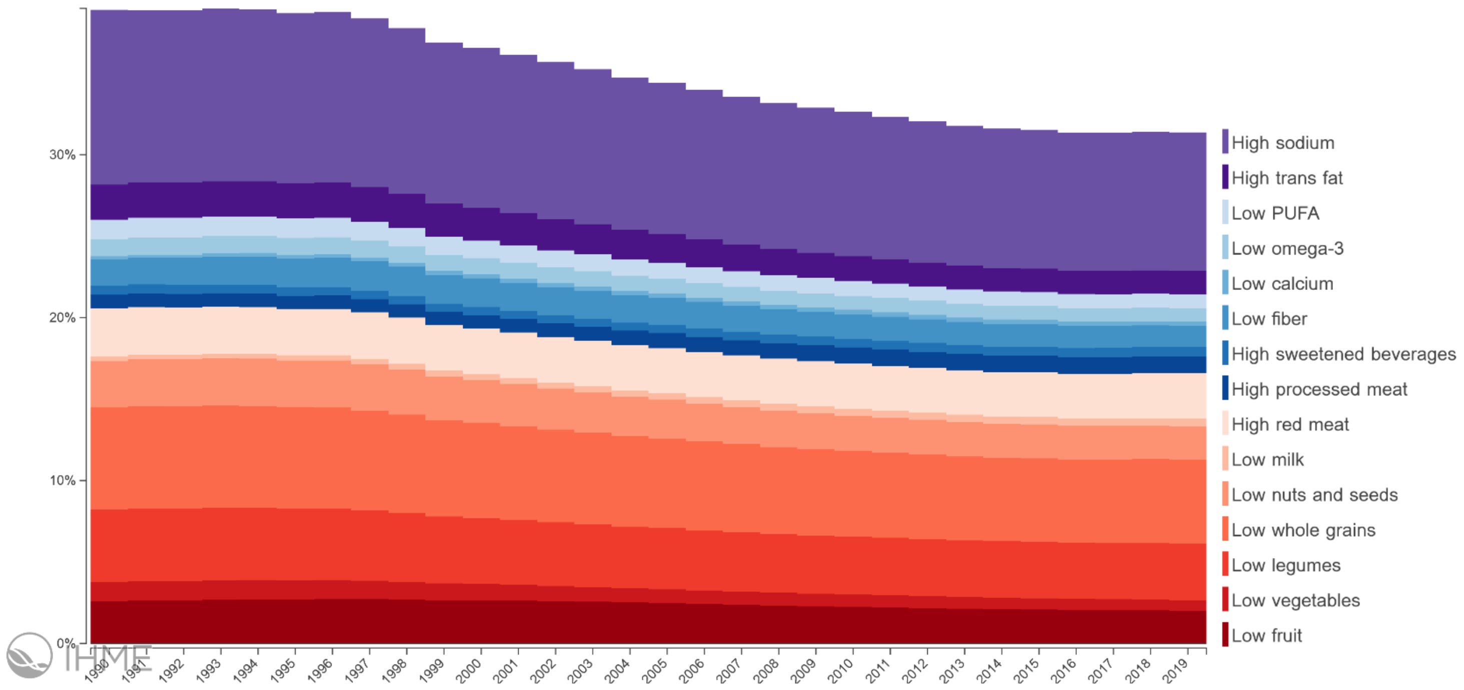
[67] high sodium; low fruit; low whole grains; low vegetables; low nuts and seeds; high processed meat; low fibre; low omega-3; low polyunsaturated fatty acids; high trans fat; suboptimal calcium; low milk; high red meat and high sweetened beverages

Figure 3-73: Evolution of dietary risks factors contribution to total deaths (in percent of total deaths) in Western (a) and Central Europe (b) between 1990 and 2019
(Source: Institute for health metrics and evaluation, University of Washington 2023 - Global Burden of Disease https://vizhub.healthdata.org/gbd-compare/)

a) Western Europe



b) Central Europe



According to WHO Europe, the increase in type 2 diabetes prevalence is strongly associated with increasing trends towards overweight and obesity, unhealthy diets, physical inactivity and socioeconomic disadvantage. Indeed, overweight and obesity account for about 65–80% of new cases of type 2 diabetes; also, consumption of high levels of refined carbohydrates and saturated fat and not enough fruits and vegetables contributes to weight gain, thereby increasing the risk of diabetes (WHO Europe, 2011).

Costs associated with unhealthy diets

The cost of unhealthy diets in Europe is significant, and increasing. It has been estimated that **non-communicable diseases (NCDs),** for which unhealthy diets are one of the leading risk factors, **generate annual healthcare costs in the European Union exceeding 300 billion euros, and costs due to productivity losses and informal care of 200 billion euros** (Pineda *et al.*, 2022).

The major costs associated with NCDs are costs for households and individuals such as decreased salaries, payments for healthcare. There are also healthcare costs linked to medical treatments, stays in hospitals, etc. the last area of costs is linked to the impact of NCDs on national economies with reduced labour available and outputs (European Commission, 2021). According to the European Commission knowledge for policy document on this topic, "*The economic burden of non-communicable diseases (NCDs) is on the rise and is projected to show steeper increases in the future, especially in less developed economies and among the poor in middle- and high-income countries*" (European Commission, 2021).

Impacts of dietary changes on the environment

Evolution of diets can have strong consequences on the environment, as food consumption directly impact food and agricultural productions. The evidence on the interaction between diet and environmental sustainability has emerged more recently than knowledge on eating patterns and human health effects (Birt *et al.*, 2017).

Numerous authors have shown that the increased consumption of energy-dense, processed food, and meat products can contribute to environmental degradation (Willett *et al.*, 2019; Tilman and Clark, 2014; Bodirsky *et al.*, 2020; FAO, 2022), by increasing **greenhouse gas emissions**, **freshwater use**, **nitrogen and phosphorus flows**, **cultivated land expansion**, and **biodiversity loss**.

For example, it has been estimated that **current food production and dietary patterns in Europe account for more than 25% of anthropogenic greenhouse gas emissions** (Mertens *et al.*, 2019b).

Lifecycle assessment methods have been implemented in order to measure the greenhouses gas emissions of different food categories. Systematic reviews of available studies conducted on that topic confirm the **greenhouse gas emission hierarchy between food categories: plant-based foods such as grains, fruit and vegetables with the lowest impact, and meat from ruminants having the highest impact** (Clune *et al.*, 2017).

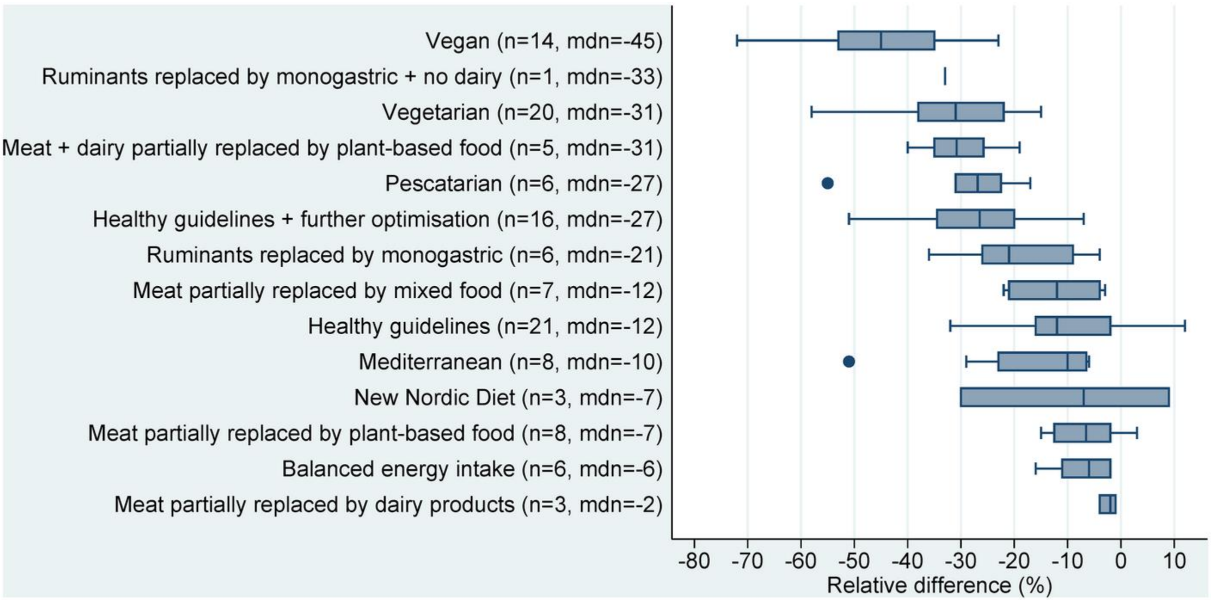
Notarnicola *et al.* (2017) assessed the environmental impact of a typical European diet using lifecycle assessment for 17 product categories. They showed that the **food categories with the highest impact were meat products** (beef, pork and poultry) and **dairy products** (cheese, milk and butter), considering the quantities consumed and individual impact of each product category. Within the lifecycle stages, the agricultural phase had the greatest contribution to the overall environmental impact in many categories, followed by processing and logistics phases (Notarnicola *et al.*, 2017). Overall, the global warming indicator of this typical European diet amounted 1 445 kg CO2eq per person per year, in line with other studies results ranging from about 1 400 to 2 100 kg CO2eq/pers./y. (ibid.).

Another study (Mertens *et al.*, 2019b), compared the greenhouses gas emissions (GHGE) of diets in four regions in Europe, based on dietary surveys. It showed that countries GHGE from diets were proportionally linked to total energy intakes, and to the composition of the diet: the most important contributors being ruminant meat, total meat, coffee and tea, while higher consumption of grain products was associated with lower environmental footprint.

In terms of dynamics of evolution, Bajan *et al.*, 2022, showed that the total greenhouse gas emissions from the food production (from input production to the distribution of the food to the final consumer) in the EU decreased between 2010-2013 and 2014-2017. However, its share in the total greenhouse gas emissions increased in the same period, from 20.3% to 21.7%, indicating that its decline has been slower than other sectors of the EU economy (Bajan *et al.*, 2022).

Beyond greenhouses gas emissions, Aleksandrowicz *et al.* (2016) reviewed the studies investigating the potential for more sustainable diets to contribute to reductions in greenhouses gas emissions, land use and water use. They showed that the **adoption of more sustainable diets could contribute to reductions above 70% of GHG emissions and land use, and 50% of water use**, in comparison with current typical Western diet (Figure 3-74). Medians of these impacts across all studies suggest possible reductions of between 20–30%. In these scenarios of more sustainable diets there was a proportionality between restriction in consumption of animal-based food and reduction in environmental footprints (Aleksandrowicz *et al.*, 2016).

Figure 3-74: Relative differences in GHG emissions (kg CO_2eq/capita/year) between current average diets and sustainable dietary patterns (Source: Aleksandrowicz *et al.*, 2016)

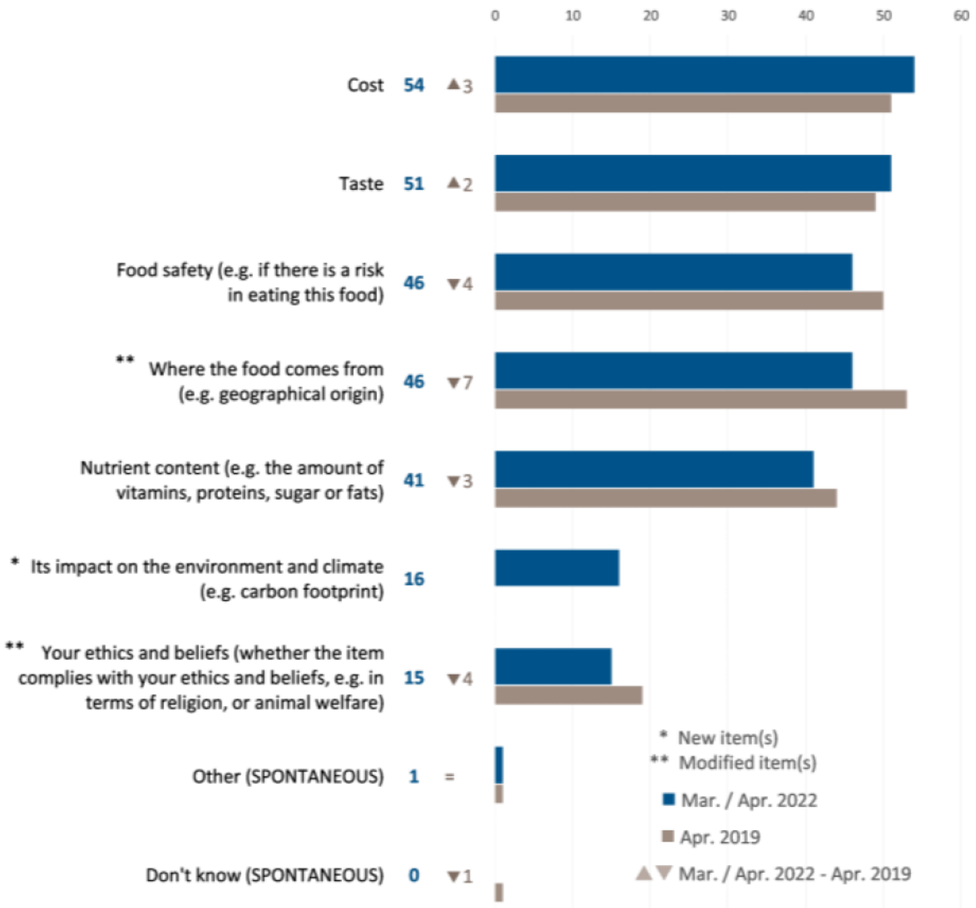


N= number of studies; mdn= median difference, in %.

Despite these data, the environmental and climate impact of food is still not one of the key decision factors for European consumers when buying food (Figure 3-75), who quote as main factors cost, taste, origin and nutritional content ahead of environmental impact (EFSA, 2022).

Figure 3-75: Factors related to food-associated decisions among European consumers (Source: EFSA food safety Eurobarometer, 2022)

Answers to the question: when you buy food, which of the following are the most important to you? Firstly? and then?



Public policies addressing nutrition, health and environmental impacts of diets

Because of the well-established evidence of the link between unhealthy diets and risks of developing non-communicable diseases, during the last decade European institutions and national governments have been developing and implementing different policies to improve diets and therefore reduce the burden of non-communicable diseases (Alves and Perelman, 2022). Examples of such European policies are the EU Action Plan on childhood obesity 2014-2020, the EU cancer beating plan, the WHO European Food and Nutrition Action Plan 2015-2020. These policies call for ambitious national food and nutrition policies in order to improve nutritional status across Europe. Instruments implemented nationally include fiscal policies, regulatory measures, limitation of food marketing to children, and communication campaigns. According to a worldwide review of nutrition policies implementation conducted in 2013, 91% of the countries in the European region had policies for obesity and diet-related non-communicable diseases (WHO, 2013).

An evaluation of the progresses made by countries within the WHO European region on the implementation of policies and policy instruments to promote healthy diets was done back in 2020 (Breda *et al.*, 2020). It showed that, overall, **countries in Europe are progressing in implementing school health and nutrition programs, such as setting standards for foods available in schools, encouraging food product reformulations, or even implementing food taxes** (10 countries had implemented such taxes). WHO Europe recommend that other policy instruments be more used; they include front-of pack nutritional labelling, children marketing restrictions on unhealthy foods, and price policies (ibid.).

More recently, in 2020, the EU Farm to Fork Strategy published by the European Commission set the objective of "*ensuring food security, nutrition and public health, making sure that everyone has access to sufficient, nutritious, sustainable food*[68]" (European Commission, 2020a). In this strategy, the Commission proposes to work on a legislative proposal for a framework for a sustainable food system, promoting policy coherence at EU and national levels, mainstream sustainability in all food-related policies and strengthening the resilience of food systems. Other measures described in the Farm to Fork strategy aimed at creating a favourable environment for the adoption of sustainable diets include: a harmonised mandatory front-of-pack nutrition labelling, the extension of mandatory origin or provenance indications to certain products, the harmonization of voluntary green claims and the creation of a sustainable labelling framework that covers, in synergy with other relevant initiatives, the nutritional, climate, environmental and social aspects of food products (ibid.).

3.4.1.2. Towards healthier and more sustainable diets?

Despite the general pan-European trend of higher consumption of resource-intensive foods, characterized by high energy, fat, protein, sugar and salt, and low fibre and micronutrient-rich foods, there seem to be some positive signals of evolutions in consumers' perceptions of healthy and sustainable diets, and some behavioural changes in some parts of the population.

FAO and WHO define sustainable healthy diets as "*dietary patterns that promote all dimensions of individuals' health and well-being, have low environmental pressure and impact, are accessible, affordable, safe and equitable and are culturally acceptable*" (FAO and WHO, 2019).

First, it seems that the importance of adopting healthy diets is very clear in European consumer's mind, although it does not always translate into changes in their food consumption behaviours. For example, a study conducted among French people on pulse showed that participants had good knowledge about the health and environmental benefits of these products, but this knowledge did not seem to be used to compose meals (Melendrez-Ruiz *et al.*, 2019).

According to the European Commission 2020 Eurobarometer food fit for the future, a majority of respondents consider that they eat a healthy and sustainable diet most of the time (European Commission, 2020b; Figure 3-76). **Two thirds of EU respondents say that they usually eat a healthy and sustainable diet**. More than half of those surveyed say that they eat a healthy and sustainable diet most of the time (56%) and a tenth of respondents say they eat such a diet always (10%). Over a quarter of respondents say they eat a healthy and sustainable diet from time to time (27%) and just over one in 20 of those surveyed say they never (7%) do so.

According to this same survey, the **majority of European citizens consider that a healthy and sustainable diet consist of "*eating a variety of different foods, having a balanced diet*" and "*eating more fruit and vegetables*".** The issue of **pesticides**, "little or no pesticide" appears clearly for 47% of the respondents as a major component of a "healthy and sustainable diet". Other components of a healthy diet, such as "*eating more of wholegrain food*", or "*not eating too many calories*" are quoted less often (European Commission, 2020b; Figure 3-77).

[68] European Commission Farm to Fork Strategy, 2020: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

Figure 3-76: Answers to the question: Would you say that personally, you eat a healthy and sustainable diet… (ONE ANSWER ONLY) Always; Most of the time; From time to time; Never; Don't know? In % respondents (Source: European Commission, 2020b)

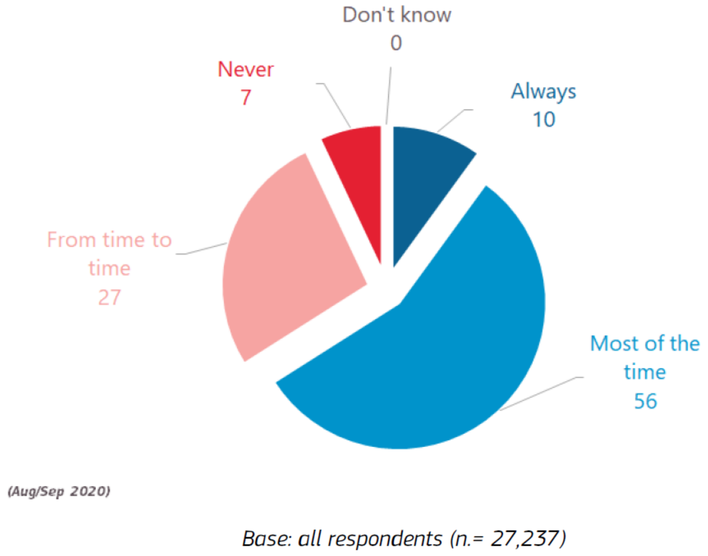
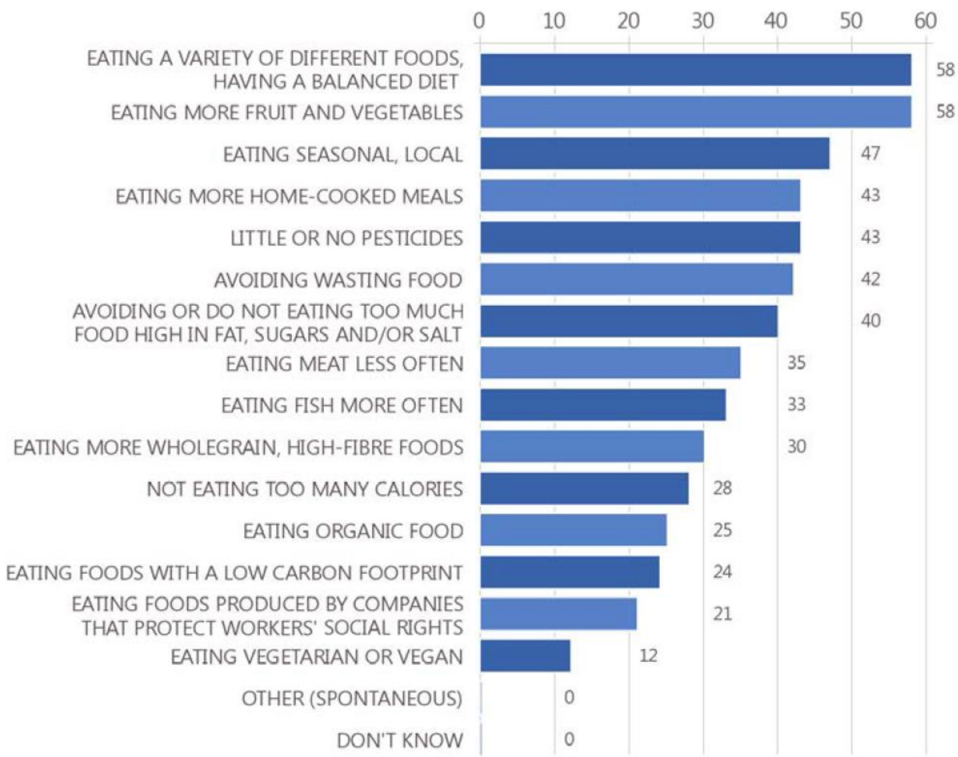


Figure 3-77: Answers to the question: What do you think "eating a healthy and sustainable diet" involves? (MULTIPLE ANSWERS POSSIBLE). In % respondents (Source: European Commission, 2020b)



Base: all respondents (n.= 27,237)

For consumers, transitioning to sustainable and healthy diets requires the adoption of new practices, with potential trade-offs with other characteristics of foods such as taste, price, social norms, convenience. Barriers to this transition towards healthier and more sustainable diets can be situated at the individual level (lack of motivation, lack of capabilities including financial). There can also be some barriers at contextual level, such as the lack of physical and social opportunities (availability of foods, visibility through notably marketing campaigns, social norms) (SAPEA, 2023). All these can at least partially explain why there can be a discrepancy between consumers' statements and the reality of the evolution of food consumption patterns.

However, recent nutrition studies observe some changes in European dietary patterns.

A recent cohort study conducted among 22 800 participants showed that **adherence to Mediterranean diet increased significantly among European adults over 50 years old between 2013 and 2019**, in most of the 13 European countries included in this study (Alves and Perelman, 2022). This trend was mainly due to the **growth in consumption of legumes, beans and eggs**, and to the **reduced consumption of animal proteins**. The authors however observed a slight decrease in the daily consumption of fruits and vegetables. This trend towards increased adoption of Mediterranean diet was higher among younger age groups, with higher income and tertiary education, and overall better self-perceived health (ibid.).

Dokova *et al.* (2022) conducted a narrative review of studies looking at food consumption data in various European countries between 1990 and 2020. They highlight **different changes in consumption trends across Europe, which, according to them, suggest changes towards adoption of healthier eating behaviours**. For example, between 2010 and 2019, sugar intakes have been reported to have decreased in many European countries (Spain, Italy, France, UK). Also, saturated fatty acids intakes decreased in Spain, Belgium, The Netherlands, remained stable in Italy and the United Kingdom, although they in Germany and Slovak republic.

There are also some recent examples of efficient public health strategies targeting dietary changes. In Finland for example, a prevention program aiming at reducing the prevalence of cardiovascular mortality was implemented in the 70's, focusing on lifestyle changes and in particular reduction of salt and fat intakes, and of smoking. Forty years later, the program proved effective, with **coronary mortality reduced by more than 84% from 1972 to 2014**, and about 2/3 of the mortality decline explained by risk factor changes (Puska and Jaini, 2020; Vartiainen, 2018).

Some consumers are **adopting more sustainable diets**, through individual behavioural changes, or by joining consumers' movements, consumers associations, etc. For example, in Germany, 11.5% of the population is vegan or vegetarian and their numbers are growing by more than 800,000 per year. It is estimated that, if that trend continues, by 2045 as many as 42% of Germans will have plant-based diets (IPES-Food & ETC Group, 2021). A very recent Finnish study identified **clusters of Finnish consumers who self-reported to have changed their eating patterns towards less red meat and more poultry or plant proteins** (Nevalainen *et al.*, 2023).

Other movements include for example community-supported agriculture, community gardens, organic food consumption; they are further described in Section 3.2 of this report.

3.4.1.3. Hypothesis of changes of diets in 2050 in Europe

Based on these trends, three hypotheses of changes in 2050 for diets in Europe have been drawn. In all three hypotheses, diets are part of chemical pesticide-free agri-food systems and thus are made up of chemical pesticide-free foods.

The detailed quantitative composition of these three diets in 2050 is presented in Chapter 5.

Hypothesis 1: BAU diets

In this hypothesis, in 2050 food diets in Europe follow 2023 trends, with only marginal changes in food consumption patterns.

In this ‘business as usual’ hypothesis in Europe, in 2050 European diets continue to be characterized by high levels of daily caloric intakes. They remain high but with stabilized (compared to 2023) consumption of animal products such as poultry or pork meat, eggs, and dairy foods, and of fat and added sugars and salts, with a high level of ultra-processed food.

A a result, combined with low levels of physical activity in urban environment, the increase of obesity and diet-related non-communicable diseases continue, and public policy objectives in terms of nutrition improvement, overweight and obesity rates stabilization are not met.

Hypothesis 2: Healthy diets

In this hypothesis, European food diets in 2050 evolve towards adoption of healthy diets.

In this evolution, given the increasing costs of treating the consequences of overnutrition and malnutrition, public health measures has been taken at European level to shift food consumption towards healthier and more diversified diets in order to address the major issue of malnutrition.

The healthy diet in 2050 is characterized by an improvement in the energy balance with reduced energy intakes, an increased food diversity, a high share of fruits and vegetables, as well as legumes and diversified cereals, and a low share of sugar, vegetable oils and animal-based foods, and a low consumption of ultra-processed foods.

This hypothesis of healthy diets has been developed in the Agrimonde-Terra foresight (Mora, 2018; Mora *et al.*, 2020) that has produced a scenario of "healthy diets", which has been recently reworked in the AE2050 study (Tibi *et al.*, 2020).

Hypothesis 3: One health diets

In this hypothesis, in 2050 European consumers shift towards diets that are both nutritionally and environmentally sustainable ("one health"). The transformation to One health diets by 2050 required strong dietary shifts, towards a diet rich in plant-based foods and with fewer animal source foods.

This hypothesis of dietary change mobilised is the "healthy diet from sustainable food systems", that has been produced by the EAT-Lancet Commission. The hypothesis that is also called FLEX diet (Willett *et al.*, 2019) consists of:

- Protein sources mainly coming from plants, legumes, nuts, fish, with optional consumption of meat products;
- Mostly unsaturated fat, from plant sources;
- Primarily whole grain sources of carbohydrates, and less than 5% energy from sugar;
- Minimum 5 servings of fruit and vegetable per day;
- Moderate and optional dairy consumption.

In Europe, this FLEX diet has an optimal caloric intake and is composed mainly of a diversity of plant-based foods, doubling in the consumption of healthy foods such as fruits, vegetables, legumes and nuts in comparison with 2023. It also contains low amounts of animal source foods, unsaturated rather than saturated fats, and limited amounts of refined grains, ultra-processed foods and added sugars.

From an environmental standpoint, the FLEX diet proposed by the EAT-Lancet Commission falls within the planetary boundaries framework, on six systems and processes affected by food production: climate change, biodiversity, land-system change, freshwater use, and nitrogen and phosphorus flows (Willett *et al.*, 2019).

3.4.2. Changes in agricultural equipment and digital technologies for cropping systems without chemical pesticides in 2050

This paragraph presents the hypotheses of change in 2050 for agricultural equipment and digital technologies. We try to answer the question: What kind of agricultural equipment and digital technologies is needed to develop cropping systems without chemical pesticides in 2050?

In the first part of the paragraph, we present a brief review of scientific literature and reports that we conducted for identifying trends and domains of change in agricultural equipment and digital technologies. The second part of the paragraph summarizes the hypotheses of change for agricultural equipment and digital technologies in 2050. The hypotheses are the result of a one-day workshop with an expert group on agricultural equipment and digital technologies that discussed the identified trends and then elaborated hypotheses of change in 2050.

These hypotheses were part of the elaboration of the scenarios of European pesticide-free agriculture (presented in Section 4.1).

3.4.2.1. Domains of transformation in agricultural equipment and digital technologies for the implementation of a pesticide-free cropping systems in 2050

First, an analysis was carried out to identify the **main transformations in agricultural equipment and digital technologies** likely to participate in the implementation of a pesticide-free cropping system in 2050. Three domains have been identified.

Observation and modelling systems

The first domain refers to **observation and modelling systems** designed to monitor and anticipate pest presence and the health of plants (Reboud *et al.*, 2022; Bellon and Huyghe, 2017)**.** These are observation tools such as sensors, drones, remote sensing instruments, crowdsourcing (gathering individual observations through a digital platform), as well as **data management** tools allowing in particular the interoperability of data, the crossing of sources and the spatialisation of data (Klerkx *et al.*, 2019; Machwitz *et al.*, 2021; Wolfert *et al.*, 2017). Then, **modelling** and simulation tools rely on big data, deep learning or mechanistic modelling to anticipate the future presence of pests (Reboud *et al.*, 2022; Klompenburg *et al.*, 2020).

Specific equipment

The second domain concerns **specific equipment** adapted to chemical pesticide-free cropping systems (Schnebelin *et al.*, 2021; Bellon and Huyghe, 2017). These are the ongoing development of **agricultural equipment** adapted to new crop management approaches (for example, the mixing of crops, or to reduce soils' compaction), precision agricultural equipment for the application of biocontrol products and the empowerment of equipment through to full **autonomy** (robots) (Keller and Or, 2022; Rose *et al.*, 2022; Duckett *et al.*, 2018; Lenain *et al.*, 2021; Bergerman *et al.*, 2016; Bournigal, 2014).

Dynamics of innovation

The third domain concerns the **innovation dynamics** that define the use of this equipment and technology. This innovation must be **co-constructed** between a multitude of actors, from farmers to equipment manufacturers, including local stakeholders (Salembier *et al.*, 2020; Toffolini *et al.* 2021). Data must be generated and processed on a **supra-farm scale**, which requires **data sharing** and **open data management** (Rizzo *et al.*, 2020). Data management and data processing, up to modelling and results diffusion can also be co-constructed. Finally, the cost and the specialisation of the equipment used call for a logic of **collective use** (Lucas and Gasselin, 2016; Tourdonnet *et al.*, 2018). Major challenges in innovation have emerged, such as the investment capacities of farmers, the impact of innovation on agricultural work, the place of farmers' skills in relation to what is delegated to technology (automation and robotisation; and sustainability of such technologies in terms of energy and resources consumption), and the sharing and ownership of data generated by farmers' practices (Rose *et al.*, 2021; Rizzo *et al.*, 2020; Nguyen *et al.*, 2020; Klerkx and Rose, 2020).

3.4.2.2. Three hypotheses of agricultural equipment and digital technologies in 2050 for implementing pesticide-free cropping systems

Based on the synthetic retrospective analysis presented in paragraph 3.4.2.1, an expert group discussed the identified trends and built long-term hypotheses of change for agricultural equipment and digital technologies for implementing pesticide-free cropping systems. The expert group comprised Baret Frédéric (INRAE), Gilliot Jean-Marc (AgroParisTech), Leclerc Melen (INRAE), Lenain Ronan (INRAE), Ienco Dino (INRAE), Naud Olivier (INRAE), Reboud Xavier (INRAE), Rizzo Davide (UniLassalle), and Vaudour Emmanuelle (AgroParisTech).

The three hypotheses of change for agricultural equipment and digital technologies in 2050 were built by providing information on the status of the three domains described above. Table 3-28 presents three contrasting visions of the relationship with farmers' techniques which differentiates between approaches centred on the modular adaptation of equipment to the cropping system, or on the pooling of data and equipment at large scales (landscape), or on the autonomy of machinery (robotisation) and the individualised treatment of plants.

First hypothesis: Modularity of equipment for their adaptation to practices

In 2050, agricultural equipment and digital technologies are modular and adaptable to the new cropping systems without chemical pesticides. The development of an architecture of modular equipment allows the farmer to combine and adapt machinery by considering the specificities of its cropping system (e.g. mixed cropping). This strategy aims at solving problems of the impact of heavier farm vehicles on subsoil compaction and of larger agricultural machinery on the increase of field (and farm) size, and to reverse classical top-down approach of innovation, by building smaller and modular machinery.

Modular equipment can mobilise limited automation of machinery with sensors, but farmers' decisions remain at the centre of the management cropping system. Farmers mobilise observation such as sensors, remote sensing instruments, crowdsourcing (share of direct observations) and modelling systems and predictive modelling designed to monitor and anticipate pest presence and the health of plants.

Modular agro-equipment has been development in places like Living Lab or third places that allows co-conception and experimentation of machinery, and involves a diversity of actor of the value chain. This conception process of designing technological blocks for modularity and adaptation goes beyond farm to address industry issues (e.g. traceability and post-harvest processing).

Second hypothesis: Pooling of equipment, sensors and data at the scale of landscapes or stakeholder organisations

In 2050, sensors and data at the landscape scale and agricultural equipment and digital technologies are based on data sharing and modelling tools for understanding the spatial dynamics of pests, and the pooling of equipment for intervention at the farm scale and beyond. The share of agricultural equipment is rooted in a specific organisation at landscape level or based on existing stakeholder organisation. The design of machinery is sharing-oriented, but machinery can include a part of delegation of agricultural practices to autonomous equipment with sensors such as companion robots.

The share of equipment answers a strategic issue that is to reduce risks at the landscape scale. The collective organisation around equipment aims to collect, share and couple diverse data from sensors, remote sensing, drones, sampling, crowdsourcing, and to use data for predictive modelling, phenotyping and visualisation tools that are designed to monitor and anticipate pest presence and the health of plants. Generating and processing data on a supra-farm scale requires data sharing, open data management and interoperability.

Such agro-equipment innovation has been co-constructed in an open innovation process between a multitude of actors, from farmers to equipment manufacturers, including stakeholders. Beside the collective organisation, a strong issue was the sharing and ownership of data generated by farmers' practices. Technological blocks of the farm machinery are designed for interoperability and cooperation. In addition, the cost and the specialisation of the equipment used by farmers call for a logic of collective use. Farmers rely on collective organisations or stakeholder organisations to provide diverse services of advice and crop management.

Third hypothesis: Autonomous robots to act on each plant

In 2050, autonomous systems act on each plant at the plot level. Reaching such situation has involved intermediate actors as equipment manufacturers, to build robots and swarms of robots.

Farmer's decisions are fully delegated to technology that combines automation with autonomy. Autonomous devices discriminate between the different crops in the plot. Using large database from real-time observation via sensors, with data from drones, remote sensing and sampling, and predictive modelling, robots implement an individualised treatment of each plant

This innovation emerged from a top-down process led by equipment manufacturers, including end-users (i.e. farmers). The implementation of these innovations by farmers has required strong investment of farmers, leaving many farmers aside. Major regulatory issues have been raised related to the competition of robots with human work, energy balance of digital technologies, and societal concerns about autonomous drones and robots.

Table 3-28: Hypotheses of agricultural equipment and digital technologies in 2050 for implementing pesticide-free cropping systems

Hypotheses for 2050 Domains	Modularity of equipment for their adaptation to practices 🡻	Pooling of equipment, sensors and data at the scale of landscapes or stakeholder organisations 🡻	Autonomous robots to act on each plant 🡻
Observation and modelling systems	Sensor/satellite/sampling networks with data coupling Spatialised and long time series data Predictive modelling	Sensor/satellite/sampling networks with data coupling Spatialised and long time series data Predictive modelling Phenotyping Visualisation tools	Sensor/satellite/sampling networks with data coupling Real-time observation via sensors and drones Data-centric modelling Predictive modelling Phenotyping
Specific equipment	Equipment adapted to new cropping systems (e.g. mixed and inter- cropping) Modular equipment Automation (without autonomy) of equipment with sensors	Equipment sharing Design of sharing-oriented equipment Strategy to reduce risks at the landscape scale Automation: scope of the delegation of practices to equipment with sensors	Automation with autonomy: robotisation, swarms of robots Autonomous devices to discriminate each plant in the plot Full delegation to technology
Innovation dynamics	Living Lab and third places (experimentation) Design of technological blocks for modularity and adaptation, to address industry issues: traceability and post-harvest processing Multi-stakeholder organisation, at the value chain level	Open innovation with open data and interoperability Design of technological blocks for interoperability and cooperation Provision of services Organisations at the landscape or territorial scale, or stakeholder organisations	Role of intermediary actors (equipment manufacturers) Regulatory issues, related to agricultural work, energy consumption and societal concerns

3.4.3. Educational and agricultural knowledge and innovation systems for chemical pesticide-free agriculture in 2050

This paragraph presents the results of a foresight work on Educational and agricultural knowledge and innovation systems (AKIS) in 2050. We try to answer the question: What kind of education and AKIS could support a transition towards pesticide-free agriculture for the different scenarios of pesticide-free agriculture?

In the first part, we present the results of a review of scientific literature and reports that we conducted, for identifying current trends in education and agricultural knowledge and innovation systems in the EU. The second part summarize *ad hoc* hypotheses for education and AKIS in 2050, which could support a transition towards the scenarios of European pesticide-free agriculture (see Section 4.1). The hypotheses were built through a one-day workshop with researchers' specialists of this domain and mobilised a backcasting approach (see Chapter 1; Table A3 in the Appendix of the report).

This work was part of the elaboration of transition pathways (presented with the scenarios in Section 4.1) towards European pesticide-free agriculture.

3.4.3.1. Educational and agricultural knowledge and innovation systems: Situation and trends

The development of a chemical pesticide-free agriculture needs to implement specific and consistent practices at farm and food system levels. Education and Agricultural Knowledge and Innovation System (AKIS) can play a central role in supporting innovation and learning at the farm and food system levels. AKIS is a notion that 'describe a system of innovation, with emphasis on the organisations involved, the links and interactions between them, the institutional infrastructure with its incentives and budget mechanisms' (EU SCAR, 2012).

This review is based on recent synthesis on Education and AKIS such as: the results of two European projects on AKIS, PRO AKIS and i2connect (Knierim *et al.*, 2017; Labarthe, 2016; Prager *et al.*, 2015; Birke *et al.*, 2022), the SCAR synthesis and report on the future of AKIS in EU (EU SCAR, 2012; EU SCAR, 2019), and specific scientific reviews and synthesis articles (Bazoche *et al.*, 2022; Klerkx *et al.*, 2019; Klerkx, 2020; Fielke *et al.*, 2020). This review of current trends in AKIS was mobilised for discussing and building, through a specific expert group, long-term hypotheses of change for Education and AKIS in order to achieve pesticide-free agriculture in Europe in 2050.

A brief history of AKIS and the current trends in AKIS

The field of agricultural research, education and extension correspond traditionally to systems of research, education and advisory services that support learning and advice farmers. Extension is defined by Christoplos (2010) "*as systems that should facilitate the access of farmers, their organisations and other market actors to knowledge, information and technologies; facilitate their interaction with partners in research, education, agri-business, and other relevant institutions; and assist them to develop their own technical, organisational and management skills and practices*".

Agricultural knowledge and innovation system (AKIS) is a new concept which appeared in the last decade in EU, that refers to the cooperation of actors from extension, research, professional organisations and also includes other stakeholders such as "*input suppliers, food processors, retailers, consumers*" and various supporting services such as "*accountants, banks, media*" (Knierim *et al.*, 2015). The term AKIS aims to describe the *plurality* of research, education and extension services that support *innovation processes*.

Historically, agricultural education and extension services have played a major role in agriculture modernization. As such, advisory services, which were mainly based on public organisations or public investments with diverse structures in Europe, have supported, after the Second World War, a dynamic of technological change towards cropping systems notably relying on chemical pesticides. Since the 1980s, Labarthe (2016) and Faure *et al.* (2012) identified the major transformations of national advisory services in three main directions.

- First, advisory services that have been historically based on advisers' skills and on direct interactions between farmers and advisors are increasingly using *digital technologies* both in interaction between farmers and advisers (described as *front-office*) and in the contribution of advisory systems to research and development activities (*back-office*).
- The second point is the emergence of new economic models of advisory services. With the partial withdrawal of the State from farm advisory systems, diverse dynamic are occurring including a reduction of public finance to national advisory system in many European countries and a development of private advisory services which commercialise services to farmers. The governance of advisory systems is also evolving with an increasing role of regional scale in implementing farm advisory systems.

- The third point relates to the directionality of the innovations processes pushed by the AKIS. New demands from farmers, private actors, public policies and citizens influence advisory systems in order to support changes that answer global concerns (e.g. by developing agroecology).

We will now analyze separately these three trends of AKIS: a plurality of AKIS, a digitalization of AKIS, and the support of AKIS to a transformational change.

A plurality of AKIS in EU

A study conducted through the PRO AKIS project shows a wide diversity of AKIS and agricultural advisory service providers across Europe, depending on institutional situation, actors and needs (Prager *et al.*, 2015; Knierim *et al.*, 2017). Figures 3-78 and 3-79 display examples of AKIS and advisory services in the Republic of Ireland and in France.

Figure 3-78. AKIS and advisory services in the Republic of Ireland (From Prager and Thomson, 2014)

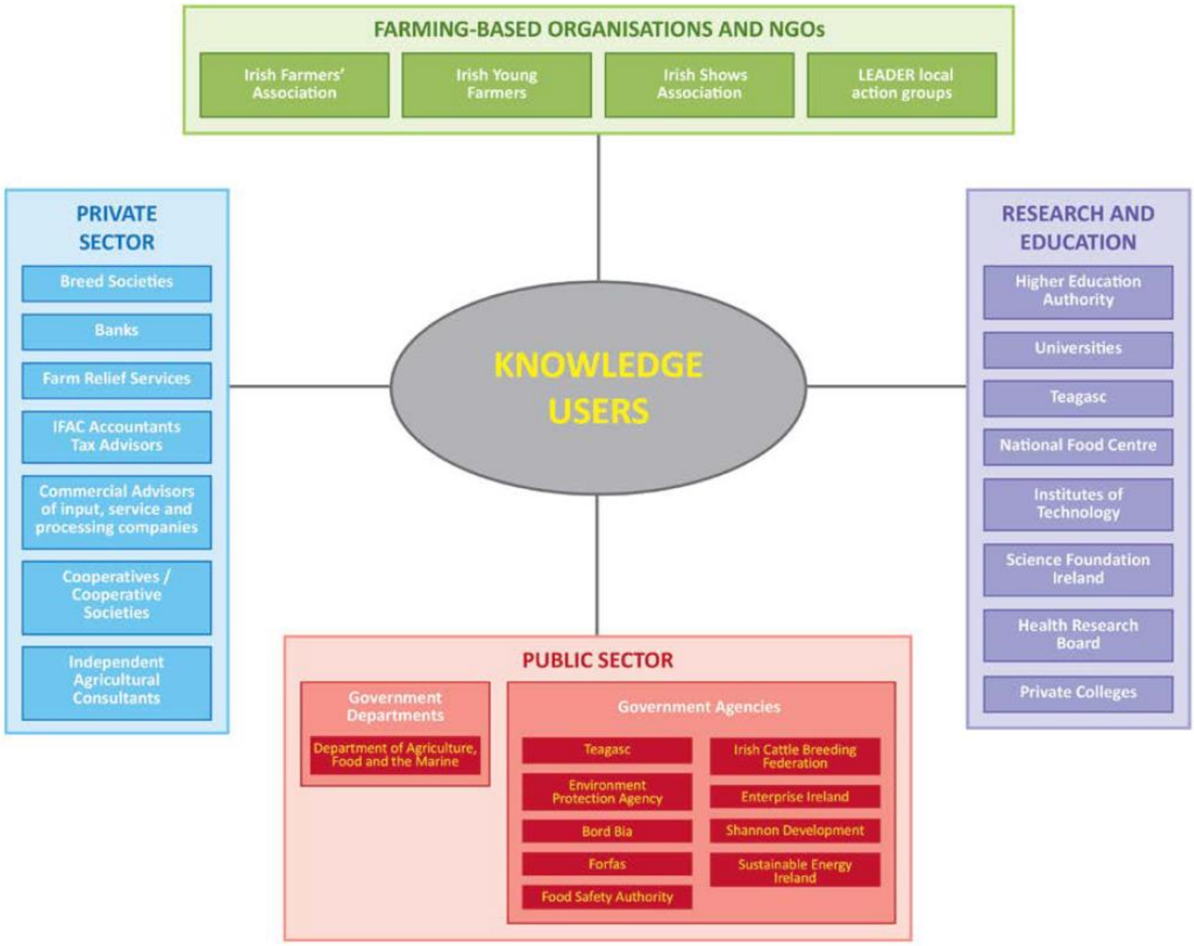
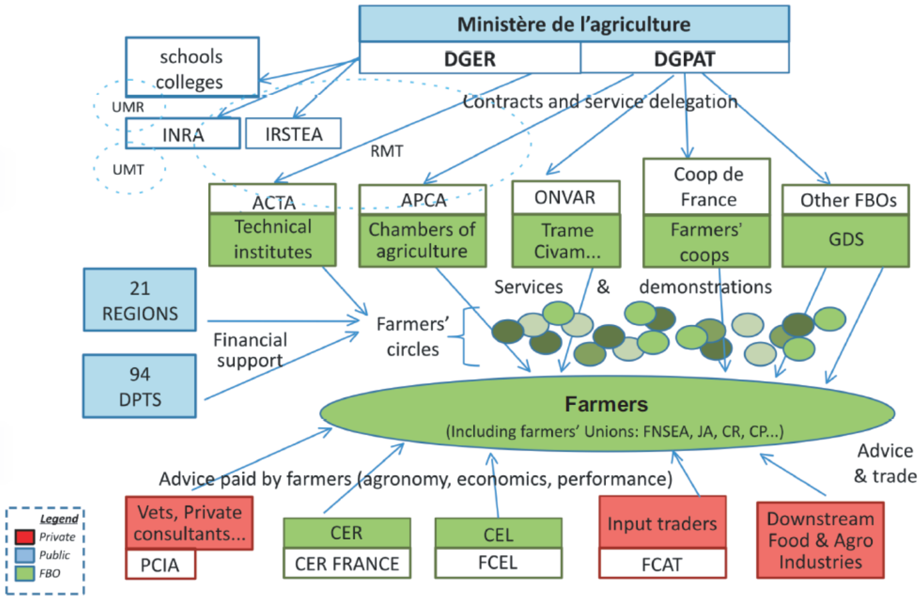


Figure 3-79. AKIS and advisory services in France (From Labarthe, 2014)



FBO: Farmer-based organisation

Generally, the public sector is a provider of information, advice and funding. Education and research institutions create knowledge and generate innovation, provide education and, in some countries, advice. The private sectors is strongly present in Europe through private and independent advisors (e.g. in Italy), big organisations (e.g. in Sweden), or farmer-based organization (e.g. in Finland) (Prager *et al.*, 2015). Pluralism of agricultural services providers in Europe is widespread. To illustrate the diversity of AKIS, we present below AKIS and advisory services in France and in Ireland. There is a strong institutional plurality of actors in National AKIS across EU.

During the last decades, the changes in AKIS in Europe were characterized by increasing commercialisation of services and privatization of public actors. Public funding is now more oriented towards supporting partnerships for advisory services and processes of innovation, than towards direct funding of national systems of agricultural advisory services (Prager *et al.*, 2015). This dynamic led to a *fragmentation* of agricultural advisory services in EU that is visible in Greece, Portugal, Italy and Spain for example. There is also a strong competition between diverse advisory organisations and we see the emergence of new actors like ngo and industries (ibid.).

Being a part of the AKIS, agricultural advisory services correspond to "*entire sets of organisations that enable the farmers to co-produce farm-level solutions by establishing service relationships with advisers so as to produce knowledge and enhance skills*" (Labarthe *et al.*, 2013). Knierim *et al.* (2017) defines five types of organizations providing agricultural advisory services in Europe, which are public authorities, public research and education, private advisory organisations, farmer-based organisations and non-governemental organisations. Using this typology, a recent European study (Birke *et al.*, 2022) shows that, in half of EU countries, public and farmer-based services are dominant providers of agricultural advisory services (Table 3-29). Combinations of the various dominant forms of advisory organisation are found in one third of the countries including federal or decentralised countries such as Belgium, Germany, Italy and Spain. Farmer-based organisations like the Chambers of Agriculture play a major role in one third on the countries, and are present in 13 European countries, but they are not necessarily the dominant form of advisory services.

Knierim *et al.* (2017) discuss the impacts of the expanding plurality of actors entering in the landscape of agricultural advisory services by underlying two points. First, the authors suggest advantages of the pluralism of agricultural service providers as "*it results in a wider variety of both staff organization and service relational with clients, which increase choice options*" and note that specialization of providers can answer new needs expressed by client groups. Second, they underline that the privatization of services could leave specific category of population at a disadvantage. While medium and large-scale farms are widely addressed, other farm groups receive less or no attention from any provider (Knierim *et al.*, 2017).

Table 3-29. Dominant actors interacting with farmers (From Birke *et al.*, 2022)

Dominant actors interacting with farmers	Countries or regions
Public organisation	Bulgaria, Cyprus, Hungary, Ireland, Latvia, Lithuania, Croatia, Serbia, Montenegro, Switzerland
Farmer-based organisation (FBO*)	Austria, Denmark, Finland, France, Portugal, Sweden, Poland, Slovenia, Belgium-Flanders
Private advisory organisations	The Netherlands, Greece
Public and FBO	Luxembourg, Malta
Public and private advisory organisations	Belgium-Wallonia, Czech Republic, Estonia
Public, FBO and private advisory organisations	Germany, Italy, Spain, Slovakia

*including agricultural chambers

The digitalisation of AKIS

Klerkx *et al.* (2019), conducting a scientific review, identified how digitalisation can be a major driver of evolution of AKIS. First, innovation processes are changed by digitalization, e.g. by incorporating big data analysis. Emerging digital agricultural is diversifying the actors of AKIS; new actors entering the system such as high-tech firms like drones or satellite manufacturers, service industries, and agricultural equipment manufacturers producing self-driving tractors for example. Regarding the critical importance of data in digitalisation and its potential disruptive role, there is a general ethical issue about data generation, data ownership, inclusion and exclusion, and privacy (ibid.). Some authors are considering how the concept of Responsible Research Innovation (RRI) could apply to deal with these ethical issues. And Labarthe concludes an article on AKIS by noting that "*the effects [of digitalisation on AKIS] will depend on the type of partnership that supports the construction of digital tools, the more or less open and transparent nature of the knowledge bases that feed them, and their ability to be inclusive tools that can be used by everyone*" (2016).

The potential role of digitalisation for the circulation of knowledge is high. Digital platform enable local and global share of information and peer-to-peer learning (Klerkx *et al.*, 2019). Agricultural advisory services that are built on the advisers skills and the interactions between advisers and farmers use increasingly digital tools both in front-office activities (interactions between farmers and advisers) and in back-office activities (interactions with networks of R&D). These digital interactions results in new skills for farmers and advisers, which link better data to decision making by the farmer. The advisor becomes a *sense-making* of digital data; his *back-office* role evolves from gathering information and conducting field experiment to data computation and interpretation (Eastwood *et al.,* 2019). According to Labarthe (2016), in specific conditions (mentioned above), the development of digital agriculture could provide advisers, farmers and researchers tools and shared databases to make better agronomic diagnoses and devise new technical solutions together. Digitalisation could help to reconnect research and knowledge system to advisory services, and make advices more accurate to the farmer situation and its objective.

In a recent scientific review, Fielke *et al.* (2020) identify five major trends linked to digitalisation (see Table 3-30): (i) diversification of information seeking behaviours and knowledge production processes by actors in agriculture; (ii) the increasing specialisation of decision-making expertise within complex advice networks; (iii) the privatisation of advice; (iv) the commodification of agricultural data; and, (v) the emergence of novel supply and service gaps in the system. The authors underline an "overarching" issue that is the need to "*includ[e] users and agricultural advisory service stakeholders in the process of design[ing]*" digital tools.

Table 3-30. Trends in agricultural knowledge and advice networks (Simplified from Fielke *et al.*, 2020)

Major trends	Sub-trends [Source/s cited by Fielke *et al.*, 2020]
Diversification of information seeking behaviours and knowledge production processes by actors in agriculture	**Continued one-to-one interaction**, farmer-to-private agricultural advisory services although some farm types may not be serviced (e.g., smaller farms and those with reduced ability to pay for services) [Labarthe and Laurent (2013); Prager *et al.* (2016)] **One-to-many interactions** increasingly conditioned on other trusted agricultural advisory services relationships [Sutherland *et al.* (2013)] **Information-seeking behaviours** move toward global sources of information [Prager *et al.* (2017)] Farmer-based agricultural advisory services continue to be important for **knowledge cocreation/experimentation** [Eastwood *et al.* (2017b)] **Group-based co-learning service** delivery supported by on-line interaction – particularly in public agricultural advisory services – **co-production of knowledge** between farmers and advisor's a prerequisite for developing solutions that are relevant/consistent with farmers' contexts/objectives and building/maintaining mutual trust [Klerkx and Jansen (2010); Rijswijk and Brazendale (2017)]
Increasing specialisation of decision-making expertise within complex advice networks	Professionalisation of agriculture [Murphy *et al.* (2013)] Recognition of **increasing complexity of multiple rural land management objectives** [Eastwood *et al.* (2017b); Phillipson *et al.* (2016)] Increasing **data/technical intensity** of decision making [Janssen *et al.* (2017); Nettle (2017); Nettle *et al.* (2018)] Increasing data-based as opposed to process-based decision making [Lioutas *et al.* (2019)] Greater **specialisation and diversification of service providers** – results in varying quality of services and clients targeted [Knierim *et al.* (2017)]
Privatisation of advice	Individual profit motive dominates rationality of **agricultural advisory services** with **fragmentation due to market and technology-based specialisation** [Fielke and Wilson (2017); Eastwood *et al.* (2017b); Paschen *et al.* (2017)] **Advice must provide/add value and maintain legitimacy** – co-benefits of advice (information, networks, technology) must be evident and advisors are now an input cost – as a result advice also needs to fit into/guide farm business plan/strategy [Robertson *et al.* (2016)]
The commodification of agricultural data	Culture of **intellectual ownership** [Klerkx and Nettle (2013)] Lack of institutional support for coordination of responsibilities of private **governance of natural resources** [Rijswijk *et al.* (2018); Taylor and Van Grieken (2015); Wang *et al.* (2017)] Internationally, **vertical integration of dominant players in the knowledge supply chain** – data through to analytics [Bronson (2018); Carolan (2018)] Data privacy/management debates about **who benefits in the agricultural space – open, closed, public, private** etc [Wiseman *et al.* (2018); Wolfert *et al.* (2017)]
The emergence of novel supply and service gaps in the system	Public agricultural advisory services unable to economically support agricultural sector beyond market failures [Hunt *et al.* (2014); Robertson *et al.* (2016)] Increasingly demanding **consumers, private organisations in the value chain, civil society and NGOs, and governments** [Fielke and Bardsley (2015); Murphy *et al.* (2013)] Counter-trend of niche **high-quality production to capture ethical values** [Fielke and Bardsley (2013)]

AKIS and education for transformative change

Some conceptual approaches define AKIS as a "*capacity-oriented perspective where the individual actors' abilities to shape promising transformational change through intentionally targeted strategic planning and decision-making in the AKIS contexts take centre place*" (Toillier *et al.*, 2022). This approach has justified a shift in AKIS from an approach centered on *infrastructures* to an approach centered on *innovation processes* designed to support a transition of agriculture towards better integration of sustainability issues (Labarthe, 2016). There is a need to address complex challenges mixing climate and ecosystem changes, economic imperative, changes in food systems and societal expectations, by conducting transitions towards sustainability in agriculture. The objective of such approach of AKIS is to redefine the nature of solutions that advisors propose to farmers.

As we know, there are different form of agricultural transition towards agroecology and chemical pesticide-free agriculture. These various transition calls for various form of advisory systems to support the transition, and for example we know that the re-conception of agricultural systems will require a more personalized technical support (Labarthe, 2016). The expanding pluralism in AKIS could be seen as a favorable trend for supporting transitions, as it could give birth to a landscape where creative advisors would imagine a diversity of services and facilitate farmers' access to relevant knowledge. But as Labarthe also note, within the framework of this pluralism, large firms could impose the same bases of knowledge to a diversity of advice providers (ibid.).

Bazoche *et al.* (2022) identify some specific AKIS elements that could support a transition towards chemical pesticide-free agriculture. Situational learning, based on the analysis of problems and innovations encountered by farmers is often seen as an important aspect of training. This group learning is likely to develop mutual support between peers, encourage the adoption of new practices, and stimulate exchanges on possible solutions and the potential difficulties of implementing them. Specific advice, called *experiential learning*, can facilitate dialogues between farmers, help to bring accurate knowledge, to develop appropriate solutions. For building an AKIS supporting such a transition, the authors note that the *back-office* should be strengthened in order to provide *front-office* advisors with the local references needed to disseminate new practices (ibid.).

As part of AKIS, living labs are seen as specific organisations that could deal with the complexity of issues arising and engage a transition process in agriculture. Indeed, answering complex challenges requires action including many different actors such as farmers, input suppliers, technology developers, researchers, agricultural advisors, policymakers, citizens and consumers (Potters *et al.*, 2022). Living labs appear as an accurate approach "*to enable and stimulate innovation in these complex, multi-stakeholder settings*" (ibid.). Living labs are characterised as open innovation processes bringing together public and private users and stakeholders, integrating research and innovation processes to co-create, validate and test new services, business ideas, markets and technologies in 'real-life' contexts. Participation, co-creation and co-design, end-user approach, open innovation, experimentation in real-life are the main characteristics of the living labs, that answer to the increasing distance often noted in the various national AKIS assessments between research and advisory services.

In the last decade, *agroecosystem living labs* were developed in Europe "*as a way to stimulate faster adoption of innovation aimed at the sustainability and resiliency of agriculture and agri-food systems*" (McPhee *et al.*, 2021). For the authors, agroecosystem living labs "*have the potential to accelerate co-creation and adoption throughout the value chain, because of their user-centric approach used to develop and co-create innovative solutions in partnership with stakeholders and tested in the users' real-life context*" (ibid.). Trying to specify agroecosystem living labs, the authors identify three characteristics: sustainability, complexity, and place-based context (ibid.). The importance of the place-based context "*stemmed from the embeddedness and functioning of the agroecosystem living lab in the agriculture and agri-food systems which brought to the table a multiplicity of complexities unseen in other living labs because of the interconnectedness of systems and contexts*" (ibid.).

In a recent article summarizing the outcomes of the European project AgriLink Living Lab, the authors underline the interest of Living Labs for dealing with specific AKIS issues: "*Living Labs can be a suitable setting for co-creating tailor-made innovation support services that fill gaps in the AKIS with respect to complex sustainability challenges*" (Potters *et al.*, 2022). In a more general way, they insist on the capacity of Living Labs to strengthen AKIS through *contextualization* and *democratization*: "*With new relations, increasing trust, the combination of explicit, implicit and tacit knowledge and new emergent understanding, Living Labs can be a vehicle for the contextualisation, democratisation and strengthening of the AKIS*" (ibid.).

Education in agriculture should also evolve to support such transition towards sustainability. Bazoche *et al.* (2022) point out several elements. First, there is a need to develop *interdisciplinary education* activities that enhance knowledge and capacities of farmers and advisors to develop chemical pesticide-free agriculture. Second point, while the practices of pesticide-free agriculture are often stemming from farmers pioneers' practices and varying from one area to another, the teaching currently given is only based on established scientific facts and tested methods. It might be good to imagine new ways of teaching these elements as they are still under construction, by relying more on innovative farmers and adapting the elements to the diversity of locations. Third point, agricultural training courses should better enable farmers to acquire skills for *managing uncertainty*, *assessing risks* and *undertaking transitions*, which are essential skills for farmers (ibid.).

3.4.3.2. Hypotheses of change for Educational and agricultural knowledge systems in 2050

Based on the synthetic retrospective analysis presented in paragraph 3.4.3.1, an expert group discussed these trends and built long-term hypotheses of change for Education and AKIS to support a transition towards European pesticide-free agriculture in 2050. The expert group comprised Bujor Oana (USAMV), Carlesi Stefano (SSSA), Ciceoi Roxana (USAMV), Christensen Henriette (PAN), Lamine Claire (INRAE), Loconto Allison (INRAE), Matt Mireille (INRAE), Möhring Niklas (CNRS), Raineau Yann (INRAE) and Robinson Douglas (INRAE).

Within the expert group, a preliminary discussion started to determine if we should build Education and AKIS hypotheses for each scenario or for all the scenarios. The discussion began by underlying what could be common to all the scenario. Some participants insisted on the use of big data in agriculture and the idea that the AKIS should be oriented towards more intensive use of data and technology. Others participants argued that it should be more knowledge intensive (farmers), based on bio-pesticides (nature-based solutions) and should include a larger view of what is technology and innovation (more oriented towards adaptative management and new crop practices).

Finally, we decided to work separately on each scenario. The result of the workshop is presented in a synthetic way in the Table 3-31 and in the paragraph below in the form of short narratives.

Table 3-31: Hypotheses of Education and Agricultural knowledge and innovation system in 2050 generated during the transition experts group workshop (15th May 2023)

	Hypothesis 1 (corresponding to scenario 1*)	**Hypothesis 2 (corresponding to scenario 2*)**	**Hypothesis 3 (corresponding to scenario 3*)**
Education	-Techno-centric agricultural education system (public & private) -Computer engineering as core training in agricultural schools, and conversely -Intensive exchange and mobility programs for students / masters from less technologized countries towards the high tech companies that provides solutions for agriculture -Increasing the competencies in novel technologies and how they can best be used -Intensive life-long adult learning programs for farmers on the use of new technologies / automations	-Radical re-orientation of education at all levels towards a new "microbiome interaction" paradigm. -Training in agroecology as core of agronomy -Education of farmers closely related to public research	-Training of agricultural engineers to know alternative approaches to co-create -Farmer education on landscape management -Training in agroecology as core of agronomy -Engaging consumers in AKIS around producing knowledge linked to the territory -Large awareness campaigns on social media about the importance of biodiversity, at and for every education level In the education curricula, farm-based learning and training experiences should be introduced from the 1st level of education (e.g. Farm days, practice days in farms) -Sensitizing the local inhabitants about local food production
Research and innovation	-User-lead R&I -Closer connection between consumers and AKIS -Responsible Research and Innovation (RRI) in universities -Large public research organization connected to big players dealing with big data issues (property, access, etc.) -Building up a network of testing fields (research stations and universities) for the new seeds / new inputs -Interactive innovation: researchers respond to farmers' problems *-Open data - if the scenario is fair and equitable*	-Standardized procedures for the approval of new microbial based products especially for food conservation -Intensive research on the long term effects and impacts of the newly developed microbial inoculants -Interactive innovation: researchers respond to farmers' problems -Changing incentives in public research sector towards more multi-disciplinary, more multi-activity with stakeholders	-Local science, society relations -Emphasis of citizen science involvement in sciences, especially in projects related to biodiversity -Territorial network of demonstration farms / living labs for diversification of crops, biodiversity enhancing practices -Research with farmers on-farm (real fields conditions) Interactive innovation: researchers respond to farmers' problems

Table 3-31 (continued): Hypotheses of Education and Agricultural knowledge and innovation system in 2050 generated during the transition experts group workshop (15th May 2023)

	Hypothesis 1 (corresponding to scenario 1*)	**Hypothesis 2 (corresponding to scenario 2*)**	**Hypothesis 3 (corresponding to scenario 3*)**
Extension and advisory systems	-Development of private advice -Dedicated advisory systems on how to access to external capital and how to deal with -Massive reconversion of farmers and AKIS actors towards new technologies and tools, and related understanding of training needs and social risks (unemployment? reconversion outside agriculture?) *-Or: build up a totally new AKIS system for the remaining family farms*?	-Agricultural knowledge system -> food systems knowledge systems -Extending the AKIS to the whole food system -Farmers to farmers sharing platforms -Knowledge infrastructure for exchange on plant, soil, food microbiomes, at EU level -Maintaining the diversity of types of advice: public – private – civic -Private consultancy: start-ups with new technologies for monitoring, sensors providing advices	-Localized AKIS in local context (specialized universities, extension services, advisors) -Networks of localized educational and experimental centres, sharing contextualized "case studies", trajectories, organizational innovations, etc. through shared observatories -Farmers to farmers sharing platforms -Platforms, networks: European platform to exchange local experiences and knowledge (public funding, farmers to farmers); Scale-up and scale out best practices; Regional and public extension services that cooperate -Maintaining the diversity of types of advice: public – private – civic

*The hypotheses correspond to the scenarios described in Section 4.1

Hypothesis 1: Educational and agricultural knowledge and innovation system based on data management and robotisation

Educational and agricultural knowledge and innovation system are data-centric (more than user-led) and focus on computer science, robotisation and data management. Private research and big players mainly dominate AKIS, but large public research organisations are dealing with data issues in relation to big digital companies. Private extension services (including agricultural advisory system dedicated to access to external capital) give advice to large farms. Intensive life-long adult learning programs help farmers to build knowledge and practices on the use of technologies, automation and robots.

Hypothesis 2: Extended educational and agricultural knowledge and innovation system to the whole food chain and focused on microbiomes

In 2050, educational and agricultural knowledge and innovation system are extended to the whole food chain and includes all the actors and activities of the food chain. The knowledge system focus on microbiomes. Public and private research partnership built new infrastructures of data and knowledge on plant holobiont, soil microbiome, food microbiome and human microbiome (including nutrition), and assess the impacts of microbial inoculants. Learning processes of farmers are achieved through education, public advice and private consultancy (start-ups) on news technologies such as monitoring, sensors and crop management, and through farmers to farmers sharing platform.

Hypothesis 3: Localised Educational and agricultural knowledge and innovation systems

In 2050, educational and agricultural knowledge and innovation systems are localised and adapted to local context, with small and embedded universities. These agricultural knowledge and innovation systems include small companies, inhabitants, and consumers. Living labs are key in the innovation processes. They work on co-creation and knowledge construction about crops diversification, landscape design, and practices enhancing biodiversity. Training of agricultural engineer and advisors focus for co-creation of knowledge with farmers. Farmer education deals with landscape management and agroecology. Farmers to farmers sharing platform accelerate a learning process at farm level. To reinforce knowledge building, local centers are well connected in a European network.

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Section 3.1

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Section 3.3

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Section 3.4

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European Chemical Pesticide-Free Agriculture in 2050

Chapter 4

European scenarios of pesticide-free agriculture in 2050 and their transition pathways, at European and regional levels

Table of contents

Introduction

Based on the hypotheses of change drawn for the different components of the food systems in 2050 presented in Chapters 2 (Section 2.6) and 3, three scenarios were built through a morphological analysis. Then, using a backcasting approach, we have drawn transition pathways for each scenario at the European level. In parallel, these three scenarios were downscaled for specific cropping systems and regions in four European regions.

In this Chapter, we present first the European scenarios and transition pathways leading to European chemical pesticide-free agriculture in 2050 (Section 4.1), and then the four regional case studies conducted in Italy, Romania, Finland and France (Section 4.2).

The scenarios and transition pathways were built by the European experts committee of the foresight and a dedicated group of experts on transition, and *ad hoc* groups of local experts for each of the four regional case studies.

4.1. Scenarios of pesticide-free agriculture in the EU in 2050 and their transition pathways

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Table of contents

Introduction

Section 2.6 of this report was devoted to the construction of hypotheses defining cropping systems without chemical pesticides in 2050. In Section 2.6, the foresight analysis was focused on identifying possible breaks in crop protection by 2050 that make it possible to imagine chemical pesticide-free crop protection systems. To achieve this, three approaches allowing us to rethink the relationship between cultivated plant(s) and pests were suggested. The first considers a cultivated plant as a living being with its own capacities (plant immunity approach). The second considers the individual formed by the cultivated plant and its interactions with microbial communities (holobiont and microbiota approach). The third considers cultivated plants and pests within a web of relationships with multiple entities at the landscape scale (landscape approach). Based on these approaches, three crop protection systems have been developed involving different modes of interaction with the environment (see Section 2.6). However, at this stage these protection systems have been defined *in abstracto* independently of their insertion in a socio-technical network comprising farms and both upstream and downstream sectors which, from collection to consumption via processing, trade and distribution, define the nature, destination and use of agricultural products.

In order to complete this initial approach, in the various Sections of the Chapter 3 we examined the other components of the system by considering farms, value chains and public policies, as well as diets, agricultural equipment and digital technologies. The future state of these components by 2050 has to be considered. For each component, three hypotheses of changes in 2050 have been constructed. These hypotheses are particularly important at the time of defining favourable conditions for the emergence of agriculture which eschews the use of chemical pesticides.

Here in Section 4.1, we assemble these hypotheses by developing images of what European agriculture without chemical pesticides could be in 2050, as well as imagining transition pathways that could lead to it.

4.1.1. The logic of scenario construction

Using the hypotheses developed separately in previous Chapters, the first step is to reconstruct several integrative images of European agriculture without chemical pesticides. This approach aims to reconstruct the entire system from the sum of its parts, making a number of additional hypotheses about what connects them. It is a systemic approach that positions the pesticide-free cropping system within a web of interrelationships with the multitude of actors that constitute the food system. The objective of this approach is to identify the systemic relationships that make pesticide-free agriculture possible and thereby define the conditions conducive to its emergence. This important point deserves to be clarified and deepened by an examination of the theory of the sociotechnical network.

Through having a connectionist conception of innovation, the notion of the sociotechnical network (Callon, 1984; Latour, 2005) makes it possible to overcome a double *aporia* when reflecting on innovation towards agriculture without chemical pesticides. This consists of imagining either that agricultural technologies alone could produce pesticide-free agriculture or, conversely, that the transformation of value chains and markets would be sufficient to bring about agriculture without chemical pesticides. In the sociotechnical network, the innovation process engages all human and non-human actors in a dynamic of mutual construction and definition (Akrich, 1992; Latour, 2005). The actors (as well as techniques and the objects circulating between them) are constructed simultaneously through reciprocal adjustments (ibid.). So, for example, the organisation of markets influences cropping systems, while cropping systems exist through their inscription in value chains that enable their products to reach the consumer. And cropping systems also rely on specific ecosystems.

In a systemic approach, we assume that the transition to chemical pesticide-free agriculture requires a simultaneous transformation of different segments of the value chain, as well as agricultural production and agriculture's upstream sector. Furthermore, systemic large-scale transformations of food systems are envisaged in the scenarios that we have developed.

4.1.2. The scenario construction method

4.1.2.1. The production of a morphological table and its use

To construct the scenarios, a method has been implemented which includes a morphological table and a European expert committee.

The morphological table is a heuristic tool that makes it possible to define a multiplicity of scenarios in a coherent and comparable way (Alvarez and Ritchey, 2015). Each line of the table describes the alternative hypotheses of change in 2050 for a component of the system. Therefore, the combination of hypotheses of change for each component of the system describes the state of the system in 2050 (Table 4-1). The morphological table is a matrix describing all the states of the system in 2050 in the form of combinations of hypotheses of change (developed in the previous stages). Therefore the morphological table contains the *morphological space* that describe the possible changes of the system, i.e. all the states of the system which can be generated from the parameters of the table (i.e. the hypotheses of change). However, in this morphological space, a very large number of states of the system do not make sense, because they present incoherent or impossible forms (ibid.).

In addition, the morphological table is only a means, a support for reflection. We must add the judgments of experts to arrive at scenarios. Indeed, all the randomly generated states of the system are not equally plausible, some of them are not plausible at all. It is the in-depth knowledge of the expert group that makes it possible to select the combinations of hypotheses that make sense (Ramirez and Selin, 2014). A few criteria are used to guide the development of scenarios. Firstly, the scenario must have *internal consistency*. In other words, the combination of hypotheses must have a logical coherence and hypotheses must not be contradictory to one another. Then the scenario must have *empirical consistency*, i.e. the scenario must not appear empirically impossible or be based on highly implausible combinations of hypotheses (Johansen, 2018). Another way of formulating the same requirement is to say that the scenario must be *plausible*. This means that there must be knowledge in the present that can constitute the premises of such a future, and that the causal patterns and underlying hypotheses are plausible (Mitter *et al.*, 2019). Finally, the scenarios must be *relevant* and *creative* with regard to the question posed to the foresight study, in particular by proposing new and original perspectives (Amer, 2013).

Finally, there must be a sufficient *contrast* between the scenarios in order to describe the wide field of possibilities. Scenarios must not be simple variations on the same theme but must be structurally different so that their diversity covers the field of possible evolutions of the system being studied (Amer, 2013). The aim here is to show the diversity of possible developments leading to European agriculture that is free of chemical pesticides.

4.1.2.2. Steps in scenario creation

Based on previous work, the morphological table was finalised in January 2022. Based on this, the European expert committee's fourth meeting (14th January 2022) constructed several scenarios by combining hypotheses of change. By focusing on the meaning of the scenarios and the contrasts between them, the project team reworked three scenarios. These were discussed by the European expert committee on June 28th in order to clarify their meaning and the internal articulation of the hypotheses. The scenario narratives were then finalised by the project team and validated by the European expert committee on 21st October 2022.

4.1.3. The selection of hypotheses defining the scenarios

The morphological table below (Table 4-1) summarises in the form of short titles the micro-scenarios developed and detailed in the previous Chapters 2 and 3.

This paragraph describes the choice of combinations of hypotheses that led to the construction of the three scenarios. All the scenarios developed are normative scenarios in the sense that they describe a desirable state that we seek to achieve. In other words, they describe a way of arriving in 2050 to a situation where European agriculture eschews the use of chemical pesticides.

Table 4-1: Morphological table for the European agriculture without chemical pesticides foresight study

Components	Hypotheses of change in 2050		
Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscapes
Farm structures	Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures
Cropping systems	Strengthening plant immunity of cultivated plants	Management of the crop holobiont	Designing complex and diversified landscapes
Agricultural equipment and digital technologies	Autonomous robots to act on each plant	Pooling of equipment, sensors and data (landscape and organisation scale)	Modularity of equipment for adaptation to practices

The hypotheses concerning value chains were particularly important in the construction of the scenarios. These hypotheses made it possible to imagine the way in which certain food uses and food demands could influence the direction taken by the innovation process and make it possible to produce chemical pesticide-free agricultural systems. Farm structures were considered both as the result of market organisation, but also as constraints or assets for the transition to pesticide-free cropping systems. From this perspective, for each scenario we have chosen the farm structure most consistent with the scenario's logic. With regards to cropping systems, several hypotheses were combined for the same scenario with a dominant hypothesis and one (or two) secondary hypothesis(es) for each one. We will return later to the differences in cropping systems between the three scenarios.

Three scenarios are briefly outlined here along with the combinations of hypotheses that underpin them. Based on expert opinion, in each case we specify the scenario's general logic, the consistency between hypotheses in the scenario and contradictions between identified hypotheses which explain why they were not included in the scenario.

4.1.3.1. Outlines of scenario 1 (Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market)

Components	Hypotheses of change in 2050		
Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscapes
Farm structures	Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures
Cropping systems	Strengthening plant immunity of cultivated plants	Management of the crop holobiont	Designing complex and diversified landscapes
Agricultural equipment and digital technologies	Autonomous robots to act on each plant	Pooling of equipment, sensors and data (landscape and organisation scale)	Modularity of equipment for adaptation to practices

Scenario's general logic

The general logic of this scenario is based on market standards guaranteeing that products come from agriculture that does not use chemical pesticides and from European and global value chains. There is a high concentration of economic actors. It is a highly capitalist and technological scenario, dominated by the major players in retailing and/or the food industry, and financialised and specialised agriculture using robotisation and high input levels.

Consistency between hypotheses

In the combination of hypotheses defined in this scenario, there is first of all a strong coherence between the hypothesis of global value chains dominated by large companies and hyper-specialisation, enlargement and financialisation of farms. In this scenario, the dynamics of agricultural systems are led by transformations in food markets driven by consumers and regulations implemented by European authorities. There is a strong coherence between farm specialisation, the focus on markets and the use of advanced technologies, using robots to combat pests and reducing farm workforces. Cropping systems also use a high level of biological inputs and crop protection seeks to control the health of cultivated plants and strengthen their immunity (and their holobiont).

Contradictions or weak consistencies between hypotheses

We considered that there was a weak coherence of this scenario with hypotheses of farm de-specialisation, given that the dynamics of standardisation and market globalisation tend to lead to a strong regional specialisation of agricultural holdings. In addition, we considered that small and medium-sized farms would not have sufficient financial capacity to access the advanced agricultural equipment (robots and monitoring) envisaged in this scenario. Finally, we considered that such a scenario would not lead towards cropping systems based on strong territorial coordination for landscape management because innovation remains centred on the agri-food sector and does not integrate (or few) territorial actors.

4.1.3.2. Outlines of scenario 2 (European food chains based on plant holobiont, soil and food microbiomes for healthy foods and diets)

Components	**Hypotheses of change in 2050**		
Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscape
Farm structures	Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures
Cropping systems	Strengthening plant immunity of cultivated plants	Management of the crop holobiont	Designing complex and diversified landscapes
Agricultural equipment and digital technologies	Autonomous robots to act on each plant	Pooling of equipment, sensors and data (landscape and organisation scale)	Modularity of equipment for adaptation to practices

Scenario's general logic

The logic of this scenario is that it is the demand for healthy food which drives the development of regional and European value chains that do not use any chemical pesticides. This means it is not only agriculture without pesticides that is targeted but a food chain without chemical biocides. The objective of healthy food impacts all actors in the value chain, mobilising cooperatives, processors and farmers in the regions. The main means in this scenario is the monitoring and management of microbiomes ranging from soils, plants, stored and processed products through to the final distributed food product.

Consistency between hypotheses

In this scenario, the consistency between hypotheses is organised around the monitoring of microbiomes throughout the supply chain. The various actors, farmers, cooperatives, processors and distributors retain their autonomy but remain constantly linked around the issues of monitoring and controlling microbiomes. The microbiome and its management make the link between the hypothesis of value chains focused on healthy food and cropping systems based on the management of the holobionts of cultivated plants (which, via the management of microbial communities in the soil, participates in plant immunity). However, to ensure effective crop protection, the cropping system also relies on farm-scale crop diversification and the soil microbiome. Agricultural equipment is adapted to the management of soil microbiomes and its monitoring, as are seeds, which are adapted to the specificities of the plots. On a regional scale, there is a coexistence between farms specialising in livestock and others focused on crops, making it possible to organise the exchange of nutrients between farms and to diversify the landscape, thereby strengthening biological regulation.

Contradictions or weak consistencies between hypotheses

The concentration of actors is less strong than in the first scenario. This scenario is not consistent with international commodity markets, nor with the continued high consumption of ultra-processed products (and requires a change in diets). This scenario remains based on a sectoral approach, with an important role for cooperatives, so it is not very consistent with strong territorial coordination for landscape management. Finally, this scenario is not consistent with robotisation because the knowledge and technologies to empower the autonomous monitoring and management of the soil microbiome will not be available in 2050.

4.1.3.3. Outlines of scenario 3 (Complex and diversified landscapes and regional food chains for a one-health European food system)

Components	Hypotheses of change in 2050		
Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscape
Farm structures	Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures
Cropping systems	Strengthening plant immunity of cultivated plants	Management of the crop holobiont	Designing complex and diversified landscapes
Agricultural equipment and digital technologies	Autonomous robots to act on each plant	Pooling of equipment, sensors and data (landscape and organisation scale)	Modularity of equipment for adaptation to practices

Scenario's general logic

This is a scenario based on territorial coordination to meet two objectives: the management of landscapes and biological regulations, and the relocation of value chains to supply consumers and inhabitants with healthy products. For crop protection, the agricultural system is based on the reinforcement of biological regulations at the landscape and soil scales and makes little use of external inputs. The agricultural system includes the diversification of crops and, at the farm scale, the combination of crops and livestock.

Consistency between hypotheses

The consistency of the hypotheses is based around the dual objectives of healthy food and biodiversity at a territorial scale. The territorial approach to diversifying and complexifying landscapes is consistent with a cropping systems approach that reinforces the microbial diversity of soils and cares about the health of the cultivated holobiont. Moreover, the search for complexification and diversification of landscapes is consistent with (and is partly achieved through) diversified farm structures that generate diversified spaces (for example, a mosaic of crops). It is also consistent with territorialised value chains that make it possible to forge links with consumers and raise awareness about the relationship between agricultural systems, the products consumed and the ecology of the landscape. This cropping system is based on very localised biological regulations and is consistent with careful adaptation of agricultural equipment to the local context and the collective organisation of environmental monitoring.

Contradictions or weak consistencies between hypotheses

This scenario is barely compatible with value chains involved in de-territorialised product markets, in which the link between the food products consumed and their impact on ecosystems is for the consumer difficult to perceive. This scenario is also incompatible with the maintenance of strong regional specialisations which lead to a simplification of landscapes. This scenario is inconsistent with the maintenance of a strong specialisation of farms which limits the possibilities of crop diversification and the recombination of crops and livestock in the cropping system. This scenario is inconsistent with crop protection systems based on a significant use of external inputs to strengthen plant immunity because it is, above all, a question of promoting through indirect actions (rotation, semi-natural habitat, crop combinations etc.) biological regulation at the landscape and soil scales. Finally, this scenario is not very compatible with the complete robotisation of agricultural activities because it requires farmers to exercise multiple skills (at the plot and landscape scales), which are specific to their system and environment, particularly in terms of understanding ecosystem dynamics and the constant adaptation of agricultural systems to pest pressure.

4.1.4. The method for constructing transition pathways and the hypotheses supporting the transitions to the scenarios

This paragraph describes how we constructed transition pathways corresponding to the different scenarios outlined.

From the outlines of the scenarios presented above, we first constructed hypotheses concerning public policies, knowledge and information systems in agriculture and education, and changes in diet consistent with the scenarios. This is a question of imagining public policies and knowledge and information systems in agriculture that are capable of supporting a transition towards chemical pesticide-free agriculture. Each public policy and each information and knowledge system in agriculture is specific to the targeted scenario (see Sections 3.3 and 3.4).

Secondly, using backcasting (see Chapter 1), we constructed a chronological timeline for each scenario showing the sequencing of actions on a European scale, their results and the interactions between system components along a trajectory running from today to 2050. So, for each scenario, a transition pathway has been constructed (see Figures 4-1, 4-2 and 4-3 at the end of each paragraph). For a better understanding of these pathways, a narrative for each trajectory has been written, presenting the successive stages of the transformation of the system to reach a chemical pesticide-free European agriculture, and the interactions between different components of the system over time (for example, between public policies and agricultural systems, and between value chains and agricultural systems).

The transition pathways were drawn up by a group of experts on European transition (Transition group), over the course of two meetings (15th June and 30th May 2022). The composition of the transition group can be found in the Appendix of the report.

The first meeting of the group was devoted to the formulation of ad hoc hypotheses concerning public policies and agricultural knowledge and information systems (AKIS) and education that were likely to support the transition towards the situations described in the three scenarios. The second meeting was devoted to the development of transition pathways through the construction of three timelines describing the transitions to match the descriptions of the three scenarios in 2050.

The European expert committee then took over, completing and finalising these timelines during a meeting on 28th June 2022. The timelines were then converted into narratives of the transition, which are presented in the following paragraph.

4.1.5. The narratives of the scenarios and the transition pathways

From the scenario outlines constructed previously using the morphological table (see 4.1.3), three storylines describing the situation in 2050 of European agriculture without pesticides were constructed. These narratives articulate the partial stories (also called micro-scenarios) that describe the situation of the different system components in 2050 (see Sections 2.6 and 3.1, 3.2, 3.3 and 3.4).

4.1.5.1. Scenario 1: Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market

The narrative of the scenario 1

In 2050, European and global food chains based on specialised farms have developed chemical pesticide-free food markets. This was made possible by the implementation of a food safety standard on the European food market, which is a pesticide-free food standard (meaning food produced without using chemical pesticides) for all food products. Farm have evolved and developed pesticide-free agricultural systems by mobilising high level of inputs, capital and technologies in order to manage pests.

Global and European value chains are vertically integrated and mainly governed by large-scale retailers and processors. Their power has expanded since 2023: they control the different stages of food value chains, from production and input supply (seeds, biological inputs, and equipment) to logistics. Retailers and processors have a monopolistic access to big data along food value chains. They use these data to optimise the allocation of production factors to what they find are most valuable uses. Information on food products is provided via retail platforms to influence food demand.

Farm structures have been specialising through financialisation (access to external capital) and investment in technologies. Under the pressure of the integration of the food value chain, they have invested to develop new cropping systems that deals with pests without using chemical pesticides.

Cropping systems rely on monitoring, big data, robotisation and high level of inputs. The crop protection strategy is focused on strengthening the immunity of each cultivated plant by anticipating pest arrival and measuring the physiological status of plants. Autonomous systems (robots) act on each plant at the plot level. Crop protection adapts constantly to evolving emerging threats, by anticipating and defining in advance new (prophylactic) solutions to influence plant immunity. Autonomous surveillance devices monitor the health status of each plant and their biotic and abiotic environment, combining real-time observation via sensors, drones, remote sensing and sampling and predictive modelling. Based on large database, autonomous devices such as robots, companion robots and swarms of robots can distinguish the different cultivated plants in the plot and implement an individualised action on each plant.

The strengthening of plant immunity is carried out by breeding through selecting genotypes resistant to pest diseases (major and minor resistance genes conferring total or partial resistance) or varietal mixtures and rootstocks for perennial plants tolerant to pest. Strengthening of plant immunity occurs also through the exogenous supply of plant defence stimulators, the introduction of plant species that produce plant defence stimulators, and by strengthening the biological interactions with the various microbiomes including the soil microbiome.

This crop protection is completed by a diversification of cultivated crops by introducing service plants into crop successions and fields, a rethinking of the spatial location of crops, and a careful reasoning about cultivated species and varieties. The management of weeds is carried out by promoting the negative interactions of crops on weeds through allelopathy and allelochemistry, by preserving the competitive advantage of cropped plants for their access to resources (for example, light and nutrients), and also more classically by reasoning crop succession and rotations. There is now an acceptance that crop systems can be maintained with weeds that are endogenous to cultivated fields. The management of animal pests is done by controlling the size of the pest population through prophylactic actions, using of biocontrol or allelochemistry (e.g., the emission of volatile organic compounds (VOCs) which can even create olfactory landscapes).

As a result, farm structures producing pesticide free products have been embedded in long and standardised value chains. Large agricultural firms financed by external capital from investors or holding companies concentrate agricultural land. In these firms, all the factors of production (land, labour, capital) are segmented and mobile. Companies offering various services for crop protection have developed. Small residual family farms, with pluri-active farmers, coexist alongside those corporate firms. They had few financial resources to grow and stayed small. Generally, the increased specialisation of farms led to a high level of geographic concentration of productions, with some negative externalities on environment.

The transition path towards the scenario 1

The transition is based on three specific hypotheses that have been designed by the expert group on European transition (see Sections 3.3 and 3.4 for full description):

- *International trade agreements banning the use of chemical pesticides (environmental and safety) [for Public policies and trade];*
- *Business as usual diet (with stabilization of animal product consumption) [for Diet];*
- *Techno-centric AKIS (public and private), big players, private advices [for Educational and agricultural knowledge and innovation systems].*

The transition towards a pesticide-free food market has been triggered by the creation of private standards of pesticide-free agriculture and food around 2025. This market orientation responded to a consumer demand for pesticide-free foods based on awareness and worrying of health risks associated with chemical pesticides.

Major actors of the value chain (processors and retailers) have developed certification and increased their standards to reach zero chemical pesticides. They have developed contracts with farmers for producing without chemical pesticides. Contracts set a price premium and directly cover the risk linked to agricultural production during a transition period. Close monitoring of the products allowed developing a private certification of value chains free of chemical pesticides. This process was backed by EU regulation that defined by 2025 a framework for “chemical pesticide-free foods” (meaning foods produced without using chemical pesticides) and set the rules for the use of pesticide-free related claims on food labels. This initiative resulted in the transition of an entire European sector to pesticide-free agriculture and food by 2026. Then, by 2035, 90% of products sold by EU retailers were pesticide-free (ie. result from agricultural pesticide-free production practices).

EU also has created an economic environment conducive to EU food markets free from chemical pesticides. First, EU brought chemical pesticide-free goal to international spheres. The EU applied, in its bilateral agreements with trade partners, chemical pesticide-free conditions with the aim of building a transnational pesticide-free food market. To impulse the transition at farm level, the CAP has implemented a strong conditionality of agricultural subsidies (pillar 1) including the non-use of chemical pesticides by farmers. After 2030, EU enforced regulation on pesticide use, setting mandatory reduction goals for all member states, up until a complete ban of chemical pesticides across EU in 2040. Then, under the impulse of the EU, chemical pesticide-free food became a common standard required for food trade at international level, agreed within the World Trade Organization (WTO) and the joint FAO/WHO Codex Alimentarius.

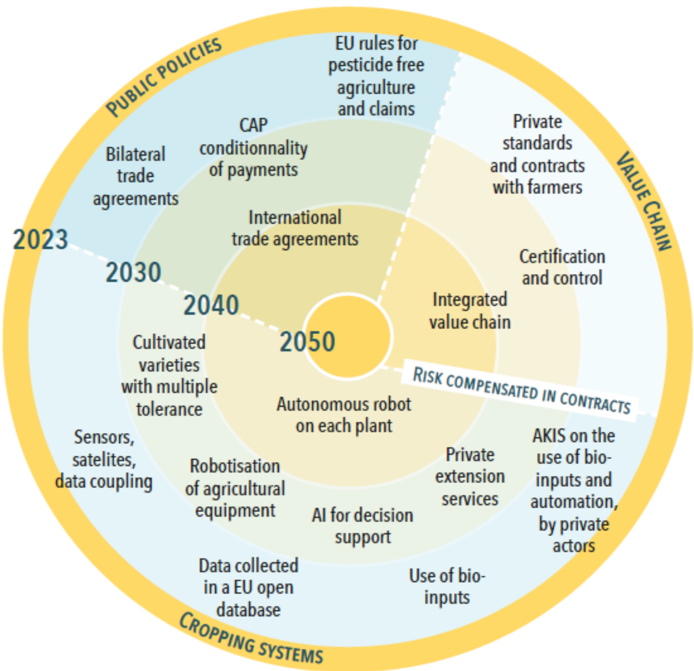
Farm transition to pesticide-free production occurred through digitalisation including the monitoring of pests and automation. Private firms of the upstream sector conducted the development of resistant seeds and varieties and provided access to bioinputs such as plant defense stimulators and bio-stimulants. Cropping systems also mobilise new cultivated varieties reaching multiple tolerance to main diseases. Through the certification of the value chain, farmers are now continuously monitored to improve production practices and the quality of crops and reduce their impacts.

From 2023, educational and agricultural knowledge system has reorganised to support bioinputs and robotisation, based on data platforms. This agricultural knowledge system is mainly dominated by big players in data collection and processing and private research, as large public research organisations are only dealing with data regulation issues in relation to digital. This agricultural knowledge system has developed a monitoring of biotic and abiotic environment and of plant health. Private extension services (including advisory system dedicated to access to external capital) give advice to large farms using artificial intelligence for decision support after 2030. Intensive life-long adult learning programs helped farmers to build knowledge and practices on the use of technologies, automation and robots.

These strong innovations were supported by a complete integration of the whole actors of the value chain from producers to retailers. They have developed a monitoring based on data and automatic reporting through block chain technologies along the food value chain. They also support the access of farms to financial investment in robotisation and sensors networks. An open pan-European epidemiosurveillance system developed through the support of EU specific policies has emerged.

Figure 4-1: Transition pathway for scenario 1, covering public policies, cropping systems (including AKIS), diet and value chain

The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components.



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- Leading role of major agri-food actors and retailers in defining private standards, certifying these standards and integrating value chain actors (and monitoring). Contracts for risk compensation.
- Important investments in robotisation and digital infrastructure (drones, sensors, satellites) on farms, facilitated by upstream and downstream value chain actors.
- Support from private firms providing advice and services to farmers.
- Importance of big data management, artificial intelligence.
- CAP with strong cross-compliance to pesticides reduction targets and withdrawal.
- International agreements to develop pesticide-free international markets.

After 2035, robotisation and automation of agricultural equipment were deployed through massive investment in farms, facilitated by public funds and bank loans, but leaving small farmers aside. These innovations have emerged from a top-down innovation process led by equipment manufacturers, including end-users (i.e., farmers). Major regulatory issues were raised by these innovations related to the property, access and use of these data by private companies, the competition of robots with human labour, the energy balance of digital technologies and societal concerns about the presence of autonomous drones and robots in rural landscapes.

National and European public policies have helped to manage the unintended consequences of the transition on those farmers that were not able to access this high-tech pathways. They have supported farmers' reconversion (financial, training, etc.). Other policies ensured the promotion of diversified agricultural systems to avoid falling into the trap of regional over-specialisation.

4.1.5.2. Scenario 2: European food chains based on plant holobiont, soil and food microbiomes for healthy foods and diets

The narrative of the scenario 2

In 2050, the EU food system provides the components of a healthy diet to protect human health. The development of pesticide-free agriculture in Europe has been a part of this change towards healthy food. The management of microbiomes in the different parts of the food system has been essential for the production of food without using chemical pesticides. Along the value chain, food is preserved by closely monitoring and managing the food microbiome from farm to fork, and minimal processing combined with biological control is favoured over the use of chemical food additives (including preservatives) and biocides. In both cases, the quality and nutritional value of food is preserved. Consumers are fully aware about the benefits of healthy food on their health and aim to achieve a diversified and balanced diet. They consume only foods produced without chemical pesticides, avoid consuming ultra-processed foods, and consume more fruits, vegetables, legumes, whole grains and nuts, and less animal-based foods, sugars, fats and salt.

Retailers, processors and cooperatives have organised and diversified regional commodity chains, notably through the creation of certifications and labels. Since 2023, large cooperatives have remained key players, linking farms with processors and retailers. The establishment of these channels has led farms to position themselves on diverse productions within the same region and to specialise in them, while maintaining a predominantly family-based structure. Farm structures are diversified, and Europe is characterised by a diversity of productions and a heterogeneity of structures within the same region.

In connexion with food value chains, farms have developed highly technical crop system that requires high level of piloting skills for dealing with pests. The management of microbiomes, mainly soil microbiome, is essential for crop protection without using chemical pesticides. Crop protection based on the crop holobiont (assemblage of a host - the cultivated plant - and its associated communities of microorganisms) seeks to strengthen the functions of the microbiota, to enhance plant protection and resistance to pests, as well as the adaptability of the holobiont in the face of biotic or abiotic disturbances. To manage the crop holobiont, several levers are used such as varietal selection to strengthen plant-microbiota interactions (breeding based on extended phenotype), the inoculation of key microorganisms. But the management of the crop holonbiont mainly lies on specific cropping practices that modulate microbiota such as tillage, organic amendment and residue management, choice of crops (e.g. diversification, rotation) and cover crops.

The disease management strategy exploits the competition within the microbiome between pathogens and other microorganisms that share the same microbiome niches in order to protect the plant by preventing diseases from taking hold. In addition, plant-microorganism interactions can improve plant defence levels and by strengthening interactions with microorganisms can provide a better response to disease attacks.

The weed management strategy combines strategies of limiting weeds through crop diversification including rotation, tillage and allelopathy effects linked to soil microorganisms, but specific weed plants can promote a reservoir of microbial biodiversity that is beneficial for the cultivated plant in the face of biotic or abiotic disturbances.

The animal pest management strategy is based on biological regulation at the landscape level (providing resources and habitat for beneficials), on the introduction or the promotion of pathogens or microorganisms that disrupt reproduction or nutrition of animal pest, and on organic compounds that disrupt pest perception or recognition.

Cropping systems implement integrative, systemic and adaptive principles that articulate the dynamic of the microbiome at the field level with the choice of crops and diverse agricultural practices. Cropping systems are highly field-specific for dealing with microbiomes and are designed by each farmer, mobilising specific modular agricultural equipment and monitoring. Continuous monitoring of the soil microbiota at the field scale measures both the effects of the cropping system on the microbiota over time and the consequences of targeted interventions aimed at modulating the microbiota through microorganism inoculations. The cropping systems mobilise also the multiple services produced by the plant microbiota for plant nutrition, mycorrhization, plant resistance to stress and plant phenotypic plasticity.

The transition path towards the scenario 2

The transition is based on three specific hypotheses that have been designed by the expert group on European transition (see Sections 3.3 and 3.4 for full description):

- *Holistic European policy on food systems, leveraging microbiomes continuum, promoting healthy diets [for Public policies and trade];*
- *Healthy diet based on food diversification (legumes, vegetables, sec. cereals) [for Diet];*
- *Extended AKIS (whole food chain) around microbiomes, public and private research partnership and advices, farmers to farmers sharing platform [for Educational and agricultural knowledge systems].*

Implemented between 2025 and 2030, a European holistic policy, going further than the F2F strategy, has triggered and supported a transition of agricultural systems and food systems towards pesticide-free agriculture and healthy diets. It met healthy food demand by consumers as well as the increasing cost burden for national health systems of expanding chronic diseases in Europe. Contrary to past silo-ed policies and their adverse effects, this holistic policy linked an agricultural policy, a food chain policy, a nutrition and health policy, and biodiversity, soil and water policies inside a common framework. This enabled to better align efforts, to reduce incoherence, and to tackle food systems challenges more effectively in order to give consumers access to healthy foods and to promote healthy diets through chemical pesticide-free agriculture.

In this process, food, agricultural and public health policies have been completely reshuffled to match with the microbiomes and plant holobiont paradigms, which have been the major tools of this transition. To achieve this transition, public and private action has been implemented at three levels: the food market level, the food chain level and the farmer level.

Public authorities and consumers' organisations empowered and supported consumers in their choices through information campaigns on food issues and third party web applications including information on traceability of practices along the value chains. Public authorities supported the adoption of healthy diets by subsidizing healthy food and taxing unhealthy ones. Subsidies to consumers, as well as support to public procurement targeting healthy foods, have been implemented since 2025 to ensure access to healthy foods for all, such as fruits and vegetables, legumes and whole grains. On the other hand, taxes have been enforced on ultra-processed foods (containing trans-fat, sugar, refined cereals, salt, additives and being ultra-processed) in order to limit their consumption. Taxes on unhealthy foods were implemented on food imports, in order to impede the entrance of such foods in European markets. EU bilateral trade agreements now include reciprocity clause related to environment and health, in order to obtain commitments from trading partners to supply healthy and chemical pesticide-free food to the European market. Also, national governments run targeted food and nutritional awareness campaigns, and promote healthy choices as part of public catering (schools, hospitals, public institutions).

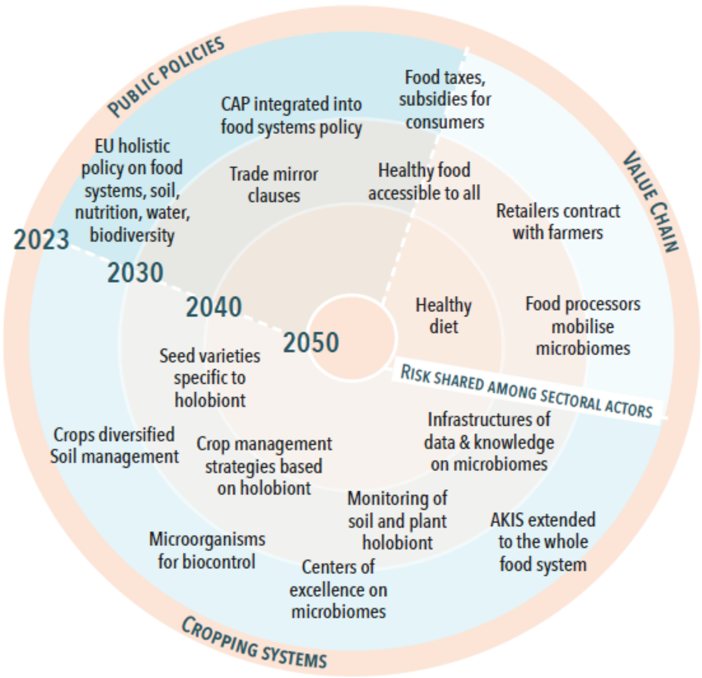
As the agricultural policy is now embedded in the holistic food system policy, the financial support to farmers is now connected to the food policy goals. Farms subsidies were conditioned to the shift to chemical pesticide-free cropping systems, and the development of agricultural productions in line with dietary targets. The cropping systems have first changed through training programs on soil management, crop diversification, biological control, and using seed varieties most adapted to local context (pedoclimatic, soil microbiome). In this first period, specific EU regulations for the approval of new biological inputs have emerged and companies producing chemical inputs have shifted their production to microorganism solutions. By 2025-2030, centres of excellence on microbiomes knowledge have been created including all the actors and activities of the food chain (farmers, equipment providers, collectors, processors, retailers). They have built new infrastructures of data and knowledge on plant holobiont, soil microbiome, and food microbiome, which also allow to assess the impacts of microbial inoculants. By 2030, these centres of excellence have developed news tools and equipment for the monitoring of microbiomes and plant holobiont health at field level, and during the storage and processing steps.

Farmers have then begun to use these new tools in their fields and to define management strategies of cropping systems. Modular agroequipment has been developed in places like Living Labs or third places to allow co-conception and experimentation of machinery, involving a diversity of actors of the value chain. The cost of the specialised equipment used by farmers induced a logic of collective organisations and a pooling of equipment. Learning processes of farmers have been achieved through public advice and private consultancy (start-ups) on new technologies such as monitoring, sensors and crop management, and through farmers to farmers sharing platforms. By 2035, all farmers and actors of the food industry are trained on the holobiont paradigm. By 2040, farmers have access to selected seed varieties favouring crop plant and microbiomes synergies, and compatible with the soil microbiomes at the field level. By 2045, the management of the crop holobiont by farmers is generalised.

At the level of the value chain, the governance of the value chain relied on partnerships and strong relationships between value chains actors (producers and cooperatives, processors, retailers). Cooperatives have evolved being engaged in the transition, opening their governance to regional and multiple stakeholders, being more area-specific (than product-specific) and diversified in terms of production, reinforcing the role of farmers in decision-making. Retailers have built contracts with farmers (and processors) with a price premium when complying with specific set of practices, including non-use of chemical pesticides and reduction of waste along the food chain. In the beginning of the transition, the risk resulting from the variability of production of pesticide-free cropping systems, was shared between the actors of the value chain. After 2035, the monitoring of microbiomes and the sharing of data on microbiomes throughout the value chain (traceability, transparency, accountability) have been implemented through blockchain technologies. This tool is used to manage the microbiomes of the product at the different stages of the value chain from soil microbiome to crop microbiome at the field level, to the food microbiome at the storage, processing and retailing levels.

Figure 4-2: Transition pathway for scenario 2, covering public policies, cropping systems (including AKIS), diet and value chain

The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components.



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- Holistic EU food system policy covering nutrition, food, agriculture, water, soil and biodiversity; which integrate agricultural subsidies (e.g. CAP).
- Taxes on products contributing to unhealthy diets, consumers subsidies for access to healthy food for all.
- Mirror clauses including nutrition and environmental standards.
- Centre of excellence/Living Labs on microbiota bringing together the actors in the sector ("extended AKIS") for research, development, training. Infrastructures and platforms to share data and knowledge on microbiomes.
- Collaboration between food industry players, and risk sharing.
- Collective learning on microbiomes functionality, use of monitoring tools and implementation of holobiont-based crop management strategies (rotation, crop choice, fertilisation).

4.1.5.3. Scenario 3: Complex and diversified landscapes and regional food chains for a one-health European food system

The narrative of the scenario 3

In 2050, territorial and regional food supply chains produce food that preserve human and environmental health as part of a transition towards a one health food system at European level. In 2050, the consumption of pesticide-free food addresses two concerns: healthy foods and biodiversity and environment conservation. This transformation is the result of a shift of civil society and food demand towards chemical pesticide-free foods, a diversification of value chains and farms and their re-embeddedness in territories and regions, and a redesign of agricultural production systems based on complex landscapes, soil microbiomes and diversified crops.

In 2050, a diversity of value chains dealing with a diversity of crops is rooted within territories and small regions. The governance of value chains is based on geographical proximity of farmers and processors and strong relationships between local actors of value chains (producers and cooperatives, processors, retailers). Evidence-based labels or third party web applications provide on assessment of the impacts of food products on the environment and biodiversity. Consumers and actors of the territory (inc. local authorities) and the value chains are involved in the monitoring of the impacts of food products on the environment and the human health.

Territories and small regions produce and supply a diversity of food products locally, resulting in a more balanced distribution of farm productive orientations in Europe. However, a part of the production is exchanged between regions to ensure a constant access to healthy and diverse foods in all European regions. Logistics is adapted to crop diversification and to the seasonality of products. Agricultural production is valorised through short and long supply chains. Food is preserved by using minimal processing combined with biological control during storage and retailing. Actors' practices are coordinated at the landscape level. Risks associated with the variability of production in chemical pesticide-free agricultural systems are shared along value chains.

For building crop systems without chemical pesticides, farmers have built complex and diversified landscapes. Through the support of cooperatives where decisions are made collectively and which carry quality certification of food products, farms have re-diversified their production, including diverse crops and livestock systems.

Farmers and local actors have redesigned the landscape to develop a strong functional diversity in the landscape that increases biological regulations of pests. Landscapes form a stable matrix of natural and semi-natural habitats combined with a mosaic of crops that can be adapted in its composition and configuration to the issues of crop protection. Farmers have increased agricultural landscape heterogeneity by reducing field size, by increasing border interfaces with semi-natural habitats (hedgerows, woodlands, permanent pastures - 20% of land covered by natural and semi-natural habitats, distributed regularly throughout landscapes). Other actors of the territory have increased biodiversity in the landscape (e.g. along infrastructure habitat).

Cropping systems are diversified over space and time, involving long rotations, multiple and cover cropping, intercropping, mixing varieties or populations within the same field, and agroforestry. Crop management practices use push-pull intercrops, barrier crops, weed-competing crops, diversity of crop cycles and resistance, resource dilution, turnover in varieties to limit risks, and manage harmful organisms and inocula, while preserving beneficials and other living organisms. Varieties and populations have been selected for the purpose of crop diversification (e.g. to promote plant-plant interactions) increasing their capacity to interact positively within the plot (mixed crops), and increasing the heterogeneity within crop varieties (genetic diversification). The development of an architecture of modular equipment has allowed farmers to combine and adapt machinery to the specificities of their cropping systems (e.g. mixed cropping).

The management of animal pest and diseases relies on prophylaxis mobilising knowledge about pest and disease cycles and biological regulations, as well as biological regulations from soil microorganisms and landscape. The weed management strategy is to find a compromise between crop losses and services provided at the landscape level, while accepting the presence of weeds that do not affect crop production in order to maintain biodiversity. Mechanical or biological control methods are used only as a last resort or transiently. To anticipate the presence of pests and the climatic context, farmers have developed collective tools (inc. sensors, remote sensing, crowdsourcing and modelling) to monitor biological regulations at the landscape level in order to inform crop protection decisions and crop choices over time.

Farmers, local actors and actors of the value chain have developed a shared governance of the territory in order to provide access to diversified healthy foods and to build complex landscapes.

The transition path towards the scenario 3

The transition is based on three specific hypotheses that have been designed by the expert group on European transition (see Sections 3.3 and 3.4 for full description):

- *Decentralized states, cross-sectoral territorial public policies, CAP rewarding ecosystem services [for Public policies and trade];*
- *Healthy diet with low environmental impact (strong reduction animal products) [for Diet];*
- *Localized AKIS and embedded universities, living labs and co-creation of knowledge, research with farmers on-farm, network of centers and EU knowledge platform [for Educational and agricultural knowledge systems].*

The trigger of this transition is the mobilisation and coordination of farmers, private and public actors at local level towards pesticide-free territories around 2025. This transition met a concern for protecting health and environment by inhabitants of rural and periurban territories, a food demand of consumers and a global awareness for biodiversity loss by citizens. Around 2030, cross-sectoral policies have been set up within the territory by local authorities (including food policy councils). These local authorities have worked through participatory process to plan land use in the local areas, and to design the landscapes for increasing biological regulation and protect water, soil and biodiversity. These institutions have relocated the food system by enforcing local food procurement, local value chain and agricultural production without chemical pesticides. Access to land was conditioned to the compliance of agricultural systems to the biodiversity targets defined by the governance of the territory. In 2030, each territory was able to monitor its biodiversity and to assess the impact of agricultural practices on the environment. A mutual fund allowed to share the benefits and costs of pesticide reduction efforts between farmers and public and private actors of the territory.

To support the transition of the territories, CAP policy subsidized farmers by promoting crop and farm diversification, landscape complexification and reduction of pesticides use during a short transition period (10 years). Then, by 2030, a new EU policy was designed (in place of the CAP policy) aimed at rewarding the ecosystem services delivered by farmers' activities, and beyond, by all the actors of the territory whose activity relates to the ecosystem. This policy comes after a complete redesign of the common agricultural policy, in context of strong decentralisation and subsidiarity of European States. These payments from EU funds were delivered by each territory, to support its own transition to a one health territory, ie. a territory that protects human, animal and environmental health. Going further, a one-health standard was developed at EU level in 2035. It included a set of criteria related to local production, water, air & soil preservation, landscape and biodiversity. This standard informed consumers and inhabitants about the environmental and health benefits linked to the product.

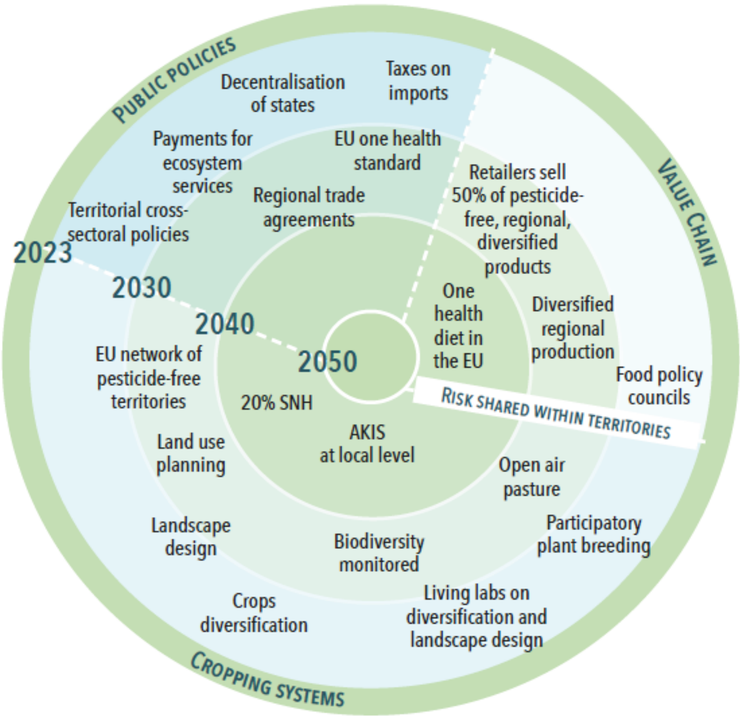
By 2025, living labs were created at territorial level, which allow co-conception and experimentation, in order to test with farmers' new agricultural practices to strengthen biodiversity and regulate pests. In ten years from 2023, educational and agricultural knowledge systems have been localised and adapted to local context, with small and embedded universities and a European network connecting local centres. Living labs included farmers, small companies, inhabitants and local authorities. They have co-created knowledge and practices for crop diversification, landscape design, and practices enhancing biodiversity. The learning process was accomplished through living labs, farmers to farmers sharing platforms, and farmers' education focused on landscape management and agroecology.

At the farm level, the farm diversification was achieved through participatory breeding and selection of crop varieties for crop diversification (mixtures of species and varieties), development of land dedicated to semi-natural habitat, reintegration of animal production in farms and development of open-air pasture for breeding. Farmers developed collective organization in order to exchange knowledge and practices for landscape management. They mobilised modular equipment for agriculture (machinery & tools adapted for small-scale fields and to the local specificities of the cropping system) and pooled equipment for the most costly. To define their cropping system, farmers implemented an adaptive learning process based on the assessment of socioecological interaction. They worked together with the actors of the landscape on designing appropriate mosaic of crops each year, and also in the longer term, on re-designing the spatial arrangement of cropping systems and semi-natural habitats. As a result, by 2030, regional production was diversified. By 2040, semi-natural habitat (including permanent pasture) and forest represented 20% of land cover.

To create a conducive economic environment for the transition in food markets, EU decided to require that imported agri-food products should conform to the health and environmental rules that are in force in European agri-food sectors and markets. EU implemented, as of 2027, high taxes on imports of products used for human food that are produced with crops cultivated with chemical pesticides. In parallel, the EU regulations have progressively banned active substances of chemical pesticides based on their health and environmental impacts (by including additional criteria, based on new scientific assessment of the "cocktail effects" of pesticides and of the mixtures of substances within a pesticide formulation, and of the impacts of pesticides on populations of organisms). These assessments led to a progressive reduction of substances available in the market, until a complete EU ban of chemical pesticides (without derogation) in 2035. Consequently, by 2035, foreign agri-food products entering European markets had to be produced without chemical pesticides. Additional requirements were also considered by regional trade agreements that relate to the nutritional quality of foods (mainly, not ultra-processed foods) and to the sustainability of agri-food systems (mainly, animal food products and related feeds non-detrimental to the environment).

Figure 4-3: Transition pathway for scenario 3, covering public policies, cropping systems (including AKIS), diet and value chain

The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components.



Credits: Lucile WARGNIEZ

- Coordination of actors at territorial level: public, private, citizens. Cross-sectoral territorial policies that aim to reorganise local value chains and develop the territory, relocate food systems.
- Payment for ecosystem services for all actors in the territory, based on a European "One health" standard.
- Regional trade agreements that systematically include the one health standard; gradual reduction of pesticides (based on criteria related to their impact on the environment) up to a total ban.
- Living Lab bringing together local actors for co-design and experimentation to create solutions and share practices.
- Building of new cropping systems based on the reinforcement of biological regulation at the landscape level with diversification, introduction of 20% semi-natural elements, crop diversification, mosaic development, and reintroduction of livestock.
- Collective organisation of knowledge and practice exchange for landscape management, participatory selection, and equipment sharing.

4.2. Downscaling scenarios and transitions at regional level: Four case studies in European regions

Authors: Claire Meunier, Olivier Mora, Sari Autio, Ana Butcaru, Stefano Carlesi, Roxana Ciceoi, Hubert de Rochambeau, Gina Fintineru, Marja Jalli, Viorica Lagunovschi, Emilia Laitala, Cécile Lelabousse, Giovanni Pecchioni, Yann Raineau

Table of contents

4.2.1. Objectives of the case studies

The regional case studies of the foresight aim at building scenarios and transition pathways towards chemical pesticide-free agriculture in 2050, in a specific sector and in a specific region. In these case studies, the term “region” corresponds to the area studied. It can be a geographical zone in a country, an official region, or an area defined by its “terroir”. The regions studied do not necessarily correspond to the NUTS classification (Nomenclature of territorial units for statistics).

The regional case studies complete the work done at European level by illustrating the European scenarios and their transition pathways at two levels: for a specific crop and food sector and for a specific region. It is also a way to check the relevance of the scenarios and their related hypothesis for building pathways towards chemical pesticide-free agriculture in 2050, in specific local contexts. Finally, these case studies enrich the European scenarios and transition pathways.

In order to conduct these studies we chose a participatory approach, involving experts in complementary domains, in the region and sector studied: scientists, farmers, representatives of non-governmental organisations, of food industries, of local authorities, etc. This allowed to understand how this foresight work can be leveraged by local actors, its benefits and limitations.

For the local stakeholders involved, these case studies pursue three main goals. First, they aim at raising awareness about the scenarios of chemical pesticide-free production. They also trigger debates on the key challenges linked to the transition. Finally, they generate collective thinking and potentially buy-in among stakeholders (Mora *et al.*, 2013; Schwoob *et al.*, 2016).

The three research questions behind the case studies are:

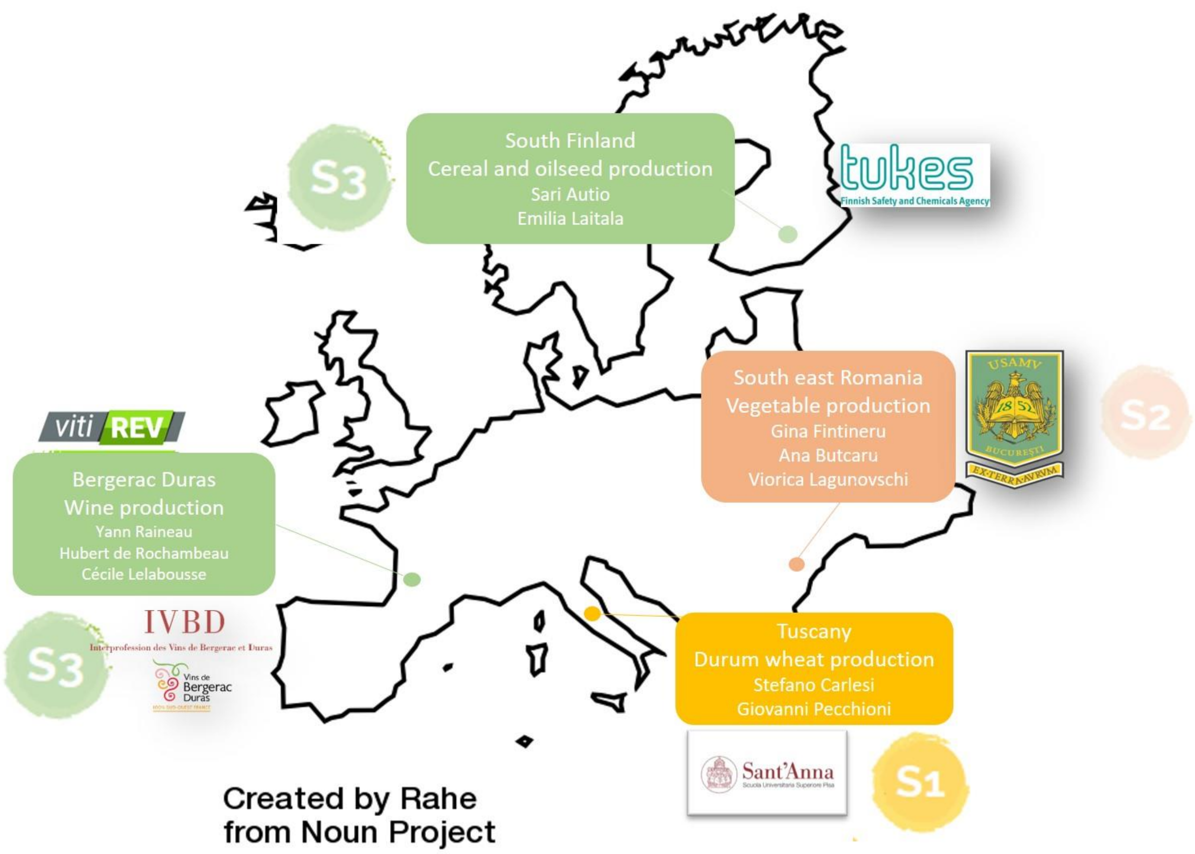
- How can the European scenarios of chemical pesticide-free agriculture be translated in a local and sector-specific context?
- How can local stakeholders leverage the European foresight scenarios to build collectively a transition pathway?
- Which transition pathway, milestones, actions, local actors foresee to achieve the desirable scenario?

4.2.2. Common methodology applied across the four case studies

In full alignment with the methodology applied at European level, we used in the four case studies the backcasting approach, combined with the scenario of chemical pesticide-free agriculture in 2050, as described in Chapter 1. We followed the same process for each of the case studies, described as follows.

For these case studies, we wanted to cover both a diversity of regions within Europe, from North to South, and West to East, and a diversity of crops, perennial and annual crops. After a call for interest among the members of the European foresight experts’ committee, four members volunteered: Sari Autio (Finnish Safety and Chemicals Agency Tukes, Helsinki, Finland), Paolo Barberi and Stefano Carlesi (Scuola Superiore Sant'Anna, Pisa, Italy), Gina Fintineru (University of Agronomic Sciences and Veterinary Medicine of Bucharest, Bucharest, Romania), and Yann Raineau (Région Nouvelle Aquitaine, Bordeaux, France) (Figure 4-4). This allowed to cover Northern, South, East and Western Europe, and also various production, perennial (viticulture) and annual (cereals and vegetable productions) crops. Volunteers of the foresight experts’ committee organised their local coordination team (called “local coordinators“ in the rest of the Section) to work on this project.

Figure 4-4: Four regional case studies conducted across Europe, with the sector covered, names of the local coordinators and European scenarios studied (S1, S2 or S3)



Tukes: Finnish safety and Chemicals agency – Finland
IVBD: Bergerac Duras wines interprofesion; vitiREV: innovate for environmentally-friendly wine production - France
USAMV: University of Agronomic Sciences and Veterinary Medicine, Bucharest - Romania
Sant'Anna: Sant'Anna school of advanced studies - Italy

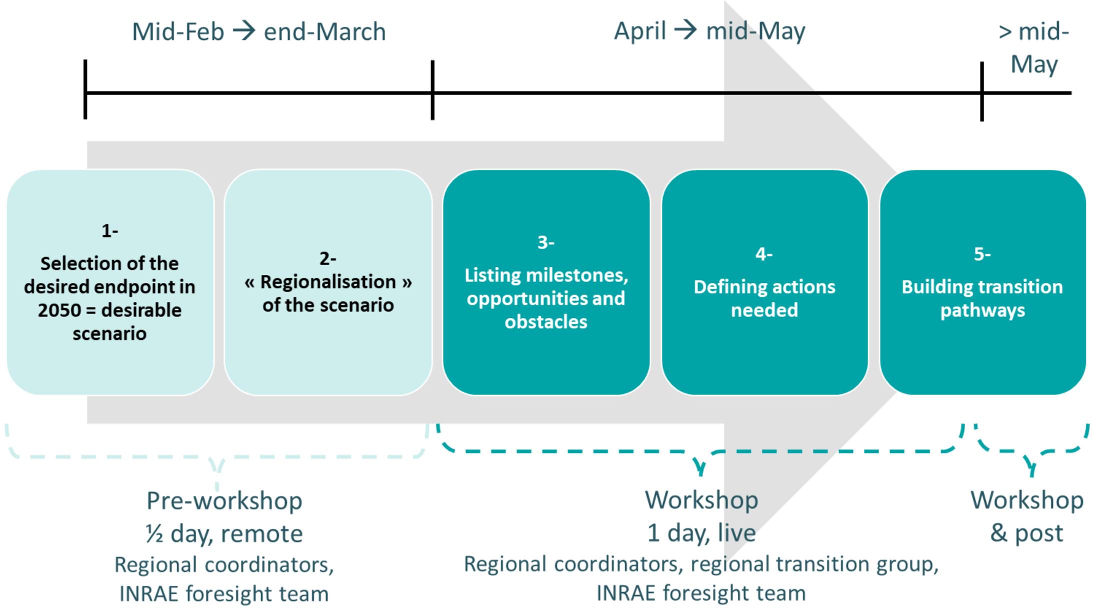
Several meetings were organised with this group gathering local coordinators and the foresight team, in order to build a common methodology, organize the work, discuss the European scenarios, and prepare for the participatory foresight workshops. The foresight team also prepared and shared with the local coordinators an animation guide, providing detailed explanation about the methodology, the process, the organisation of work, the animation of the workshop and tools required.

In addition to these joint meetings, each region followed a five-steps process (Figure 4-5), using the backcasting approach, and a method developed for these case studies, inspired from previous foresight studies (see for example Kok *et al.*, 2011; Hines *et al.*, 2019).

Steps 1 and 2 happened between mid-february and until end of March 2022. The foresight team members prepared the process and template, and animated the discussions. The preparatory work and the retrospective analysis were done by the local coordinators. The "regionalization meeting" gathered the foresight team, the local coordinators, and local experts invited by the local coordinators.

Steps 3, 4 and 5 happened during a one day workshop organized by the local coordinators.

Figure 4-5: Process followed in each of the case studies over the 2022 year



Step 1: Definition of the desired endpoint in 2050: selection of the desirable scenario

For each of the case studies, the experts select one of the three European scenarios. The local coordinators, with the support of the foresight team, choose the most relevant European scenario. The scenario should be relevant for the region, crop and value chain studied. Several criteria can be used, such as the relevance of the scenario and its plausibility in the specific context of the region and the crop, and its attractiveness for the regional stakeholders.

Step 2: "Regionalisation" of the scenario

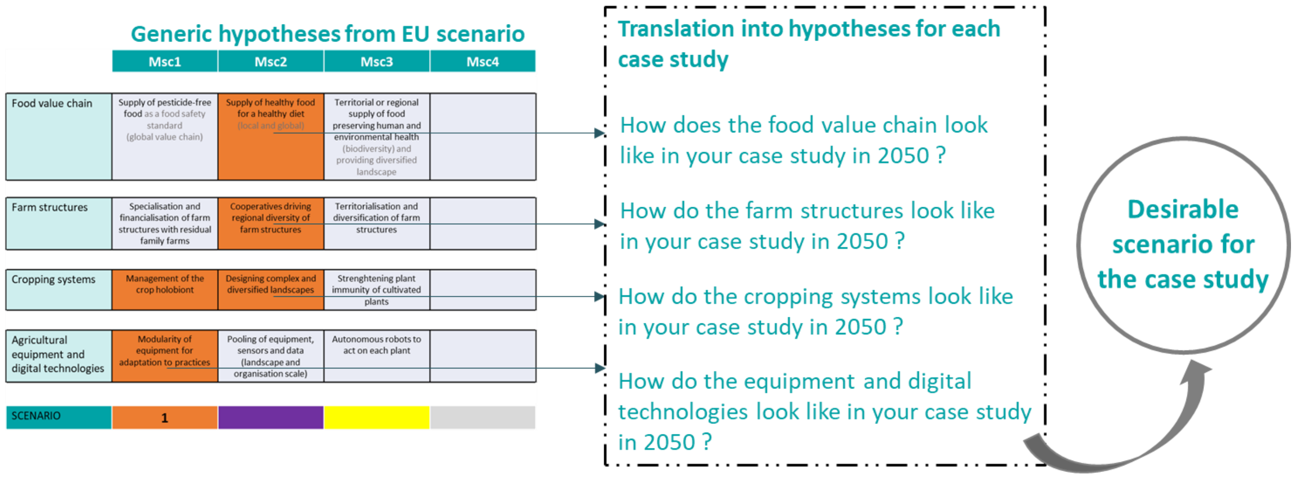
The selected scenario is adapted to the cropping system, the farm structures, the value chain and the region considered.

First, the local coordinators, supported by local experts, run a retrospective analysis to identify the past and current regional trends for the cropping systems, the food value chain, the agroequipment and the farm structures in the local area, and for the sector studied. They use scientific and grey literature, and outreach to researchers or stakeholders to inform this step. They answer the following questions for each components:

- What have been the major changes (in the past 10 to 20 years)?
- Who are the key actors involved in these changes?
- What are the main trends?
- What are the weak signals?
- What are the possible ruptures?

Then, thanks to this retrospective analysis, the European generic hypotheses of change (of the desirable scenario) are adapted for the specific region and sector. A brainstorming session is animated by the foresight team members, to translate the generic hypotheses of each component of the system into specific hypotheses fitting with the region considered, as shown in Figure 4-6. This is done by referring to the morphological table of the desirable scenario chosen. For each hypothesis, for each component, the participants of the brainstorming session are asked: What does this hypothesis mean for the region and crop considered?

Figure 4-6: Translation of the generic hypotheses from the European scenario into specific hypotheses



The outcome of this step is a regionalised scenario, in the form of a narrative and summary table of hypotheses.

One-day participatory workshop to build transition pathways (steps 3, 4, 5)

A one-day participatory workshop is organised to build transition pathways towards the desirable scenario prepared with the local coordinators. It gathers around fifteen participants, academic scientists and stakeholders from different sectors and complementary expertise (farmers, representatives from farmers' organisations, from industry associations, from consumers' organisations, from government or administration). They mainly work in the fields of agriculture, environment, transition, food production, public policies.

The workshop is conducted in the local language, or in English when possible, to ensure that participants are comfortable expressing their views and ideas. It is divided into four main activities: a presentation and discussion around the scenario, followed by the three remaining steps of the backcasting approach.

Step 3: Listing obstacles, opportunities and milestones

The objective of this step is to identify the key intermediate steps needed to be achieved, in order to reach the desired objectives, and issues and opportunities arising from them. Milestones, obstacles and opportunities are discussed for each of the components of the system and their hypothesis, linking to the desirable scenario and its morphological table.

- **Milestones** are defined as the main steps from the desirable future to the present, or the achievement of an event in the future, towards our desirable future (Van Vliet and Kok, 2015; Bengston *et al.*, 2020; Hines *et al.*, 2019). Milestones can for example be a 50% reduction in the use of chemical pesticide by farmers in the region in 10 years.
- **Obstacles** are elements that are limiting the achievement of a milestone. They can for example be: a lack of resources, an alternative biocontrol solution not known to all, a lack of financial incentives for transitioning, perceived risks of transition, etc.
- **Opportunities** are elements that are in favour of achieving a milestone. They can for example be consumers' willingness to buy products from pesticide-free agriculture.

Step 4: Identification of actions and actors

In this step, the objective is to define the key actions that are needed to reach the milestones identified previously, and the actors involved.

An action is defined as an initiative enabling to achieve a milestone, by leveraging an opportunity, or by reducing the possibility of an obstacle (Bengston *et al.*, 2020). Actions can be a regulation, a policy instrument, a research program, an education program, a communication campaign, a monitoring, a technological solution, capacity building. Actions can be, for example, a decision by a local authority to only buy pesticide-free products in the school canteens, the development and marketing of new combination of living microorganisms as a biocontrol solution, increasing the plants resistance to pests, a local NGO campaign to sensitise the population on biodiversity preservation.

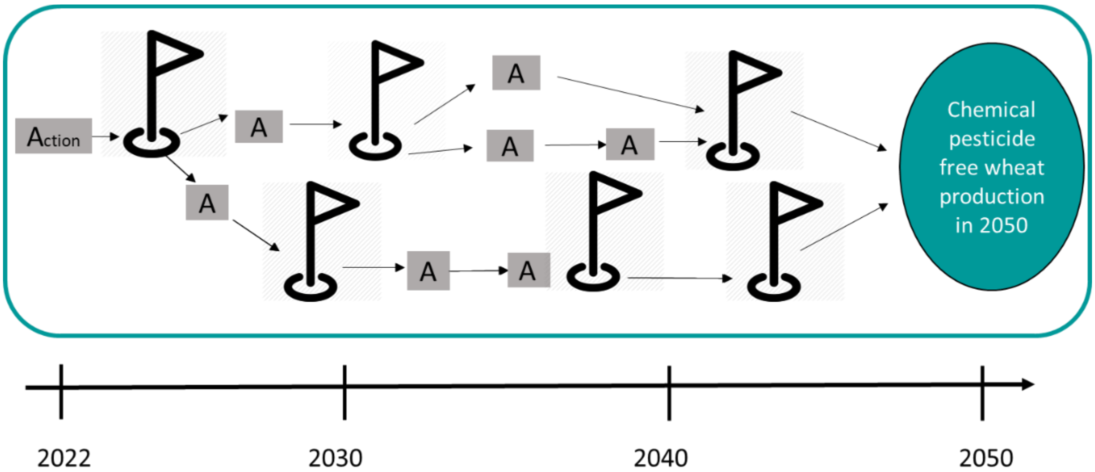
Participants are tasked to identify actions that will allow to reach the desirable future. For each of the components, they think of the actions needed to: (1) Overcome the obstacles; (2) Seize the opportunities; (3) Reach the milestones. Each action is linked to a related milestone.

When thinking about an action, participants are asked to be as precise as possible, and consider in particular: What type of action is required (regulation, research program, communication, training)? Who is involved?

Step 5: Building transition pathways

In this step, milestones and actions are articulated in a backcasting timeline, in order to build transition pathways. This allows to visualise how each action on a component of the system will interact with other actions on other component of the system. The various actions and milestones are organised in order to identify strands of connected actions and milestones that could ultimately form the transition pathway, as in Figure 4-7.

Figure 4-7: Schematic representation of the transition pathway, articulating milestones (represented as flags) with actions (A squares)



Participants start with the milestone closest to 2050, and discuss which milestone – or which action – it is connected to. They repeat the task with other milestones until they reach year 2022. This provides a series of milestones connected together. It is an iterative process, as several attempts are necessary to build relevant connections between milestones. When an agreement is reached on the connection between two milestones, one participant connect them with masking tape.

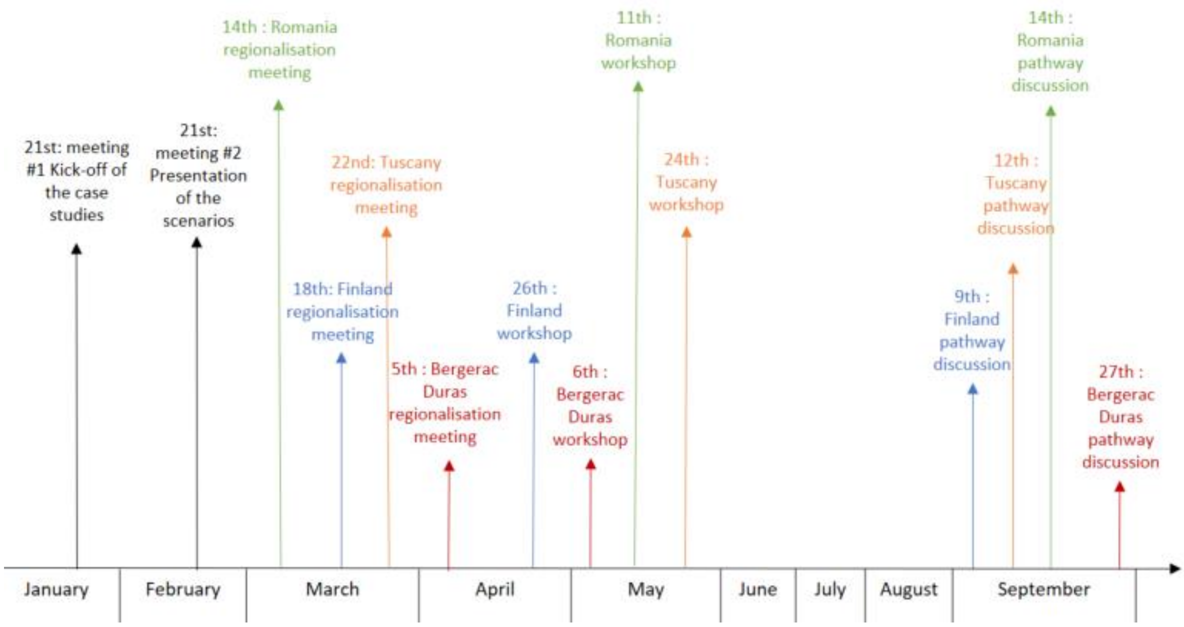
At the end of the session the group gather around the pathway and the facilitators review and comment it, and discuss whether or not some additional milestones are needed.

After the workshop, the transition pathway is translated into English (when necessary) and all milestones, actions, opportunities, obstacles are transcripted in an excel document (version 1 of the transition pathway). Then, the foresight team studies this first version, considering the logic and its coherence with the scenario. A second version of the pathway is proposed to the local coordinators and participants to the workshop, together with a narrative describing it. In a dedicated meeting this second version is discussed, as well as pending items. It allows to draw a final version of the transition pathway, included in the regional case study report.

The whole process lasted from January to September 2022, and Figure 4-8 summarises the various meetings organised with the four regions.

Figure 4-8: Organization of the work from January 2022 to September 2022

In black: meetings common to all; in green: meetings related to the Romanian case study; in blue: meetings related to the Finnish case study; in red: meetings related to the Bergerac-Duras case study; in orange: meetings related to the Tuscany case study.



In the following paragraphs, we will describe the outcomes of each of the four case studies, covering three items:

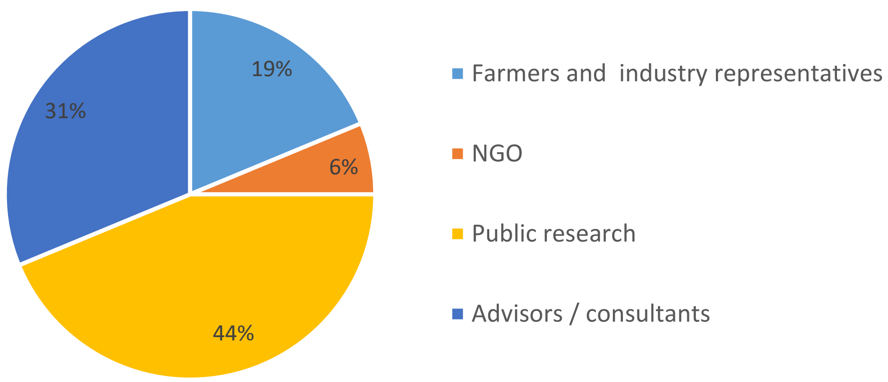
- An analysis of the major past trends of the agricultural system in the region considered (retrospective analysis);
- A presentation of the desirable future built with the local coordinators, that is a scenario of a chemical pesticide-free production in each region (the full scenarios are presented in Appendix 4-1);
- An overview and discussion on the milestones, actions and transition pathways built in the participatory workshops conducted in each region. In Appendix 4-2 some pictures taken from the workshops outcomes are displayed.

We conclude with a paragraph discussing the insights gathered from these case studies, as part of the whole foresight project.

4.2.3. Chemical pesticide-free durum wheat sector in Tuscany in 2050

This case study has been conducted by Stefano Carlesi and Giovanni Pecchioni from the Crop Science Research Center, Scuola Superiore Sant'Anna, Pisa, Italy, with the support of the foresight team members Olivier Mora (coordinator of the foresight) and Claire Meunier. The one day workshop happened in Pisa, on May 24th, 2022. It gathered 17 participants, two facilitators (Stefano Carlesi and Giovanni Pecchioni), and Claire Meunier from the foresight team (INRAE DEPE). There was around 40% of academic scientists, 30% of advisors technicians, and 20% farmers (cooperatives). There were also two representatives from non-governmental organisations (Figure 4-9; members of the workshop are listed in the Appendix of the report, Table A6).

Figure 4-9: Profile of participants to the Tuscany workshop



4.2.3.1. Presentation of the Tuscany region and durum wheat production

The Tuscany Region ("Regione Toscana" in Italian) is a region in central Italy with an area of about 23,000 square kilometres and a population of about 3.7 million inhabitants (ISTAT[1]). The region is surrounded and crossed by major mountain chains, has few (but fertile) plains, and the landscape is dominated by hilly country used for agriculture. Hills make up nearly two-thirds (66.5%) of the region's total area. Plains occupy 8.4% of the total area (ISTAT).

Durum wheat production and its value chain was chosen for this case study. Durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) Husnot) is cultivated worldwide, the largest producer being the European Union, where production and cultivation areas are concentrated in the Mediterranean area. Italy is considered the leader of durum wheat production in Europe, with an average production of 4.26 million tons in the last decade (1.28 million ha growing area) (Xynias *et al.*, 2020). 75% of the Italian durum wheat production is located in central and southern Italy and the islands (Bianchi, 1995). After cultivation, durum wheat is milled to produce durum wheat semolina, and then processed mainly into pasta. There are 3 main steps for pasta production: dosing and mixing (semolina and water), kneading and shaping (by extrusion or sheeting), and drying. Pasta products are then sold to consumers through various channels. Pasta is an important part of Italian people's diet, Italian people consume on average 23.1 kg pasta per year, followed by Tunisians, Venezuelans and Greeks (Bresciani *et al.*, 2022).

[1] ISTAT (Italian National Institute of Statistics) database: http://dati.istat.it/Index.aspx

4.2.3.2. Key trends related to durum wheat production and value chain in Tuscany

The retrospective analysis and identification of trends are based on interviews with 16 farmers from the IPMWORKS[2] arable crops hub conducted by Stefano Carlesi and Giovanni Pecchioni in the last quarter of 2021, and their own knowledge in the area. It has been completed by a short literature review (non-exhaustive) using the Web of Science database[3], documents from the European Commission (EC, 2020a) and foresight operations conducted in Tuscany (Arcuri, 2022). It was discussed during the regionalisation meeting that gathered Stefano Carlesi, Giovanni Pecchioni and members of the foresight team Olivier Mora and Claire Meunier.

Major trends identified on durum wheat cropping system in Tuscany

In Tuscan cereals systems there is currently an orientation towards specialized system, with a narrowing amount of crop choices between durum wheat, common wheat, sunflower, maize, sorghum, soyabean, faba bean, few pulses such as chickpea, lentil and common bean, or most rarely alfalfa or clover (mainly Egyptian clover, *Trifolium alexandrinum*). The crop sequence varies generally from 2 to 4-5. Because of climate change, crops choices have decreased over the past years and moved to crops with less water needs (i.e. switch from maize to sorghum) (Nassi o Di Nasso *et al.*, 2011; Pecchioni *et al.*, 2020 ; Dalla Marta *et al.*, 2011). Also, crops choices are limited due the increased presence of animals such as wild boars (Amici *et al.*, 2012). In the future, we foresee this trend to continue with less crops available and specialisation increasing still. Organic farming is more interesting in mixed cropping (Leoni *et al.*, 2022) and the specialisation is already higher with mainly forage crops (alfalfa, clovers, sulla) in rotation with durum wheat.

Varietal choice for durum wheat has evolved towards selection of resistant cultivars to the main fungi. It has also evolved to rediscover old cultivated varieties (CV) that increase durum wheat quality, and are valorised with consumers. In the future, selection should continue to evolve towards development of cultivated varieties that are both resistant and tolerant to fungi diseases (De Vita *et al.*, 2007; Lazzaro *et al.*, 2019).

The main pests affecting durum wheat production are weeds, fungi (*Fusarium*, *Septoria* and *Puccinia*), and, more recently, insects. Current pest management practices therefore include use of herbicides and fungicides, with resistant issues developing especially for weed management (Scarabel *et al.*, 2020). Alternative pest management solutions are increasing. They include longer crop rotation with forage crops, intercropping, cover crop and mulching (Adeux *et al.*, 2019; Antichi *et al.*, 2022). Against weed, mechanical management is developing, with an interest from farmers to invest in machinery and robotisation.

There is a trend towards reduction of the use of synthetic fertilisers because of increasing energy costs. After years of no-till and reduced tillage, there is an increased interest in ploughing during soil preparation to control resistant weeds.

Major trends identified on durum wheat food value chain in Tuscany

Durum wheat is mainly processed into pasta. It is the main source of carbohydrate in Italians' diet. Pasta consumption has slightly reduced over the past 10 years[4]. In future, there could be an increase in the consumption of secondary cereals, and of specific varieties, triggered by consumers increased

[2] https://ipmworks.net/, last consulted in June 2023

[3] WOS query "tuscany AND cereal" conducted in February 2022, limited to "topics", generated 33 results, 7 of which were selected based on abstracts.

[4] U.N.A.F.P.A, 2021 data: https://www.pasta-unafpa.org/newt/unafpa/default.aspx?IDCONTENT=102

interest in these products. Consumers expect more quality for pasta products, linked to gluten and presence of residues of pesticides (like glyphosate). This explains the development of certifications and labels promoting high quality pasta, such as organic pasta, which currently represents around 10% of total durum wheat production in Italy (Bux *et al.*, 2022). In the future, this trend should continue with even more importance to local production, diversification of pasta products towards no pesticides residues, healthy products (whole wheat pasta or high-protein pulse pasta) and labelled organic. Italy exports around 50% of its pasta production to mainly Europe and the US (Conca Messina, 2015), and also imports durum wheat from abroad even if this trend is decreasing. In the future, exports of Tuscany production could even increase.

Major trends identified on agroequipment and digital technologies in Tuscany farms

There is currently a medium penetration rate of innovations and digital technologies in Tuscany farms that are still transitioning to digitalised agriculture. The 10% farms have access to Real Time Kinematic (RTK), mapping and Decision Support Systems (DSS), which were absent 10 years ago. In future, digitalization – automated machinery, drones, other technologies – should spread among more and more farms, provided that obstacles on costs and technology accessibility are removed, and that farmers get convinced and trust their benefits (EC, 2020b).

Major trends identified on Tuscany farm structures

The size of farms has increased over the past 10 years, and number of farms have decreased. Average farm size is around 200 ha (from 30 to up to 500 ha) with probably a stable trend in future years on average. Two trends are currently coexisting:

- Younger farmers starting with smaller capital and farms and a much more differentiated product range;
- Selling of farms to capital investing firms, with an aggregation to larger farms.

Farms have specialized strongly over the past years, with a polarization of animal production and cereal production. There is currently a niche development of smaller size and differentiated new farms.

The source of capital is and should remain private mainly, with public subsidies focusing on specific targeted investments.

4.2.3.3. Scenario of chemical pesticide-free durum wheat production in Tuscany in 2050

Choice of the desirable scenario from the European scenario

The local coordinators chose the desirable scenario for this case study from the three European scenarios. They chose the scenario "**Global and European food value chains for pesticide-free food markets**" (S1). The main reasons for this choice are the current trends in terms of specialisation and increased size of farms, the development of digital technologies, the distribution market for pasta (50% export and increasing consumption of pasta globally), and the market development opportunities.

Regionalised scenario

The regionalised scenario was built from the hypotheses generated during the regionalisation meeting, for each of the components. The complete scenario is available in Appendix 4-1. A shorter narrative and a summary table of hypotheses is presented below (Table 4-2).

Scenario of chemical pesticide free durum wheat production in Tuscany in 2050 (short narrative)

Tuscany exports its know-how and high quality, chemical pesticide-free durum wheat products on the international food markets.

In Tuscany in 2050, durum wheat is produced without chemical pesticide, in compliance with market standard. Durum wheat production happens in large and specialized farms in Tuscan plains, equipped with cutting-edge technologies, allowing farmers to work at very large scale without too much labour forces and with a high working speed. The use of precision farming is spread and almost all the equipment used for the main operation, from sowing to mechanical weeding until harvesting, are satellite-guided.

Durum wheat immunity has been strengthened, through genetic control for the selection of cultivated varieties multiple tolerant to rust and producing plant defence stimulators for increased allelopathic effects. Seeds are coated with biostimulants for better crop rooting and establishment, or with beneficial microorganisms to induce resistance to fungal diseases caused by Fusarium species. Different varieties of wheat are sown together in order to form composite crops, more resistant to fungi. Beneficial micro-organisms are spread at various stages of its development, and competitive non-harmful fungi species are sprayed to compete with the species causing diseases. Weed management measures include longer crop rotation also to break disease and pest cycles and inter cropping selection. Different sowing machines and techniques and highly efficient mechanical weeding equipment can solve the issue of weed-wheat competition. Farmers use user-friendly technologies to monitor pest developments on the plots and get advice on crop management options. They remain the decision makers, and are helped in their choices by the use of Decision Support System (DSS) tool services. These tools build upon artificial intelligence based on years of observations, and predictive modelling. They are connected with drones, sensors for real time detection of pests. The precise application of targeted control decided by the farmer is executed with small autonomously navigating robots. Laws regulate the property and use of these data to ensure proper ownership, access and use.

Once harvested durum wheat is stored in storage facilities equipped with preventive solutions to avoid development of pests - particularly insects. To deal with variable quality of durum wheat, production facilities are equipped with seeds sorters that select the durum wheat grains according to quality criteria, and mix different varieties together.

Durum wheat is used for producing semolina and pasta, delivered to national, European and international markets. Indeed, the high quality reputation of Tuscan durum wheat has spread beyond Italy. Export market of Tuscan pasta is very developed in Europe, America, and have reached Asia. In addition to the standard pasta, premium pasta ranges valorise local Tuscan production, with old traditional durum wheat varieties, top quality taste and product attributes. They are produced using re-fashioned old equipment in the pasta factories with simpler materials integrated in highly automatized and digitally controlled production lines. Thanks to the blockchain technology, pasta products are fully traceable throughout the supply chains, from the crop to the fork, in a secured, unmodifiable and transparent way.

Table 4-2: Summary of the scenario for Tuscany and durum wheat production

Cropping systems	Durum wheat is protected from pests with solutions that strengthen the plants immune system. They include genetic control, use of biostimulants and of biocontrol solutions to protect against fungi. Mechanical weeding and longer crop rotation are used against weed-wheat competition. Organic and organic-mineral complex fertilizers, as well as fertilizers coming from different by-products are commonly used.
Agricultural equipment, digital technologies	The use of precision farming is spread and almost all the equipment used for the main operation, from sowing to mechanical weeding until harvesting, are satellite-guided. Farmers are helped in their choices by the use of Decision Support System (DSS) tool services which build upon artificial intelligence based on years of observations, and predictive modelling.
Food value chain	Durum wheat is used for producing semolina and pasta, delivered to national, European and international markets (America, Asia), due to the high quality reputation of Tuscan production. Products include standard pasta and premium pasta ranges valorising local Tuscan production, with old traditional durum wheat varieties, top quality taste and product attributes
Farm structures	The majority of Tuscan farms are large and specialized. They are equipped with cutting edge technologies. They require limited labour forces.

Comments on the scenario

The regionalised scenario prepared by the local coordinators and the foresight team was presented to the participants of the workshop, who discussed it around four questions: *What are the keywords from the scenario? What are the main challenges around the scenario? How clear is the scenario on a scale from 1 to 5? What can be added to make it more explicit?*

After reading the scenario, participants put forward keywords related to technologies: "**technology and innovation", "automation", "automation control", "Decision Support System", "technology costs".** They also identified "**large structured farms**". They choose keywords related to cropping systems and specially to breeding ("**breeding"**, "**old varieties"**), to the supply chain ("**internationalisation for exports"**, "**product processing"**, "**pesticide free from farm to fork")**. They also referred to transversal items such as "**economic sustainability"** of the scenario, the cooperation at various levels ("**horizontal and vertical cooperation"**), and "**re-evaluating tradition")**.

The participants identified several challenges linked to the scenario. They pointed out the **need for education and AKIS** (Agricultural Knowledge and Innovation Systems) for farmers but also for consumers. They also highlighted the current relative weakness of the value chain of durum wheat in terms of added value for farmers. Without **economic sustainability**, farmers will not be able to invest or experiment new practices. They questioned the **importance of technology in the scenario**: according to them, automation can pose some risks and will need to be controlled. These technologies also have a cost that may not be affordable to all. The question of **traceability** was raised as a challenge, linked to the necessary controls. The participants also had some questions about the value chain in terms of **product availability to reach the international markets**, and the capacity of raw product processing to meeting consumers demand.

Participants considered that the scenario was pretty clearly described in the narrative (rated 3 and 4 out of 5). However, they insisted that according to them the scenario was difficult to reach, too idealistic.

They suggested several additions in order to make it clearer. First, they recommended to discuss the **status of the uplands** (the so-called "colline", referring to the hilly inland areas of Tuscany) in 2050, since they are important part of the landscape in Tuscany (currently, the "colline" landscapes are very attractive for the tourism; what will be their status in 2050?). Participants would also like the scenario to be completed with information about the **future of small farms** in the scenario. Indeed, the scenario focuses mainly on the specialisation and increase of farm sizes; the evolution and status of small farms in 2050 should further be discussed. The scenario talks a lot about export outside Tuscany and even internationally. Participants recommended that we also address the question of **food sovereignty at local level**, which is priority before export. Similarly, they proposed to discuss how the competition on the international market will evolve by 2050, taking into account climate change, the evolution of the production capacities of the other countries. They also suggested to complete the scenario by justifying the need for all the **technologies** used. Finally, they suggested to consider the place for **organic production** in the transition towards the scenario.

Most of the challenges identified were addressed by the participants during the next steps of the workshop, when building the transition pathway (education and AKIS, role of technologies and control of automation, traceability system implementation). However, the status of uplands and its evolution was not discussed further.

4.2.3.4. Building the transition pathway towards chemical pesticide-free durum wheat production in Tuscany by 2050

After the presentation and discussion on the scenario, the 17 participants to the foresight workshop followed the backcasting process.

Milestones and actions necessary to achieve the transition

In two groups, participants first identified the key milestones – intermediary steps necessary to achieve the desirable scenario - and then the actions that will lead to these milestones. The full list of milestones and actions identified is in Appendix 4-3 (Table A.4-3-1). The main ones are further described below.

Milestones and actions related to cropping systems and agroequipment / digital technologies

Breeding is very important all across the transition, to develop varieties with multiple tolerance to pests. It is a continuous process from now to 2050, supported by a long term and ambitious "Italian national agriculture plan" to promote research and innovation transfer, funded by the national government. Very early in the transition, farmers' access to digital technologies is facilitated by **de-taxation**. Research and innovation investments are supported by national regulations. A network is created to connect pilot farms with farms for knowledge transfer, funded by the Tuscany region. In 2030, a **Decision Support System tool** is adopted by farmers. It has been created by a joint work of software specialists and agriculture specialists, with EU funds to digitalization projects. In 2030, 50% of arable land is using **precision agriculture**. Farmers have been trained by agronomists, and financed by banks loans. Cooperatives have bought the machinery and lend it to farmers for free trials of innovative machines. By 2030, cropping systems have evolved in favour of **promoting biodiversity protection and enhancement planning**, with longer crop rotations, intercropping, agroforestry, and cover crops implementation. This is as an outcome of the "national agriculture plan" for research and for 'innovation brokerage' to transfer the innovations, including at regional scale through farms networks. In 2040, use of **organic fertilizers** has increased to reach 50% of total fertilisers use, incentivised by public policies and regulations to stimulate the organic fertilizers market growth. In 2050, in **Tuscany rate of soil organic matter** has increased by one point vs its content in 2022, as an outcome of previous milestones, research programs, and Common Agriculture Policy (CAP) measures for easier farmers' adoption. In 2050, there is a **new professional role for farmers as "innovation brokers**", who deliver innovations adapted to needs of Tuscany durum wheat production.

Milestones and actions related to durum wheat value chain & diet

The value chain and its actors are key in the transition. In the transition, starting now, **contracts are implemented for farmers**, to compensate for extra-costs due to the transition towards chemical pesticide free products, and due to climatic events. Management of risks is shared across the sector (economical risks, resources). Also, for creating a pesticide-free standard, market requires **certification, information on labels**, to valorise with consumers the 'premium' quality - including chemical pesticide free - of Tuscany products. It will also require controls. A set of criteria is defined by the government (and EU). Certification is voluntary and is a way to ensure higher revenues for the farmers and the food industry. Technical assistance is developed to deal with a much more complex system, oriented towards technologies, diversification, DSS, etc. and diffusion of knowledge to the farmers. This is enabled by the creation of a **participative network on innovation**. This is a national AKIS system, free and public, gathering universities, farmers, producers, which organizes common innovation platforms, collective contracts, incentives for adoption of innovation, de-taxation, etc.

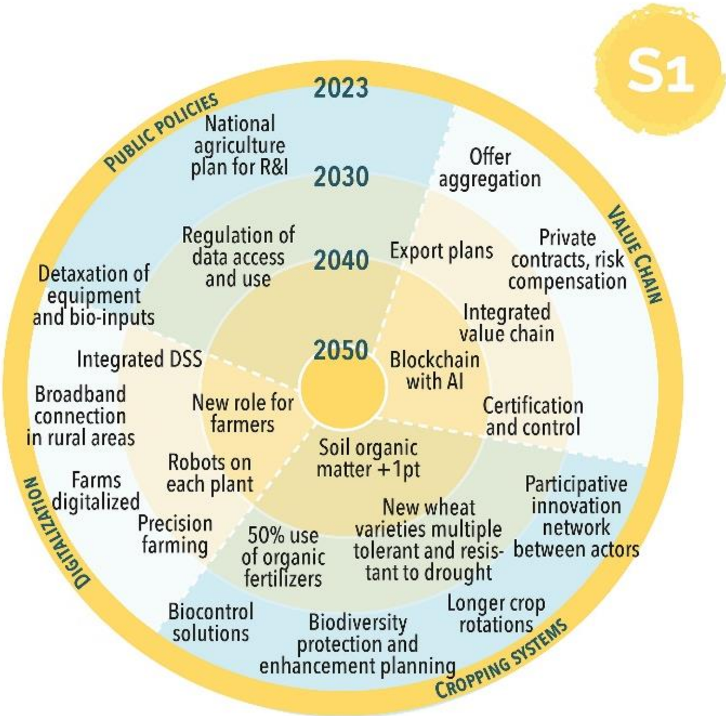
The **aggregation of products** - stage in the food supply chain where agricultural food products are gathered and moved to their processing or distribution point[5] – is an important milestone in the transition to allow farmers to have a higher commercial power in the supply chain. By 2040, **logistics models using artificial intelligence** are implemented, such as blockchain. They ensure full traceability from the crop to the fork. This is enabled by public investments to improve the internet network all across the region. Also, a technical school trains future experts in newest digital technologies in the whole food system. Ultimately, there is an **integration of the whole sector**, also including the supply chain (logistic).

[5] https://www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b10-value-chains/chapter-b10-2/fr/

The transition pathway

The last session of the workshop was dedicated to the building of the transition pathway, by connecting the milestones and the actions together, in a chronological and logical way. After the workshop, a second version of the transition pathway was proposed and discussed during a post-workshop meeting with the local coordinators. This led to a final version of the transition pathway that was shared with the participants of the workshop. It is presented in Figure 4-11. A simplified version of the transition pathway, in a gradient form, is also presented below (Figure 4-10), together with a narrative describing the transition pathway.

Figure 4-10: Target diagrams summarising the key transition steps in the transition pathway of Tuscany towards chemical pesticide-free durum wheat production by 2050



Credits: Lucile WARGNIEZ

Narrative describing the transition pathway

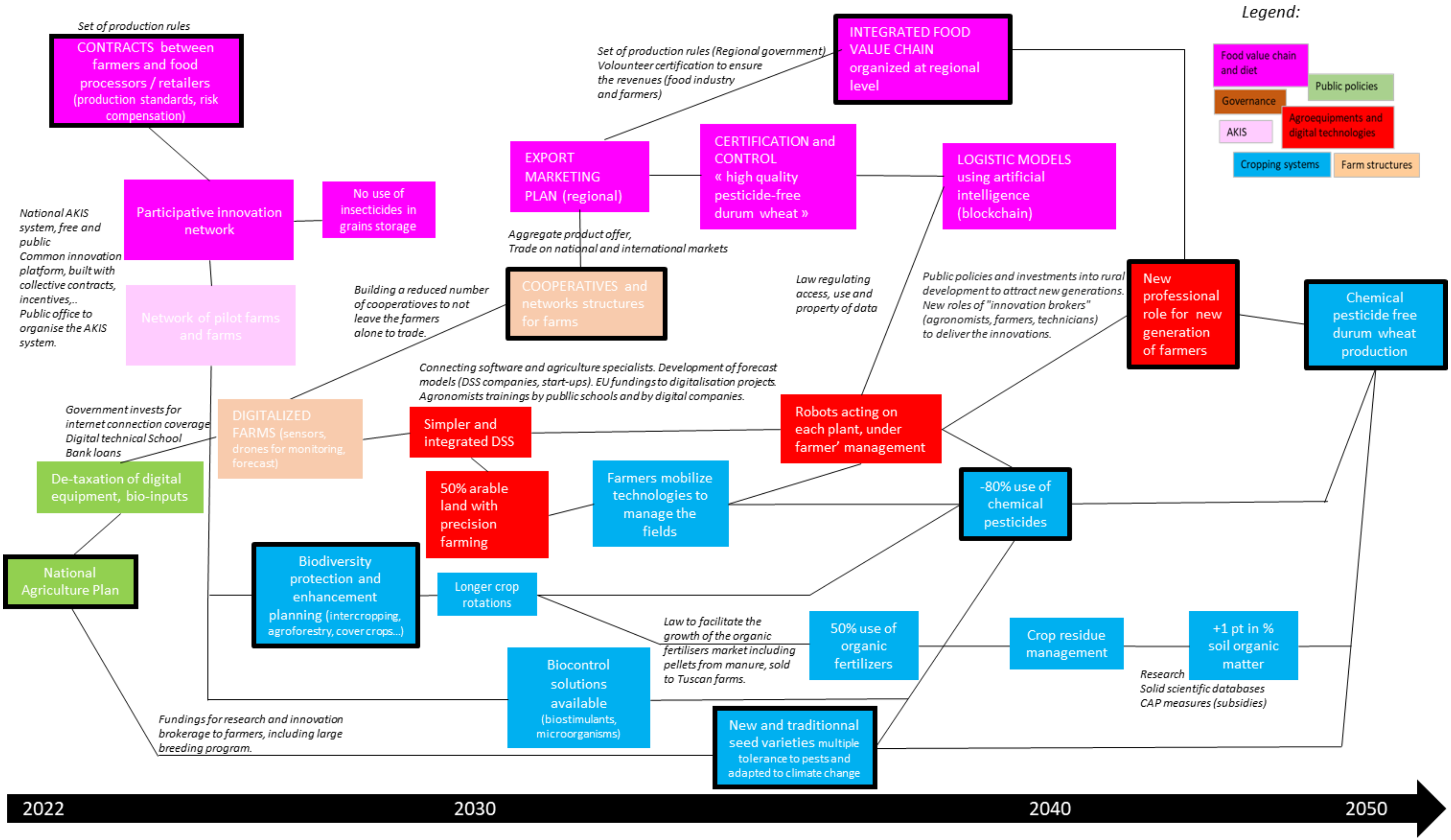
As of 2022, private food companies set standards for chemical pesticide free production and processing of durum wheat (sustainability commitments, goals, timings, etc.). In exchange for compliance with their production standards, food processors provide contracts for risk compensation to farmers. They join the participative innovation network created by the Italian government that gathers farmers, producers and researchers. This network allows to build common innovation projects, to co-develop solutions such as the removal of pesticide use in grain storage units, and the transfer of knowledge. This innovation network is connected to a farmers' network of pilot farms funded by the Tuscan region that experiments solutions proposed in the innovation network.

Thanks to these networks and strong AKIS system in place, farmers adopt new practices towards less use of chemical pesticides, according to the standards set by private companies. From 2025, a long term and ambitious "national agriculture plan" provides funding for research and innovation brokerage to farmers. An important breeding program is financed through this plan, and lasts all along the transition. New and traditional durum wheat varieties are issued out of this program and proposed to farmers. They combine several criteria and in particular a strengthened immunity allowing multiple tolerance to pests. They are also adapted and resilient to climate change (drought, extreme events). Also, cropping systems evolve to be more adapted to reduced chemical pesticide use, promoting biodiversity and the interactions between the cultivated plants and their environment. This includes the introduction of intercropping, agroforestry, and cover crops, after successful testing through the network of pilot farms. Also, longer crop rotations are implemented, including crops such as alfalfa, which, together with the increased use of organic fertilizers, and crop residue management, contribute to the restoration of soil health and increased percentage of soil organic matter. Alternative solutions to chemical pesticides are developed by biocontrol companies, and implemented progressively after testing through the pilot farms.

Digitalisation of farms facilitates the transfer of knowledge and innovations to farmers. As of 2022, the Italian government invests for fast broadband connection coverage in rural areas, accelerating the development of digital and knowledge skills in Tuscan rural areas. A new technical school is created to train future professionals at the pace with the newest digital technologies in agriculture. These professionals spread digitalization among farms. Adoption of new tools is promoted by public funds (de-taxation, incentives) and private loans provided by banks. Monitoring tools such as sensors, drones, collect many information in the fields that are compiled in big databases, and enable the development of forecast models. These are then turned into DSS tools advising farmers about the best preventive methods to apply on fields. Cooperatives buy and lend new machineries and digital tools to farmers who try them and adopt successful solutions. In 2030, 50% of arable land practice precision agriculture. This allows the most efficient use of pesticides. It also gives farmers more capacity to manage their fields and mobilize technologies, thanks to mapping of the soil, precision mechanical weeding, application of targeted biocontrol solutions, etc. By 2037, robots act on each plants, and are managed by farmers who remain the decision-makers on their most efficient and safe use.

Farms continue to grow in size and to specialize. They gather into a smaller number of big cooperatives or network of farms, in order to aggregate their product offer, and trade them on national and international markets. The endorsement of high pesticide-free production standards set by food processing companies gives a competitive advantage to Tuscany durum wheat producers on the market. This is acknowledged by a voluntary certification scheme "high quality Tuscan pesticide-free durum wheat". I*n 2040, 80% of Tuscan farms produce pesticide free wheat. By 2035, the durum wheat value chain is integrated from farmers/producers, to retailers. This vertical integration (coordination) of the durum wheat supply chains has advantages for farmers (share of risks, access to distant markets, stable revenues) and for processors (guarantees of products delivery and respect of production standards). The digital tools in place enable the set-up of efficient logistic platforms. In 2040, blockchains integrate data from the crop to the fork in a secured, unmodifiable and transparent way. Durum wheat farming attracts new generation of farmers who are interested by the high life standards in Tuscany rural areas, as a result of strong public policies and investments into rural development. These new farmers are on point with new digital technologies in agriculture, and well integrated in the durum wheat value chain. They act as "innovation brokers" who lead the way for Tuscany national and international market growth and reputation of high quality, pesticide-free durum wheat products.*

Figure 4-11: Final transition pathway for pesticide-free durum wheat production in Tuscany

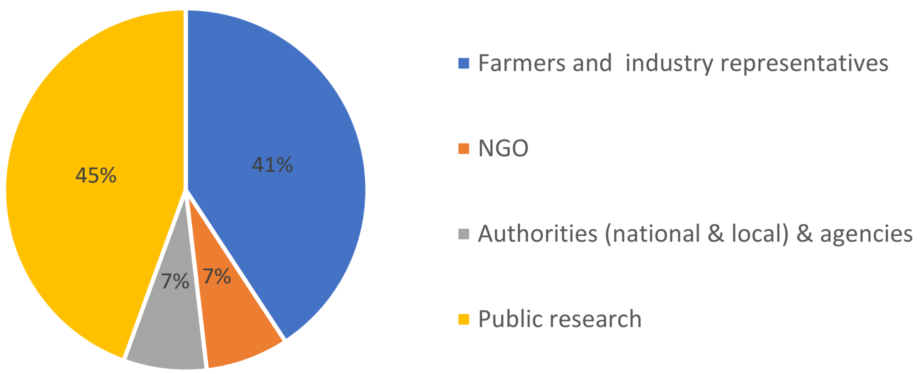


4.2.4. Chemical pesticide-free vegetable production in South and South-East Romania in 2050

The case study on South and South-East Romania was prepared with Prof. Gina Fintineru, Prof. Viorica Lagunovschi and Dr. Ana Butcaru, who are respectively Vice-rector on Research & Innovation, Professor and Researcher at the Research Center for Studies of Food Quality and Agricultural Products in the Bucharest University of Agronomic Sciences and Veterinary Medicine (UASVM[6]).

The one day participatory workshop to build the transition pathway towards chemical pesticide free vegetable production in South South-East (SSE) Romania happened in Bucharest, on May 11th, 2022. The facilitators of the workshop were Ana Butcaru and Roxana Ciceoi from the University of Agronomic Sciences and Veterinary Medicine in Bucharest. In total there were 22 participants to the workshop. Almost half of the participants were farmers and industry representatives, the other half were researchers (Figure 4-12; members of the workshop are listed in the Appendix of the report, Table A6). There were also two representatives of public authorities and two representatives of non-governmental organisations.

Figure 4-12: Profile of participants to the South South-East Romania workshop



Note: some participants combined two activities, for example researcher and farmer.

4.2.4.1. Presentation of the region studied and vegetable production

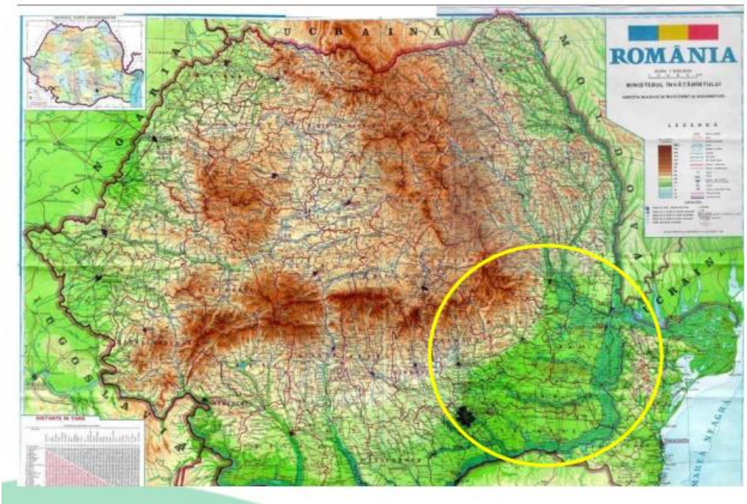
Romania is a European country, member of the European Union since 2007. Agriculture in Romania is very important for the country economy and its employment. In 2018 it represented 61% of the added value of the food chain. The most important sectors in terms of production value in Romania are cereals, vegetables, horticultural plants, and industrial crops. Vegetable production accounts for 13.1% of total agricultural input (2018 data, EC, 2020b).

The regional coordinators chose to study vegetable production. South and South-East of Romania (Figure 4-13) is considered the most favourable area for growing vegetables. All species can be grown in high yields, including thermophilic ones (melons, oats, cucumbers, tomatoes, eggplants, etc.) both

[6] https://www.usamv.ro/index.php/en/home-eng

in early, summer-autumn crops or crops for industrialization. Vegetable production is of 3.501.427 tons (2020 data), with a very low share of organic[7].

Figure 4-13: Area studied in the SSE case study



The most cultivated vegetables are tomatoes, white cabbage, peppers, eggplants, dried onions and dry garlic. Between 2014 and 2018, although the areas cultivated with vegetables have decreased, production has increased (Chiurciu and Fulgeanu, 2019).

4.2.4.2. Key trends related to vegetable production and value chain in SSE Romania

The local coordinators completed a retrospective analysis template supplied by the foresight team members, based on their knowledge and experience. They also reached out to several experts: Dr. Costel Vînătoru, eng. Ghiță Coman, and eng. Tudor Stanciu. In parallel, the foresight team conducted a short literature review (non exhaustive) using Web of science (WOS)[8] and documents from the European Commission (EC, 2020b). This retrospective analysis was discussed during the "regionalisation meeting" on March 15th, attended by the local coordinators and their invited experts, and members of the foresight team Olivier Mora and Claire Meunier. A summary of the main trends identified is presented below.

Major trends identified on vegetable production in SSE Romania

Farmers choose to cultivate both established varieties and new varieties that have emerged, according to the region and local conditions. More recently they diversify production to answer processors and traders' demand. At the moment, 85% of the varieties used come from the seed market (mainly foreign hybrids). There is a consumer trend for traditional taste and old "look and feel" for vegetables, where Romania traditional varieties could be used.

The biggest problem in terms of pests in vegetable production are weeds; they are managed through manual weeding in most cases. Predatory insects, entomopathogenic nematodes or bacteria/fungi are used to control greenhouse pests. Copper and sulphur are used against phytopathogens, and mechanical traps against rodents. With climate change and the introduction of new varieties, new

[7] www.insee.ro

[8] WOS query "Romania AND vegetable AND trend" conducted in February 2022, limited to "topics", generated 13 results.

pests have and will continue to emerge. Also, resistance to insecticides start to appear. In future, biological control of pests should become the standard protection strategy, with products based on baculoviruses and entomopathogenic fungi and viruses. Also, the integration of new pests monitoring devices (pheromone traps, satellites) will help farmers in their pests' management practices.

Fertilisation methods have developed a lot over the past years, with several new products reaching the market (biostimulants, water soluble fertilizers, foliar fertilisers, etc.), but chaotically used because not accompanied with training and advice. This chaotic use has affected soils (EC, 2020b) and water qualities. In future, farmers need to be supported by consultants, soil analysis and diagnosis in order to choose the best fertilization strategy. Water use will also become a challenge in future years due to climate change. At the moment drip irrigation covers more than 90% of the vegetable sector.

Major trends identified on vegetable value chains

Vegetable production has diversified over the past years, and now comprises of numerous vegetables (beets, carrots, peppers, tomatoes, eggplant, broccoli, celery, potatoes, onions, garlic, beans, cucumbers, zucchini, squash, etc.) (Chiurciu and Fulgeanu, 2019). In the past, there was no supply chain management but progressively connections are beginning between manufacturers, traders, processors (Popescu, 2016). This means that nowadays, value chains are not well developed nor structured. During the pandemic home cooking has intensified. Vegetables play a central role in Romanian diets (Constantin *et al.*, 2022). Still, Romanian consumers are affected by global nutrition issues (childhood obesity and other diet-related diseases) (EC, 2020b), lack of knowledge about food, rising domestic products and energy costs. They look now for higher quality vegetables, without residues of pesticides for health reasons. Demand for organic products is also increasing by more than 10% each year. They are perceived by consumers as high quality products, natural, environmentally friendly, without chemicals. In the future, the vegetable value chain should further develop and integrate actors such as: cooperatives as groups of manufacturers, processors and storage units, retailers and ultimately consumers. Vegetables are mainly sold fresh, especially local productions. They are mostly manually sorted and are stored either sold directly to consumers or stored in cold storage facilities. In future, and in line with the European Green Deal, organic vegetables should continue to grow. Traceability throughout the product cycle should also develop, enabled by the integration of the value chain, and development of digitalization.

Major trends identified on agroequipment and digital technologies in SSE Romanian farms

Machinery used in vegetable growing is unevenly distributed and is often old and/or lacking (Constantin *et al.*, 2022). Basic digital and software skills in Romania are among the lowest in the EU (EC, 2020b). Romanian farmers haven't been encouraged to digitalise vegetable crops in the past 10 years; only in the last 4-5 years has a niche appeared with some digital tools' development. Currently monitoring schemes are mostly made up of thermometers, traps, UV lamps and weather stations. Some innovations are developing such as 3D video cameras, which can measure the volume of the plant, recognize colours, etc. Farms are still in a stage of transition in general and regarding agroequipment in particular: large farms have managed to invest and implement modern monitoring systems. In future, grants and consultants should support small and large farmers in their adoption of modern tools. They can come from the state, retailers, digital IT companies, and European aid programs.

Major trends identified in SSE Romanian farm structures

Farms cultivating vegetables are in the vast majority managed at the family level (EC, 2020b; Marinescu *et al.*, 2021). Vegetable farm size varies from 0.1 to 10 ha. The vast majority of employees are members of the family, and for certain works day labourers can be employed. Large farms are starting to seek the help of consultants and to invest in new technologies. Capital comes from family funds and EU-supported projects. Some farmers are also trying to create integrated chains to maximize profits. In future, access to markets could be facilitated through online platforms. Also, consumers increasing requirements for healthy and high quality vegetable products should provide development opportunities. Challenges lay with the lack of collaboration between small farmers, the lack of qualified staff and competition with import products.

4.2.4.3. Scenario of chemical pesticide-free vegetable production in Romania in 2050

Choice of the desirable scenario from the European scenario

The local coordinators chose the desirable scenario "**European and regional food systems, soil and food microbiomes for healthy food and healthy diets" (S2)**. The reasons for this choice are based on the trends identified in the retrospective analysis, mainly consumers' trends: increasing interest for healthy diets where vegetables play a central role. Also, the agronomic conditions of the area and in particular the very favourable soil conditions. Finally, the crop protection trend towards the development of the use of bacterial, fungi and virus-based solutions.

Regionalised scenario

The regionalised scenario was built from the hypotheses generated during the regionalization meeting, for each of the components. The complete scenario is in Appendix 4-1; a shorter narrative and a summary table of hypotheses (Table 4-3) is presented below.

Scenario of chemical pesticide-free vegetable production in SSE Romania in 2050 (short narrative)

South South-East Romanian organizations of farmers leverage good soil conditions and maintain strong microbiome interactions from the soil to the plant, to produce pesticide-free vegetables that are major contributors to healthy Romanian diets.

In 2050 in south east of Romania vegetables are grown without chemical pesticides, and provide the local and national consumers with highly nutritious products, that are contributors to healthy diets. Vegetables are produced in family farms that are grouped together at regional level, in order to share storage facilities, develop brand, marketing and selling strategies. Farmers have access to several modes of action in order to avoid the use of chemical pesticides in their cropping system. These are based on four main levers: management of the microbiomes from soil to the vegetables, monitoring of the soil and pests, diversification of crops, and fertilisation practices. Vegetables production is diversified and include tomatoes, cucumbers, eggplants, melon, onions, broccoli, etc. Vegetables are grown in open fields and protective spaces (greenhouses, solars, etc.). They are mostly sold fresh, directly from farm to consumers, in regional storage facilities that are owned by the regional cooperative. They can also be sold in local and peri-urban markets, in particular those of Bucharest city region. There are processing units, owned by the farmers' organizations, where vegetables are dried, or frozen, or canned, and sold to the local, regional and national markets, and even internationally in the case of quality labelled vegetables.

Romanian consumers pay a lot of attention to the healthiness of their diets. The impacts of chemical pesticides on human health are well known to consumers and public health authorities, who have decided to ban their uses. Healthy diet means consuming a diversity of food products, seasonal, in majority cooked at home, little processed, produced with "like home" recipes. Diets rich in vegetables are encouraged as a way to balance the gut microbiome and prevent development of non-communicable diseases, linked to the increasing consumption of ultra-processed foods. Vegetables are accessible to all since they are considered priority products, and therefore are supported and promoted by the health authorities in the Romanian government.

Different scales of value chains are used by vegetable producers. They range from short food supply chains and local food systems to more sophisticated value chains. In some places, consumers contribute to the vegetable production *by helping with the picking, buying vegetables directly from the farmers. Farmers leverage short chain distribution channels to build trust and conveys information directly to the consumers. Vegetables are also sold outside the production region by valorising the quality and region identity of the vegetables. Vegetable producers' cooperatives are regular suppliers of major retailers, via contracts. They focus on blockchain, data integration, data traceability, collective agreements in order to enhance food quality along the value chain.*

Average farms size has increased but there remains diversity of farm sizes in the region. They are mainly owned by families working together with the support of neighbours. Young farmers get access to education and trainings. They are encouraged to adopt innovations on crop protection.

Vegetables crops are protected from pests without the use of chemical pesticide. Beneficial organisms are integrated in the farm ecosystem. An important lever for protecting vegetables from pests is the management of the plant holobiont, and of the microbiomes from the soil to the plant. By analyzing the soil microbiome composition, farmers understand better reservoirs of microbial diversity (soil, air, weeds and water). Farmers modulate microbiomes using biocontrol solutions through inoculation of micro-organisms and through crop choices. Vegetable varieties are selected in the Romanian genes bank, to be adapted to local agro and pedoclimatic conditions, and soil microbiome. Crops and cover crops are chosen in order to raise the soil organic matter and boost the plants immune system. Precise and non-chemical fertilisation is preferred in order to reinforce the recruitment capacities of cultivated plants and reduce pest virulence. Agroecological solutions for crop protection also include the choice of association of crops to limit the development of pests, by associating together vegetables, cereals, legumes, aromatic plants.

This cropping system requires strong cooperation between actors : farmers within the cooperatives, that provide tools, data on and biofertilizing solutions. There is also a strong network with researchers who provide advice, planning and prevention support, and with ICT (information and communication technologies) companies. All these actors are partners in the entire food chain.

Table 4-3: Hypotheses in 2050

Cropping systems	A diversity of vegetables are grown without using chemical pesticides, leveraging 4 main levers : the management of the microbiomes from soil to the vegetables, the monitoring of the soil and pests, diversification of crops, and fertilisation practices.
Agricultural equipment and digital technologies	Technology is applied in farms, with different sensors, imagistics (satelittes, drones, etc), applications for farms with Decision support systems and epidemiological services to measure soil health indicators and pests dynamics.
Food value chain	Vegetables are key parts of the diets of Romanians, who pay a lot of attention to their health. They eat a diversity of vegetables, mostly from short food supply chains and local food systems, and also through more sophisticated distribution channels. Vegetables are accessible to all since they are considered priority products, and therefore are supported by health authorities.
Farm structures	Family farms are grouped together at regional level, in order to share storage facilities, develop brand, marketing and selling strategies. Young communities of farmers are educated and trained. Farmers, researchers, ICT companies, etc. are partners in the entire food chain.

Comments on the scenario

The regionalised scenario prepared by the local coordinators and the foresight team was presented to the participants of the workshop, who discussed it around four questions: *What are the key words from the scenario? What are the main challenges around the scenario? How clear is the scenario on a scale from 1 to 5? What can be added to make it more explicit?*

Participants quoted keywords related to the cropping system in 2050 related to "**soil fertility**", "**soil microbiomes**", "**biological control**", "**beneficial micro-organisms**". They also listed keywords on farm structures and their evolution towards "**association of farms**", "**cooperatives**", and other forms of farming. The keywords on the vegetable value chain are linked to the "products processing", "**storage"**, "**logistics"**, "**branding and marketing"**. "**Health**" is also quoted in both groups, as an important keyword in this scenario around healthy products for healthy diets.

The challenges identified by participants in order to reach the scenario are linked to "farmers' **reluctance to change"**, in particular to create "**associations of farms"**. They also quoted the challenge of "**educating farmers but also consumers"**. Both groups also referred to "**legislation"** as a challenge in achieving the scenario of a chemical pesticide free vegetable production in 2050; the legislative framework needs to be revised in order to make the transition happen. They also highlighted the **"socio-economic factors as a challenge"**, and in particular "price and affordability of vegetables" (buyers vs consumers behaviours).

Participants considered that the scenario was clearly described in the narrative (they rated them as 4 out of 5 and 5 out of 5 on a scale from 0 to 5). They highlighted some elements that could however be added to the scenario to make it even clearer and complete:

- They suggested describing more the **diversity of vegetables** and of the varieties adapted to the different value chains;
- They also suggested revising the scenario to make it more coherent, and provide more clarity to **the way pests will be managed in 2050** without chemical pesticides;
- They suggested to describe how the **legislation**, the policies will guide towards the transition to a chemical pesticide free vegetable production in 2050;
- They suggested to better describe the link between **vegetable producers and big cities**: how will the big cities, such as Bucharest, be supplied with fresh regional vegetable productions in 2050?
- They also proposed further insisting on the **cooperation** all across the value chain, on the consumers' and producers' information about the advantages of consuming organic vegetables. Consumers could also play a role in the vegetable growing and be directly involved with farmers: going to the farms, picking vegetables;
- They also recommended **describing the role of innovations in technologies** (robots, innovations in the supply chain to replace man labour).
- Finally, they highlighted the **role of urban horticulture** in 2050: composting stations in cities, small greenhouses in the roofs, urban and community gardens, etc.

Most of the challenges identified by the participants were addressed in the transition pathway: public policies and legislation evolution to support the transition, education of farmers and of consumers, food price, retail and supply chain organization, new forms of horticulture including urban farming, climate change and water preservation.

4.2.4.4. Building the transition pathway towards chemical pesticide free vegetable production in SSE Romania by 2050

Milestones and actions necessary to achieve the transition

After the presentation and discussion on the scenario, the participants of the foresight workshop followed the backcasting process to build the transition pathway.

In two groups, they identified first the milestones – intermediary steps required to achieve the desirable scenario. Then, they identified actions that will lead to these milestones. Table A.4-3-2 in Appendix 4-3 lists the selected milestones and actions for the transition towards chemical pesticide free vegetable production in South South-East Romania by 2050. They are commented below.

Milestones and actions related to vegetable cropping systems

One of the key milestones identified in the transition towards chemical pesticide-free vegetable cropping systems is the increase in the biodiversity in farms, by building up specific crop schemes (through collaboration with research teams), introducing new species combinations, a varied assortment of crops including repellent species. This will require collaboration between stakeholders, development of technologies easy to use and implement, and policies supporting crop rotations, flower strips, use of innoculants (micro-organisms), etc.

Another important milestone is “building soils” which requires monitoring through soil samples analysis and controls, crop rotation and diversification, inclusion of green crops for soil protection, windbreaks, reforestation among others.

The pest management evolves progressively with two milestones: a 50% reduction in use of pesticides facilitated by the diversification and association of plants, and then 100% reduction (ie. total suppression). These require the availability of organic pesticides, the development of resistant varieties, and a state support for the transition.

Support to farmers comes from public subsidies, free specialist advice, demo lots, strong collaboration between researchers and farmers.

Milestones and actions related to vegetable supply chain

As presented in the retrospective analysis, in the past there was little supply chain management for vegetables in the region, but progressively connections are beginning between manufacturers, traders, processors. In order to implement short supply chains by 2050 there is a need to set up a legal and regulatory framework that will define and then support its development through subsidies, etc. Then, digital platforms will be created in order to share information and communicate about these short chains, evolving to IT platforms and blockchains.

A series of economical instruments - national, European public subsidies - can help with this transition, activated through the future CAP reform starting in 2028.

Also, consumers' education about the importance of healthy diets is a very important action, through media campaigns, children education curriculum.

Milestones and actions related to Farm structures

Similarly, a legislative framework for family farms will enable the support of their development and create an environment favourable to the cooperation: association of farms, small producers joining and working together. This association of farms in cooperative systems is supported financially, both for its production and for the infrastructure provision.

The group also proposed a milestone related to microfarms, where people produce their own vegetables. People can refer to demonstration models, and they have access to a platform with all the information needed to produce vegetables. These microfarms can be set up in urban and peri-urban areas or in the countryside close to the cities. These microfarms are developed by local associations interested in the program. They form a new business model.

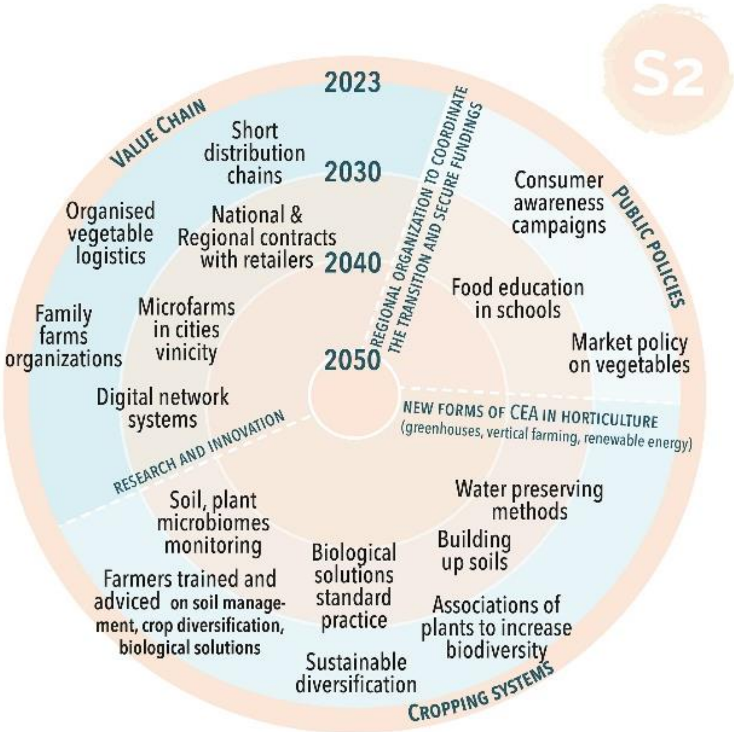
Milestones and actions related to agroequipment used in vegetable production

Milestones and actions on agroequipment aim at putting in place relevant monitoring tools in the different vegetable production areas, in order to be able to get precise data on soil, plant microbiomes, as well as nutrients. This requires research, innovation and training of farmers for adoption of these tools. There are also a milestone related to use of renewable energy for controlled environment agriculture (CEA) systems.

Transition pathway

The last session of the workshop was dedicated to the building of the transition pathway, meaning connecting and articulating milestones and actions logically and chronologically. After the workshop, the transition pathway was translated into English, and transcripted on an excel document (version 1 of the transition pathway). Then, a second version of the transition pathway was discussed in a post-workshop meeting; on September 14th. The final version of the transition pathway is presented in a simplified version in Figure 4-14, and in a more detailed version in Figure 4-15. It comes with a narrative describing the transition, as follows.

Figure 4-14: Target diagrams summarising the key transition steps in the transition pathway of SSE Romania towards chemical pesticide-free vegetable production by 2050



Credits: Lucile WARGNIEZ

Narrative describing the transition pathway

*In order to organise, monitor and secure the transition towards healthy diets including chemical pesticide free vegetable consumption, national and regional **organizations (in charge of implementing the healthy food systems policy)** are created. The transition is articulated around four main workstreams on 1) organizing the vegetable logistics and supply chain, 2) developing the information systems, 3) transitioning the cropping systems towards the management of the holobiont, and 4) leading consumers' diet change.*

The organization first addresses education of consumers on healthy diets and purchase behaviours. For this, media nutrition campaigns are financed and delivered by the ministry, promoting the nutritional benefits of consumption of pesticide-free vegetables. Also, in schools, local initiatives on food education are run by volunteers with the school teaching staff, and then the whole school curriculum includes mandatory courses on nutrition, healthy food. Price policies are set up in order to enable affordability of these healthy vegetables to all.

*The value chain work stream starts as of 2023 with the organization of the logistics locally: associations of farmers create warehouses, with the financial support of local and national authorities through European funds and other programs supported by retailers. Once these warehouses are created, three different distribution channels for vegetables are developed. First, the association of family farms grow into **cooperative systems**, to share agroequipment, crop and soil monitoring data. They are supported by the national policy for the development of the* *production, and by European funding for the infrastructure provision (subsidies provided by the holistic European food system policy for logistics storage facilities, protected cultural areas).* ***They contract with retailers*** *for the distribution of vegetables on the national market. Second, a* ***short chain distribution*** *channel is developed, connecting directly farmers to consumers. Farmers' market, cooperatives local outlets open close the farms. The national policy supports their development, and in particular the digitalization so that they can communicate with consumers through digital platforms. Farmers are encouraged by fiscal incentives to gather into local cluster of producer groups and develop these short chain distribution channels. Third (in the 2040's),* ***microfarms*** *are developed in the vicinity of the cities, for individual chemical pesticide-free vegetable production. Universities together with other stakeholders create a functional model for these farms, municipalities identify and allow lands, protect them, and build relevant infrastructure (roads, fencing, utilities, plots). These microfarms are run by associative organization of applicants.*

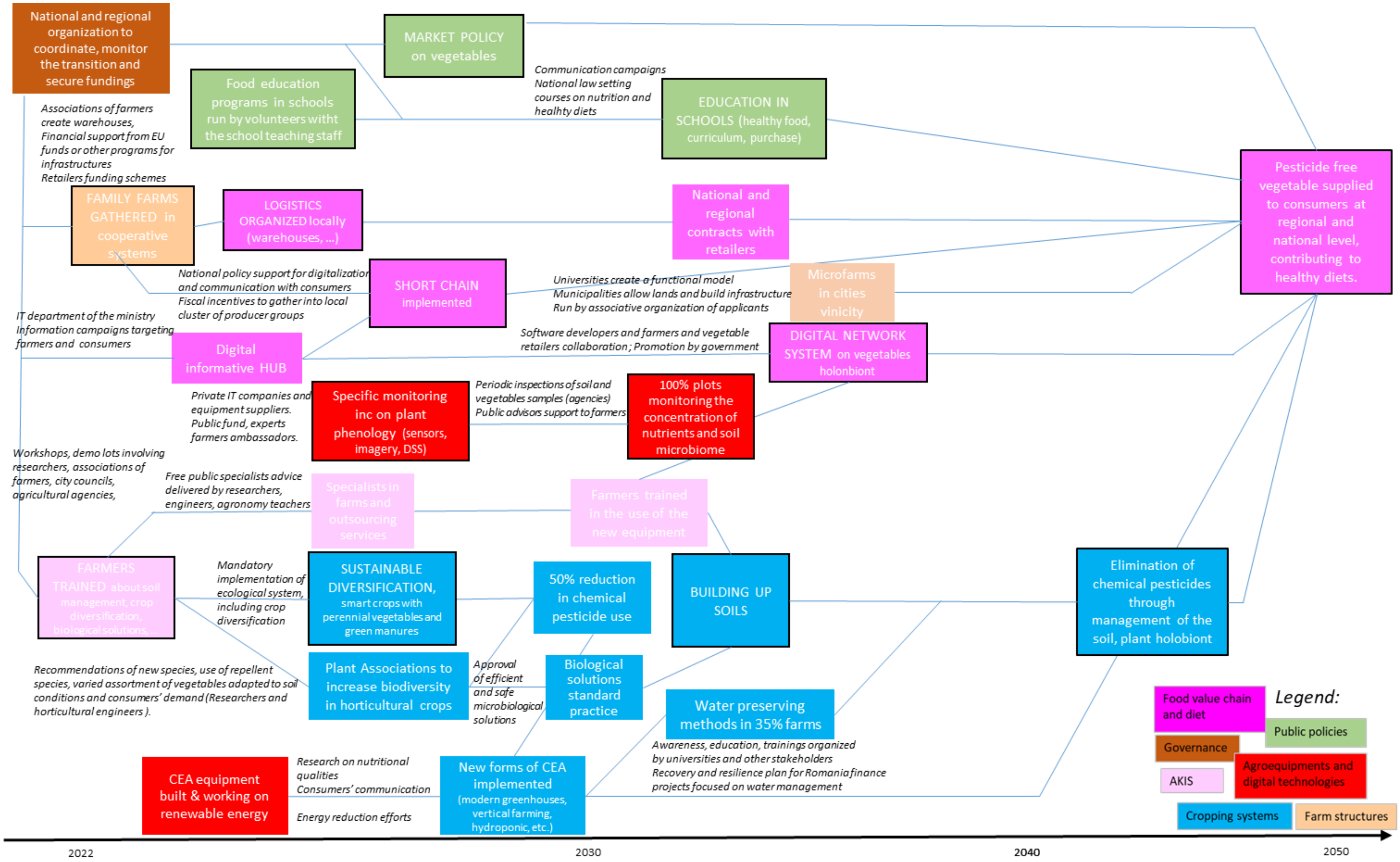
To facilitate the development of the vegetable supply chains, and to educate consumers about the importance of healthy diets, information systems are necessary. Digitalization starts with the creation of an ***informative digital platform*** *where data on vegetables are provided by farmers and shared with consumers (who, where, which product). The IT department of the organization sets up of the platform, where data are collected from farmers. Information campaigns are run through these digital platforms, targeting farmers and consumers. By 2035, this platform gathers more and more data thanks to the monitoring tools on the vegetable cropping systems. The platform now includes information on the plant holobiont, and becomes a* ***digital network system*** *shared with all the actors of the value chain. Software developers collaborate with farmers and vegetable retailers to facilitate the access to this network and make it user-friendly. The network is heavily promoted and widely adopted by consumers who are now very well aware about the importance of healthy diets.*

The national organization puts in place several initiatives to ***train and educate farmers****: workshops, demo lots involving researchers, associations of farmers, city councils, agricultural agencies, etc. From 2025, public incentives favour the adoption of vegetable cropping systems achieved in an ecological system, including crop diversification. Farmers are supported in their transition by free public specialist advice delivered by researchers, engineers, agronomy teachers. This leads to the* ***large implementation of diversification of crops****, use of green manure and* ***increased biodiversity in horticultural crops*** *through plant associations. Researchers and horticultural engineers provide recommendations for introducing new species that do not have the same specific pests, use of repellent species with multiple functions, and varied assortment of vegetables adapted to the soil conditions and to consumers' demand. By 2030, efficient and safe microbiological solutions are approved for use in vegetable crop protection, and Romanian vegetable production achieve* ***a 50% reduction in chemical pesticide use****, according to the regulatory objective set in the food system policy.*

The digitalisation also reaches the different vegetable cropping systems, the fields, the greenhouses, etc. ***Monitoring tools*** *are developed by private IT companies and equipment suppliers. Their adoption by farmers is funded under the "food system policy" and European funds, supplier investment, etc., and facilitated by expert farmers who have already been advised how to use the equipment. Starting from sensors, satellites information, these tools evolve by 2032 to enable the* ***monitoring of the soil nutrient and micro-ecosystem*** *(holonbiont). Agencies provide analytical services based on periodic inspections of soil and vegetables samples, informing farmers about the soil and microbiomes conditions. Farmers – helped by public advisors - use these data to* ***build up their soils*** *and adapt their vegetable cropping systems accordingly, to maintain healthy soils (choice of varieties, crop rotations, biofertilization, micro-organisms inoculation, windbreaks, reforestation, etc.), without the use of chemical pesticides. Monitoring of the phenology of the plants also allows to better understand their reaction to climate change and increased extreme events (frequency of summer droughts, late spring frost).* ***Solutions for water preservation*** *are implemented progressively thanks to a recovery and resilience plan for Romania financing projects focused on water management, and education programs run by universities. In parallel to the transition of the open-air vegetable production, there is a development of* ***controlled environment horticulture****. This includes greenhouses, solariums working with renewable energy, and new forms of horticulture such as vertical farming. Their development is enabled by consumers' education campaigns on CEA, nutrition research and innovation efforts for energy reduction in vertical farming.*

In 2050, the vegetable production in South South-East Romania has successfully managed the transition towards chemical pesticide-free practices. In addition to the management of microbiomes and vegetable holobiont at field level, other forms of horticulture have developed according to the food systems policy for a healthy and sustainable vegetable supply. ***New forms of pesticide-free horticulture have emerged*** *such as vertical hydroponic farming, microfarms. Horticulture in controlled environment is now modular and using renewable energy modules developed by new companies. The different value chains deliver these pesticide free vegetables to Romanian consumers, contributing to a large part of their healthy diets.*

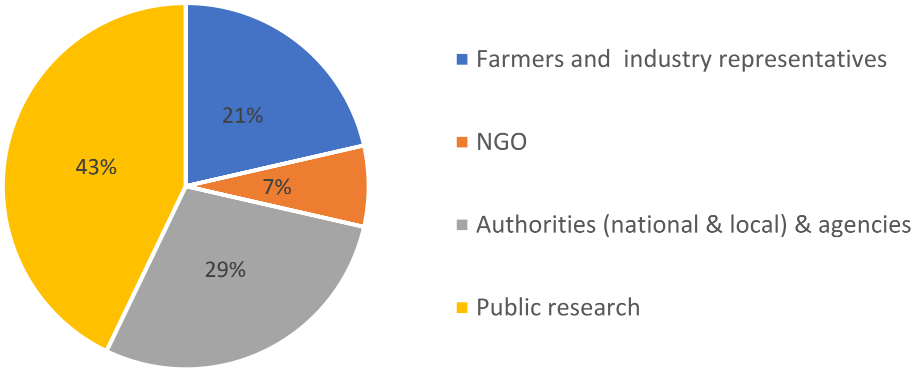
Figure 4-15: Final transition pathway for chemical pesticide-free vegetable production in SSE Romania by 2050



4.2.5. Chemical pesticide-free cereals and oilseeds production in South Finland in 2050

The case study in South Finland was conducted by Sari Autio, Senior Officer at the Finnish Safety and Chemicals Agency Tukes[9], with Emilia Laitala, Senior Officer at the Finnish Safety and Chemicals Agency Tukes, and Marja Jalli, Special Researcher at the Natural Resources Institute Finland Luke[10]. The participatory workshop to elaborate transition pathways towards chemical pesticide-free cereals and oilseed production happened on April 26th, in Helsinki. It gathered 14 participants, as represented in Figure 4-16 (members of the workshop are listed in the Appendix of the report, Table A6).

Figure 4-16: Profile of participants to the South Finland workshop



4.2.5.1. Presentation of the region chosen, cereals and oilseeds production

Finland is located in Northern Europe, mainly between the 60th and 70th latitudes, and is a part of the European Union. The northern location sets some limits, for example with regard to what plants can be cultivated. On the other hand, the cold winter reduces the occurrence of plant diseases and pests. The utilised agricultural area in Finland totals 2.3 million hectares, mainly in the Southern and Western parts of the country. Agricultural land accounts for around 8% of the country's surface area (VYR, 2014).

The local coordinators chose to study cereal and oilseed crops. They are cultivated annually, in an area of approximately one million hectares. Cereals represent around 14% of Finland agricultural output (EC, 2021; 2018-2020 average). Finland is the world's northernmost grain-producing country. Four cereal crops are produced on a larger scale: barley, oats, wheat and rye (VYR, 2014).

[9] https://tukes.fi/etusivu

[10] https://www.luke.fi/en

Figure 4-17: Grain production and processing places in Finland
(Source: Finnish cereal committee[11])

The studied area corresponds to the South of Finland.

[11] https://www.vyr.fi/document/1/804/f800e82/huonee_29ec443_Grain_production_and_processing_places_in_Fin.pdf

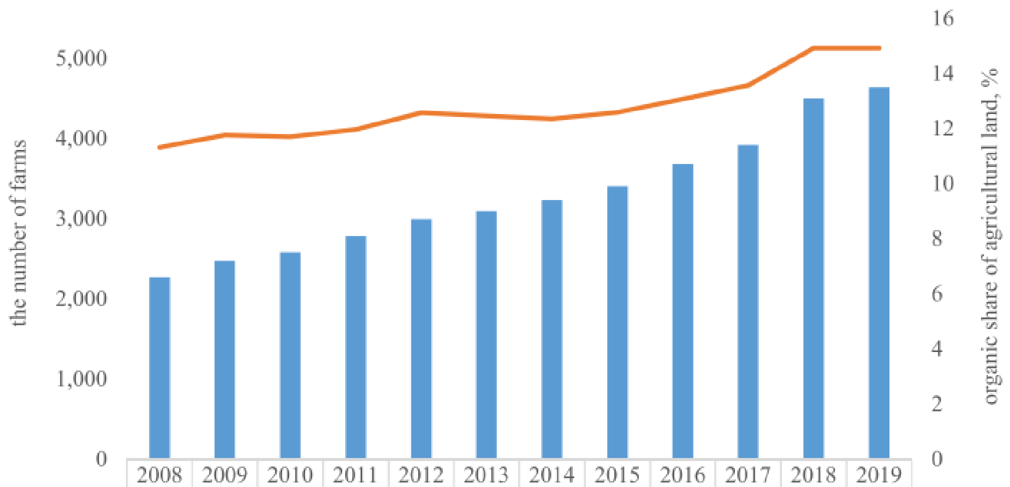
4.2.5.2. Key trends in the region for the production of cereals and oilseeds products

The retrospective analysis and identification of trends have been prepared by the local coordinators, and completed with a short literature review (non-exhaustive) using the Web of Science database, documents from the European Commission (EC, 2020c) and foresight operations conducted in Finland. It was discussed during the regionalisation meeting that gathered the local coordinators and members of the foresight team Olivier Mora and Claire Meunier.

Major trends identified on cereal and oilseed cropping systems

The main cereals and oilseeds produced in Finland currently are wheat, rye, barley, oats, and protein crops (oilseed, pea, faba bean). The share of organic farming has increased over the past 10 years to reach in 2019 around 13.5% share of agricultural land as shown in Figure 4-18 (Kujala *et al.*, 2022).

Figure 4-18: Evolution of the share of organic in agricultural land in Finland from 2008 to 2019 (Source: Kujala *et al.*, 2022)



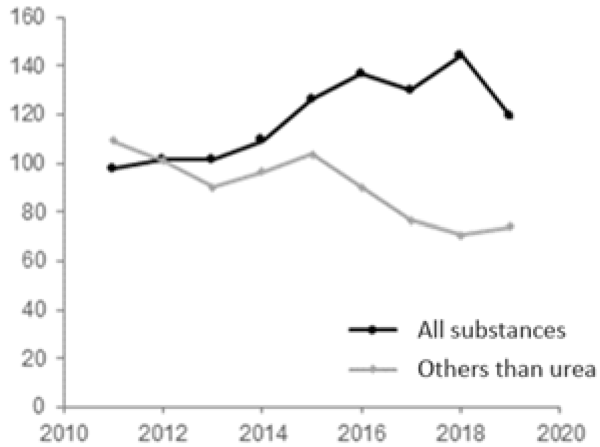
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
share of agricultural land	6.6	7.2	7.5	8.1	8.7	9	9.4	9.9	10.7	11.4	13.1	13.5
number of farms	3890	4043	4022	4114	4322	4284	4247	4328	4493	4665	5129	5129

Seeds used are varieties adapted to the specific Nordic climate conditions (short growth season with cool climate and long daily hours). There is a growing interest in reduced tillage: ca. 10% of the field area is now on direct sowing. The main pests to manage are weeds (Salonen and Hyvonen, 2002), leaf diseases insects such as flea beetles. The use of chemical pesticides in Finland show a trend towards reduction, except for urea (Figure 4-19) (Tukes, 2021). Crop protection measures include the use of chemical pesticides and alternatives such as cultivar resistance, diversified crop rotation (Peltonen-Sainio and Jauhiainen, 2019), catch crops, mechanical control (Vanhala *et al.*, 2006). Also, crop protection decisions are based on field observations, following threshold values of occurrence of pests and weeds. For example, the web-based monitoring application LukeKasKas for observing weed, plant disease and pest situation and planning for control measures is freely available for the farmers[12]. The choice of plant protection products available and adapted to Finnish conditions decreases, potentially causing an increased risk of resistance. This is due to the small market of pesticides in Finland for chemical companies, and to the European risk assessment and approvals

[12] https://maatalousinfo.luke.fi/fi/cms/kasterveys/lukekaskas

process. In future, there should be an increase in transition to organic farming, profitability of organic products being higher than conventional production, and being supported by payments from the Common Agricultural Policy (CAP). Finland has launched in 2021 a national program for organic production development by 2030 (Ministry of agriculture and forestry of Finland, 2021). An important factor for the future evolution of cereal and oilseed production in Finland is climate change. There are already observed increased temperatures during the growing seasons of cereals, with reduced yield variability (Peltonen-Sainio *et al.*, 2009), and evolutions in pests and diseases (Hakala *et al.*, 2011). More generally, maintaining the economy and profitability of Finnish agriculture is an important challenge for the future (Huan-Niemi *et al.*, 2017).

Figure 4-19: Evolution of the Harmonized Risk Indicator #1 in Finland from 2011 to 2019 (Source: Tukes, 2021)



Major trends identified on cereal and oilseed value chains

Cereals are mainly processed into bread and milling products for food consumption, and oilseeds to vegetable oils. Roughly, half of annual grain production is used as feed for livestock to support the domestic animal production (cereals and squeezing cakes) (VYR, 2014).

Bread and milling products are basic food products in the diet of Finnish people. Especially rye and oats are important contributors to traditional finish diets. Over the past years, there has been an increased demand for plant-based foods, like oat-based “milk”, vegetable oils, and for organic products. This change in people’s diet expectations is triggered by healthy and environmentally friendly choices (Saba *et al.*, 2010; Dean *et al.*, 2007). The value chain is organized at regional level (Figure 4-17). The milling industry represents 9 big companies, and 100 small and medium enterprises. There are more bakeries (78 big companies and 871 small and medium enterprises). Retailers are more concentrated with 3 main chains of groceries (EC, 2020c). Local direct selling is an increasing trend with local direct selling events or network such as REKO[13].

Labels are developed on cereal and oilseed products, to inform consumers about their nutritional and environmental benefits: EU organic label, healthy choice (for heart health), domestic production (for example the label “produced in Finland” or delicious from Finland[14]. In future, there should be an even higher demand for diversified products (for health reasons and diversified diets, but also curiosity testing of new choices). The importance of local production should also increase as a driver of consumers' choices, and community supported agriculture.

[13] What is REKO? - (aitojamakuja.fi)

[14] The Hyvää Suomesta (Produced in Finland) label | Hyvää Suomesta (hyvaasuomesta.fi)

Major trends identified on agroequipment and digital technologies in Finnish farms

Finland is an innovative and knowledge-oriented society with a strong emphasis on digitalisation and research (EC, 2020c). New technologies are available and accessible to farmers. They include remote sensing, drones, IoT (internet of things), mobile applications for agricultural services, virtual trainings of the inspectors of spraying equipment, soil scouting and other techniques to analyse local conditions. Among farmers, young generations are more eager to apply these new technologies. Also, wide application of these technologies depend on their prizes and digital knowledge among farmers. Active research and long-term funding for the development of technologies applicable to Finnish conditions are important. There should be an increasing interest in these IT solutions, driven by environmental concerns among farmers, and increasing interest in analysing and interpreting the local cultivation conditions (soil health, microbiome, etc.).

Major trends identified in Finnish farm structures

In Finland there are typically family farms, 86% are owned by private individuals. There is a past trend towards reduction in the number of farms and increased size (Peltonen-Sainio and Jauhiainen, 2019), even if average field area remains rather modest (49 ha average, 63 ha in organic farming). Finnish agriculture is highly dependent on CAP payments (Huan-Niemi *et al.*, 2017): agricultural policy and targeted subsidies are a key driver to the general structure of agriculture (EC, 2020c). Forestry income is another source of capital for farmers. Cereal farms usually do not employ significant external employees, labour force being primarily farmers and family members. Farms are specializing (32% of farms are specialized in grain production in 2020). We can notice an increasing interest among farmers, consumers and the society in general in environmental protection. Climate change and its consequences in terms of instability could make it difficult for new generation of farmers, at least full time.

4.2.5.3. Scenario of chemical pesticide-free cereals and oilseeds production in South Finland in 2050

Choice of the desirable scenario from the European scenarios

The local coordinators chose the European scenario **“Territorial and regional coordination, complex and diversified landscapes for a one health food system”** as a desirable scenario for the local study. The reasons for this choice are based on the trends identified in the retrospective analysis, mainly consumers’ trends: increasing interest for diversified healthy products, local production, community supported agriculture. Also, the increasing interest from farmers in analysing and interpreting the local cultivation conditions and adapt their practices thereof, and the value chain, mainly oriented towards local and regional distribution channels, justify this choice. Another option could have been to study the scenario “European and regional food systems, soil and food microbiomes for healthy food and healthy diets”, since consumers trends are oriented towards healthy diets. The regional coordinators considered that scenario “Territorial and regional coordination, complex and diversified landscapes for a one health food system” was more appropriate, given the importance of both individual health and environmental concerns among Finnish society (Lehikoinen and Salonen, 2019).

Regionalised scenario

The regionalised scenario was built from the hypotheses generated during the regionalisation meeting, for each of the components. The complete scenario is in Appendix 4-1. Below we present a short narrative and a summary table of hypotheses (Table 4-4).

Scenario for chemical pesticide free cereals and oilseed production in South Finland in 2050 (short narrative)

Finnish cereals and oilseed sector produces sustainably healthy milling and vegetable oil products, and delivers ecosystem services to local consumers & citizens who are concerned about environmental and human health preservation.

In Southern and Western Finland, in 2050, cereals and oilseeds are produced without chemical pesticide, in order to answer Finnish consumers' demand for food preserving human and environmental health. Consumers look for food with a high nutritional value and that are little processed. Finnish people are very concerned about environmental protection, preservation of rural areas, and about food sovereignty. In 2050, Finland is self-sufficient in producing protein rich plant crops for animal feed as livestock production has reduced and mainly switched to organic dairy and for biogas. Finnish society acknowledges the ecosystem services of agriculture, and farmers' environmental protection services are explicitly targeted by public subsidies. Healthy and environmental friendly food are affordable to all thanks to targeted public subsidies.

Cereal cropping systems are diversified and represent maximum 3/5 of the crop rotation. Other crops include legumes for plant protein, feed nutrition, but also to contribute to healthy soils. Green manure is used as a source of fertilization and also to strengthen soil microbiome. The seeds selected are local, adapted to the specific climate conditions in Northern Europe, and also to pests and diseases. They are heat-treated to prevent seedborne diseases and increasing risk of mycotoxins along the humid weather conditions. Crop protection is ensured through biological regulations by complexification of landscape including forests, crop diversification, with field strips and buffer zones to maintain beneficial arthropods and other biodiversity, beetle banks and flowering zones around the plots, honey bees and wild pollinators for oilseed crops pollination. Non-chemical solutions, such as late sowing are used for some specific pests such as Phyllotreta spp. on oil crops. Crop diversification and complex landscape are also very important to strengthen the resilience of cropping systems to extreme climatic events that are now more frequent because of climate change. Circular economy if favored and supported by the bioeconomy Finnish strategy: farms aim to closing the cycles of inputs and outputs, e.g. by local production of biogas and return of nutrients into the soil via biogas digestates.

Cooperation between farmers, advisory organisations, and other actors at territorial level is in place in order to monitor efficiently the weather but also the state of ecosystem and the dynamics of animal pests, weeds and diseases. IT monitoring systems based on diverse remote sensing data and crowdsourcing of information are available, accessible to farmers, and allow online and collective book keeping to base decisions.

Farmers are educated and regularly trained virtually on agroecology and the use of digital tools. They are supported by independent advisory organisations. They cooperate at territorial level to share machinery, knowledge, monitoring. Non-farm activities have developed (part-time farming) such as advisory services, own baking productions, part-time research, etc. Participatory research and development through Living labs have increased the co-development of innovative solutions by gathering researchers, farmers and machinery companies.

Cereal productions are transformed locally into milling and oil products that are very diverse, little processed, of high nutritional value thanks to the use of wholemeal cereal flours, legumes flours that are rich in plant proteins, fibre, and micronutrients. Milling and bakery industries remain local small and medium size enterprises (SMEs). Pulses are also valorised in animal nutrition, improving Finnish self-sufficiency for feed.

Consumers buy these free-pesticide products from a diversity of food chains: big/national retailers, local food markets, and direct distribution channels allowing them to be in direct contact with farmers through digital platforms. Community supported agriculture, improving the link between consumers and farmers, is very popular. Responsibility, sustainability claims (such as organic label) and certificates are checked and approved by public authorities before being used on food labels. This public verification of environment and health claims has reinforced consumers trust in Finnish products. Food chain have reduced the transport of food from long distance, and food packaging is fully recyclable and leverage the bio-based resources materials from forests.

Table 4-4: Summary of hypothesis per component

Cropping systems	Diversified cereals, oilseed and legumes crops, protected from pests by preventive farming practices, leveraging biological regulations and arranging a mosaic of areas at landscape scale.
Agricultural equipment and digital technologies	Cooperation between farmers to share equipment and also monitoring of weather, ecosystem dynamics and pest developments.
Food value chain	Local and diversified cereals and oilseeds products, certified by Finnish authorities as healthy and environmentally friendly.
Farm structures	Larger family farms owned by farmers concerned about the environment, rewarded for their ecosystem services, and involved in other activities (part time farming).

Comments on the scenario

The regionalised scenario prepared by the local coordinators and the foresight team was presented to the participants of the workshop, who discussed it around four questions: *What are the key words from the scenario? What are the main challenges around the scenario? How clear is the scenario on a scale from 1 to 5? What can be added to make it more explicit?*

After reading the scenario, participants put forward "**cooperation"** as an important keyword. They also mentioned keywords related to cropping systems such as "**profitability**", "**mixed production systems", "diversity", "environmental footprint**", **"self-sufficiency", "keeping up production"**. They quoted key words related to value chain: **"local chains", "transparency".** Some keywords were more transversal, and relate to **"transparency", "shared knowledge", "digitalisation", and "public subsidies".**

The challenges identified in order to reach the scenario are linked to the **economic situation and sustainability of Finnish farms** and also of small and **medium size enterprises** (SMEs) such as cereal processing companies. Indeed, the Nordic location of Finland brings a lot of constraints for its agricultural production. According to the European Commission, between 2010 and 2018, the income of farm households has decreased, whereas it has increased in households relying on non-agricultural entrepreneurial income or salaried employment (EC, 2020c). Ensuring the profitability of Finnish agriculture in 2050, and a fair distribution of value within the value chain is a challenge.

Participants questioned the co-existence of different production systems in 2050: **farming without the use chemical pesticides, and organic farming**. As described in the retrospective analysis, the share of organic farming has increased over the past 10 years to reach in 2019 ca 13.5% share of agricultural land (Kujala *et al.*, 2022). Will the transition towards chemical pesticide-free agriculture happen through organic certification for all farms? Will there be a co-existence of various systems: organic, organic with new standards, pesticide free farming with other criteria (biodiversity, etc.)? The consensus within the group was that there should be no opposition between the various schemes and especially between organic and others farming systems without chemical pesticides, and that the transition towards chemical pesticide-free agriculture can be achieved through different farming systems.

Participants highlighted the **heterogeneity of consumers**, not all being concerned nor willing to pay the price for environmental preservation. Similarly, there is also a **heterogeneity of the farm structures**, with different reactions or adaptability to the scenario.

Participants considered that the scenario was pretty clearly described in the narrative (rated 3 and 4 out of 5). They suggested several additions in order to make it clearer. First, they recommended to define more clearly in the scenario what we mean by "**chemical pesticide-free agriculture**". This generated a general discussion about the scope of the foresight, with the particular case of urea. Urea is used as a repellent against root rot in forests. The Finnish Forest Damages Prevention Act obligates forest owners to carry out pest management in loggings of predominantly coniferous forests during the summer. Urea is also used as a fertiliser in agriculture and forestry. Unlike most plant protection products, urea is not primarily designed with the intent to kill the repelled organisms. In addition, data on pesticide use and risks in Finland show decreasing trends except for urea, as described in the retrospective analysis.

It was also commented to refer to the EU farm to fork strategy for the definition of chemical pesticides. Indeed, it sets targets on the use and risks of chemical pesticides, where chemical pesticides are defined as those containing active substances in categories B (chemical low-risk substances), D (other chemical substances), E and F (more hazardous active substances), and G (non-approved active substances)[15].

The participants also suggested to add information about the **evolution of the production in 2050**: will there be an increase in production, more export? Several aspects could be added to the scenario:

- Increases in production: due to improved growing conditions especially with climate change (winter crops introduction, longer rain periods, thicker ice);
- Opportunities to export cereals outside of Finland;
- Fairer split of value across the chain.

They also proposed to describe the **impacts of climate change on Finish cereals and oilseed production** conditions. Indeed, in 2050, due to global warming, there could be the introduction of winter crops, and also the emergence of new pests.

They also discussed the opportunity to add information about the **nutrient cycle issue**, and leaching of nutrients.

Participants highlighted an **apparent contradiction between consumption of less processed food and vegan diets.** For example, oat-based beverage is a plant-based alternative to cow milk, but can be considered as a processed food. They recommended to add information about **food prices**: how will the food prices evolved by 2050: will they be cheaper, more expensive, and still affordable to all? How to manage potential inequalities in access to food? They also suggested to discuss more **plant breeding as one of the tools for adaptation to climate change**. Finally, they proposed to **include retailers as actors who can support the transition** – in addition to public subsidies.

All the challenges highlighted by the participants were then addressed in the next steps of the workshop, when identifying milestones and actions in the transition pathway (food prices, diet evolution, plant breeding, anticipation of the impact of climate change, evolution of the retail).

4.2.5.4. Building the transition pathway towards chemical pesticide free cereal and oilseed production in South Finland by 2050

Milestones and actions to achieve the desirable scenario

After the presentation and discussion on the scenario, participants to the foresight workshop followed the backcasting methodology. In two groups, they identified first the milestones – intermediary steps required to achieve the desirable scenario. Then, they identified actions that will lead to these milestones. Table A.4-3-3 in Appendix 4-3 lists the milestones and actions for the transition towards chemical pesticide free cereals and oilseed production in South Finland by 2050. They are further commented below.

[15] See file for calculating the F2F indicator 1, available at : https://ec.europa.eu/eurostat/web/agriculture/agri-environmental-indicators/information

Future pest development

Participants identified two milestones on cropping systems related to the management of future pests on cereals and oilseed crops: "**Foresight and scenarios available regarding future pests risks in Finland due to climate change**", and "**Pesticide-free control methods for future pest risks are identified**".

Indeed, with climate change, participants anticipate that future pests will emerge in Nordic regions, requiring adaptation in terms of crop protection. For this, they have identified the need to conduct a Northern European research project on the most probable pests (insects, diseases, weeds) in Nordic countries and their potential effects on cereals and oilseed crop production. Once the future pests are identified, they propose to learn from all available and successful control methods already available among farmers, in Finland and in other countries.

Milestones related to organic food consumption development and to changes in diets

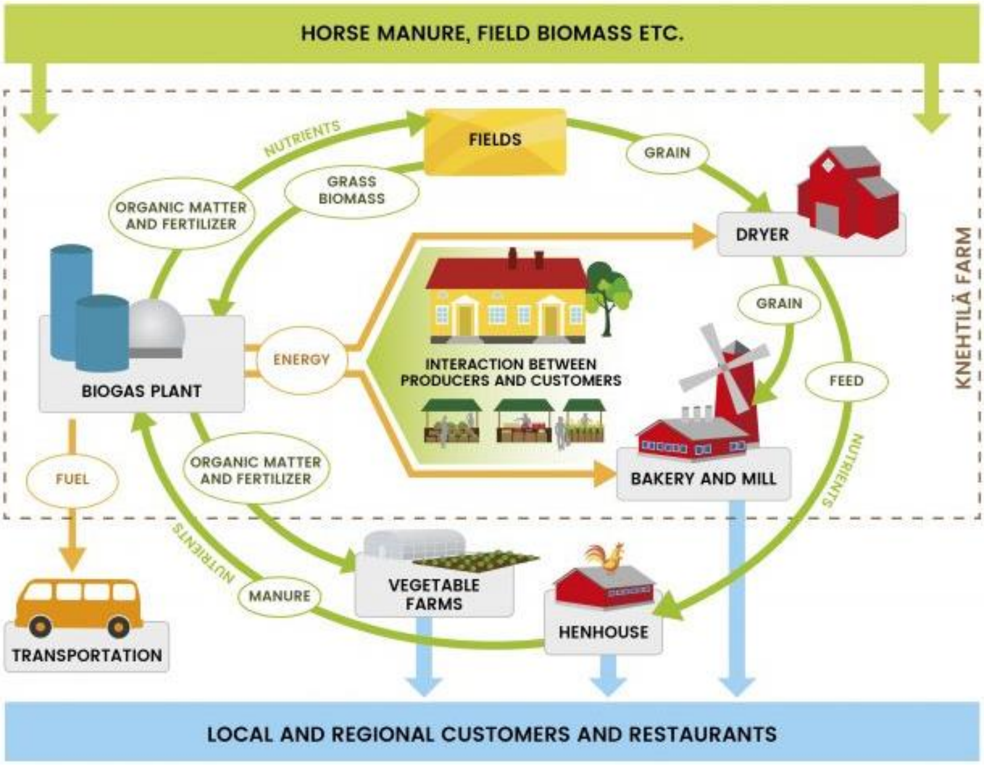
Several milestones in the food value chain relates to the development of organic food consumption, in both food services and in retail: "**organic food will account for 25% share in food services and 10% market share in retail in 2030**", and 60% and 20% in 2040. These milestones build on the current trend of development of organic production and consumption in Finland (see paragraph 4.2.5.2). It will be supported by CAP subsidies targeted towards organic growth, and by the use of the EU school scheme to promote organic food consumption in canteens.

Also, an important milestone in the value chain is the **change of Finnish people diet towards plant-based products and low-processed foods**; as the share of consumption ultra-processed food was 31% of the total food consumption in 2020 (Mertens *et al.*, 2022). This change is triggered by Finnish citizens' concerns about the environment and biodiversity preservation. It also drives a "**renewal of the food offer in the Finish market"**, which has evolved to answer changes in consumption habits and now includes more diversified, plant-based and locally produced foodstuffs. This opens new opportunities for small and medium-size enterprises (SMEs). **Price policies** influence food behaviours changes, as well as **a label**, created at European level, for "good food" – based on nutrition and environment criteria. This label further evolves in time to include social criteria. As part of this plant-based diet, pulses play an important role. These products are well accepted by Finnish consumers thanks to the use of new varieties, and thanks to new low processing technologies developed by the R&D of private companies, to manage potential digestion issues (digestive tolerance).

Agroecological Symbiosis

When discussing farm structures, a milestone was positioned at the end of the backcasting timeline: **agroecological symbiosis in place in the territory**. Agroecological symbiosis (AES) is a food production and processing symbiosis of farms and food processors. In addition, as a localized food system model, AES is expected to have cultural and socio-economic benefits (Koppelmäki *et al.*, 2016; Helenius *et al.*, 2020). There is already one AES system in the village of Palopuro in southern Finland, a cooperative food production system based on energy and nutrient self-sufficiency (Figure 4-20). This multi-enterprise network aims to produce local, organic food using bioenergy and recycled nutrients. This model of integration requires very strong cooperation between farmers, processors, and energy producers.

Figure 4-20: Palopuro Agroecological Symbiosis system
(Source: Koppelmäki *et al.*, 2019)



Collaboration between farmers

"**Collaboration**" is quoted in several milestones in the transition (in 9 milestones across the different components), and has been intensively discussed during the workshop. Indeed, the scenario requires strong collaborations, between farmers, and other actors in the value chain. Cooperation happens at various levels and serves various needs: it starts by creating mutual trust, cooperation to share equipment, field usage collaboration models in place based on experiments results, collaboration platforms for farmers, and ultimately the integrated system of agroecological symbiosis. This aspect is very important in the transition since farmers are used to be working rather isolated, due to the distance and historical practices. For these collaborations to happen, local farmers' organizations play a key role, as well as farmers' advisors, who can encourage and promote exchanges of best practices. Also, communication campaigns can promote models of cooperation, and public subsidies can finance the creation of in projects in cooperation with other farmers.

Demo-farms

A key action identified by the participants in the transition is to rely on demo-farms, which could test innovations, new practices in terms of crop rotation, pest protection, and then share the results with the wider community of farmers.

Transition pathway

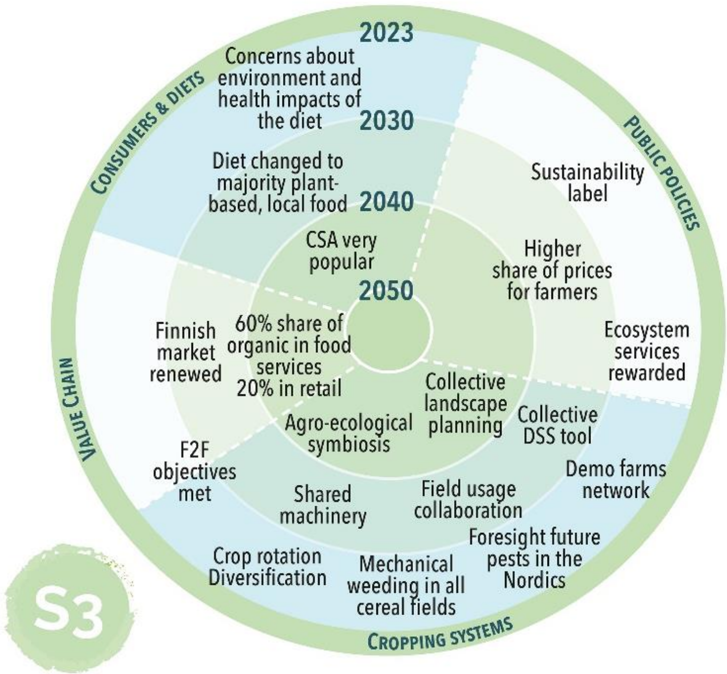
The last session of the workshop was dedicated to the building of the transition pathway, by connecting the milestones and the actions together, in a chronological and logical way. After the workshop, a proposal for a second version of the transition was prepared and discussed during a meeting on September 9th, with the local coordinators and the participants to the workshop.

There was a discussion on the current crisis situation with the war in Ukraine and how it impacts Finnish agriculture: increases in energy prices, input prices for farming (access to mineral fertilisers and chemical pesticides), and food prices. As for some participants, this situation could slow down the progress that they had imagined it during the workshop, other argued that it could also be an enabler to the transition, since the current situation should lead to efforts aiming at reducing dependencies.

The final version of the transition pathway is presented in Figure 4-22, with its simplified version in a form of target diagram (Figure 4-21). A narrative accompanying the transition pathway was also produced, as follows.

Figure 4-21: Target diagram summarising the key transition steps towards chemical pesticide-free production of cereals and oilseeds in South Finland by 2050

CSA : community supported agriculture ; F2F : farm to fork ; DSS : decision support system



Credits: Lucile WARGNIEZ

Narrative describing the transition pathway

The transition starts with consumers' change in attitude: they become even more concerned about the impact of their consumption on the environment. They are better informed about the environmental and nutritional footprint of the food they buy thanks to a sustainability logo appearing on product labels. Also, price policies encourage consumption changes towards products that are better for human and environmental health. This leads to a growth in organic food consumption, which represents in 2030 10% of the share in retail, and 25% in food services. Public policies support this evolution by subsidizing farmers' conversion to organic farming (CAP), ensuring a fairer split of food prices along the food value chain and by leveraging the EU school scheme to increase the share of sustainable procurement in canteens. This also leads to a change in Finnish diets towards a majority consumption of locally produced plant-based food. In 2033, the Finnish food market has been renewed, and proposes a variety of plant-based diversified food products including pulses. It is also less centralized and more developed locally, close to local productions.

Consumers' increased demand for sustainable, organic, plant-based food stimulates the diversification of the crops produced in Finland. Farmers' crop rotation and diversification successes are promoted through "demonetwork" and facilitation of transfer of organic farmers' knowledge to conventional farmers. Collaboration between farmers, and with researchers, advisors, is encouraged by public subsidies, and allows sharing of best practices, operational support, and dissemination of results from experiments.

Pest management practices evolve towards less use of chemical pesticides through the continued development of organic farming, acceleration of crop diversification and widespread use of mechanical weeding. As of 2024, digital tools – satellite, weather forecast, autoguides – help farmers to anticipate risks and support action by prophylaxis. The Farm to Fork objective of 50% pesticides reduction in 2030 is reached. In parallel, a research program on Northern Europe future pests on cereals and oilseed crops identifies future pests developments linked to climate change, and builds scenarios of future crop protection. This leads to the development of new biological control solutions, based on farmers' knowledge and R&D efforts from biocontrol companies. In 2036, farmers use mostly low risk substances and microbiological solutions.

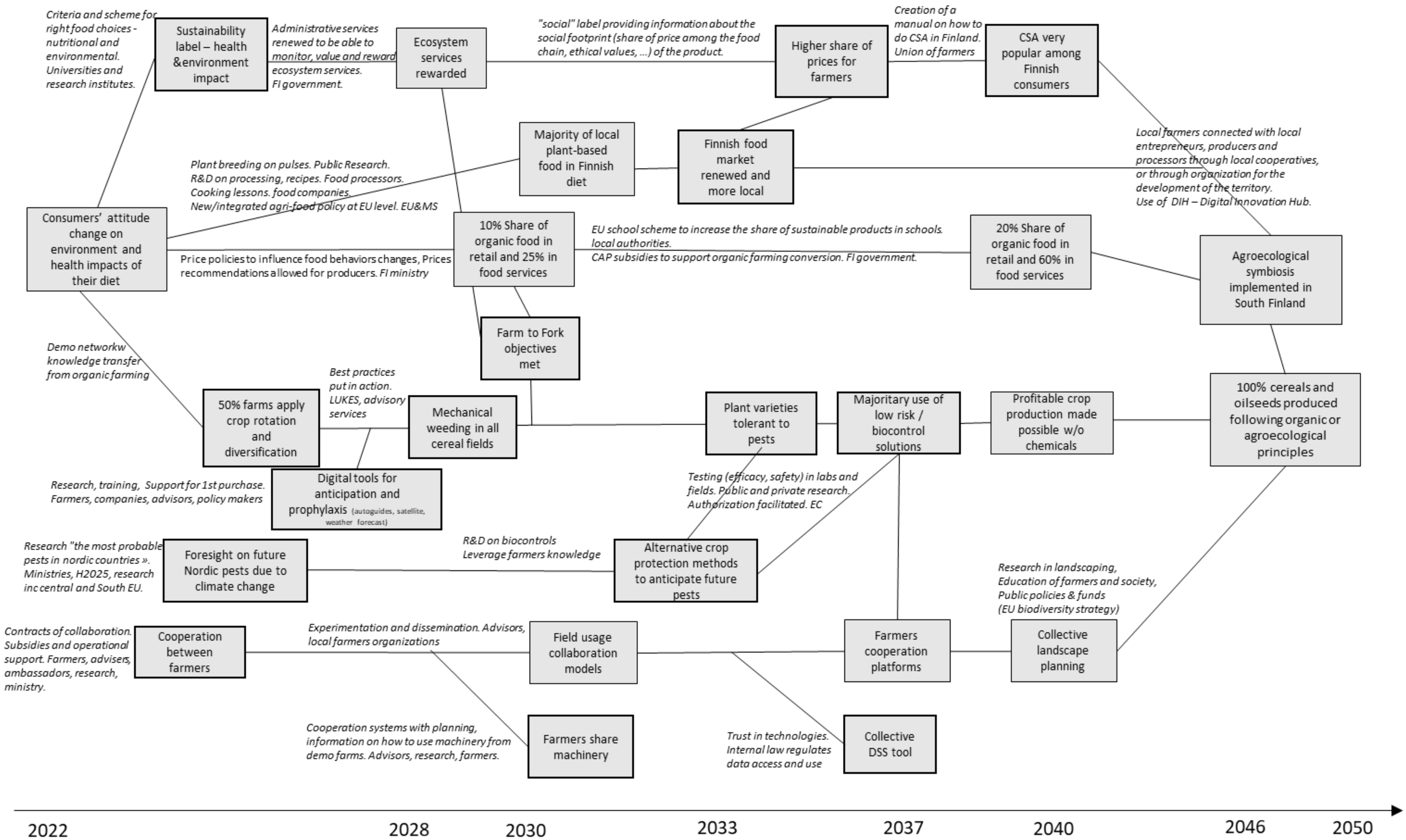
In 2030, the ecosystem services provided by farmers are legally acknowledged. They are monitored and rewarded by the renewed administrative public services. This reinforces the farmers' local cooperation: in 2030, they collaborate to share machinery. They also conduct together field experiments, coordinated by local farmers' organizations, whose results enable the development of field usage collaboration models adapted to the local conditions. By 2037, collaboration platforms are set up to exchange information, to monitor the biological regulations and the biodiversity at the landscape level. All the data gathered through this platform are aggregated and treated by a collective decision support system tool. Thanks to research in landscaping, education of farmers and citizens, as well as EU Biodiversity strategy implementation, the collaboration further develops into collective landscape planning by 2040, where it is discussed collectively and transparently, between all actors involved.

In the 2040's, Finnish consumers' expectations in terms of food sustainability enlarge to also include its social dimension. This leads to the creation of a new sustainability logo informing about the social footprint of food. Community Supported Agriculture becomes very popular among the Finnish population.

By the mid-2040's, cooperation goes one step further with the implementation of agroecological symbiosis (AES) in South Finland. AES is the integration, at local level, of farmers with food processors and energy providers, to base farming and cereal production on renewable bioenergy, to close nutrient cycles, be more connected with consumers, and revitalize the rural spaces. Local farmers are connected with local entrepreneurs, producers and processors through local cooperatives, or through the creation of an organization for the development of the territory (region). Digital tools such as DIH – Digital Innovation Hub – connect remotely these actors working on the same goal. They produce produce pesticide free cereals and oilseed products, in addition to their own energy, from local biomass. AES brings together all local actors in the food chain up to consumers, provides environmental benefits, generates a local food culture and enhance local rural livelihoods and economy.

In 2050, 100% of cereals and oilseed are produced without chemical pesticide, following organic or agroecological principles. There is a coexistence of organic production – that has evolved to include new criteria - and chemical pesticide-free production.

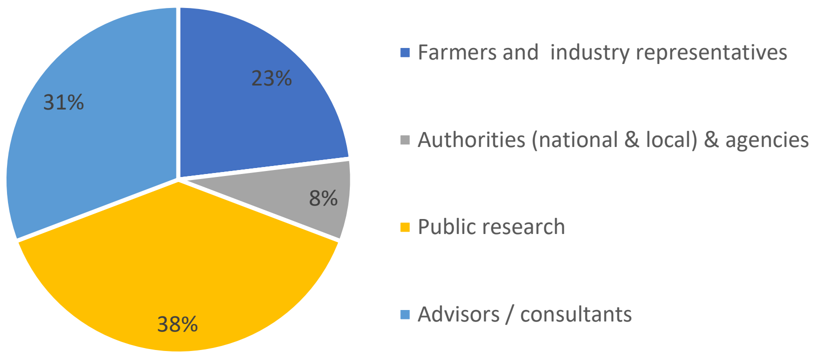
Figure 4-22: Final version of the transition pathway for cereals and oilseed production without chemical pesticides in South Finland



4.2.6. Chemical pesticide-free wine production in Bergerac Duras in 2050

The case study on chemical pesticide free wine production in Bergerac Duras was prepared with several people: Cécile Lelabousse, in charge of the environment at the Bergerac Duras wine interbranch organisation (association Interprofessionnelle des Vins de Bergerac Duras, IVBD), Yann Raineau, at the time in charge of coordinating the vitiREV program within the Nouvelle-Aquitaine Region, Hubert de Rochambeau, in charge of a mission animating the archipelago of the 'living labs', Natacha Elia, coordinator of the Laboratoires d'Innovation Territoriale (LIT) (Territorial Innovation Laboratories) for the Gironde Chamber of Agriculture, Claire Gouty-Borges and Denis Salles from ETTIS – INRAE. The one-day workshop happened in Bergerac on May 6th, 2022, and has been organised by Cécile Lelabousse. The facilitators of the workshop were Claire Meunier and Olivier Mora from INRAE. In total there were 13 participants to the workshop. The workshop brought together participants from a wide variety of backgrounds, divided fairly evenly between representatives of the farmers and the wine industry (wine growers, trade organisations), advisers from local public agencies, and scientists (INRAE, ISVV, Bordeaux sciences agro) (Figure 4-23; members of the workshop are listed in the Appendix of the report, Table A6).

Figure 4-23: Profile of participants to the Bergerac Duras workshop

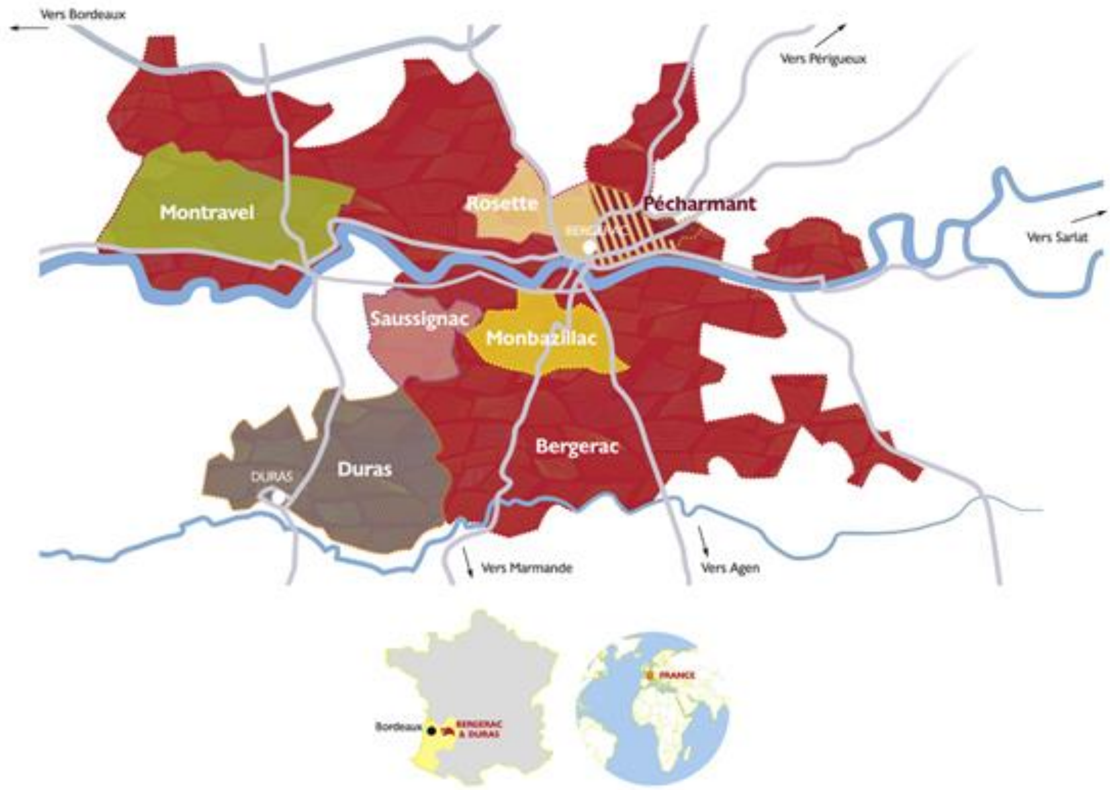


4.2.6.1. Presentation of the Bergerac Duras territory and wine production

Within the Nouvelle-Aquitaine region in France, the Bergerac-Duras territory was chosen to conduct the study. The Bergerac-Duras vineyard is located near the Bordeaux vineyard, in Périgord, on both banks of the Dordogne River, and in Lot-et-Garonne for the Duras area (Figure 4-24). The Bergerac Duras wine trade association has been participating since 2019 in the VitiREV program (environmentally friendly viticulture), as a Laboratory of Territorial Innovation (Laboratoire d'Innovation Territoriale – LIT) which is called "Fab'coop : coopérons pour les transitions" (cooperate for the transition in Bergeracois) (IVBD, 2021). Within this laboratory, several projects are underway, co-constructed with different actors of the territory, in the service of the environmental transition. One example is the realization of territorial and individual diagnoses on the Pécharmant sector, to allow a global landscape reading and the implementation of actions such as the installation of agroecological infrastructures (IVBD, 2021).

Viticulture in Bergerac Duras is the major crop of the territory: 11,800 hectares of vineyards are cultivated, for a production of 552,000 hectolitres or 73,600,000 bottles of wine per year[16]. The vineyard represents 2.8% of the French AOC vineyard surface.

Figure 4-24: Bergerac Duras territory (Source: IVBD - Interprofession des Vins de Bergerac Duras[17])



4.2.6.2. Key trends related to wine production in Bergerac Duras

The local coordinator completed the table before the regionalization meeting, based on her knowledge and experience. In parallel, the foresight team conducted bibliographic research on the trends in viticulture in Bergerac Duras and in New Aquitaine. In particular, the LACCAVE project carried out between 2012 and 2016 was very instructive (see in particular Ollat *et al.*, 2016, project website: https://www6.inrae.fr/laccave), as well as the results of the PhytoCOTE project (Macary *et al.*, 2020). Research in progress within the framework of the PPR Cultiver et Protéger Autrement (Growing and Protecting crops Differently) was also consulted, and in particular some of the work on viticulture was presented at the professionals and researchers' meeting 'Moving away from pesticides in viticulture' organized on 8 March 2022[18]. The activity report of the IVBD trade association also gives information on the evolution of the vineyard, and its numerous activities, as well as the specifications of the

[16] https://www.vins-bergeracduras.fr/decouvrez/presentation-et-histoire/

[17] https://www.vins-bergeracduras.fr/carte-des-appellations/

[18] See for example the VITAE project : https://www6.inrae.fr/cultiver-proteger-autrement/Les-Projets/VITAE and the replay from the meeting "moving away from pesticides in viticulture" : https://www6.inrae.fr/cultiver-proteger-autrement/Evenements/Evenements-passes/Retour-sur-la-Rencontre-Chercheurs-Professionnels-Sortir-des-pesticides-en-viticulture#:~:text=%5BREPLAY%5D%20Rencontre%20Chercheurs%20%2D%20Professionnels,%3A%20Beaune%2C%20Montpellier%20et%20Bordeaux

Bergerac and Duras designations of origin. This retrospective analysis was discussed during the "regionalisation meeting" on April 5th, gathering 5 local experts, Olivier Mora and Claire Meunier.

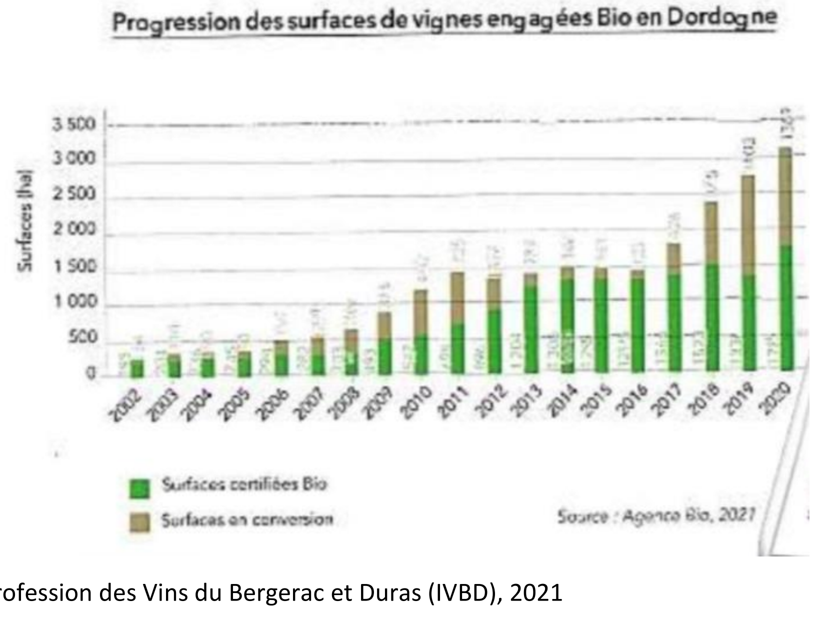
A summary of the main trends identified is presented below.

Main trends identified on the viticulture in Bergerac Duras

The Bergerac Duras vineyard covers 12,500 ha of vines (INSEE, 2018), 30% of which are certified organic or in conversion. Dordogne is the French department with the largest share of organic vineyards in New Aquitaine (IVBD, 2021). There is a strong increase in certifications - Organic farming (Figure 4-25) and HVE (High Environmental Value). The varietal choices are made in compliance with the Bergerac Duras AOC and IGP specifications. The IGP catalogue allows for the testing of resistant grape varieties and some are currently being tested in the Duras vineyard. Two conservatories of grape varieties have been created, including one dedicated to indigenous varieties (muscadelle, merille).

The main pests for the grapevine on the territory are mildew, powdery mildew, flavescence dorée, for which pesticides such as copper, sulphur, and insecticides are used. Regulatory pressure is increasing on the use of pesticides, notably via the no-treatment zones (ZNT) which mainly impact peri-urban vineyards. Winegrowers are implementing alternatives (Barbier *et al.*, 2018), and are involved in research and development programs (vinopole, vitidata, etc.). They would like to be even more connected to research and benefit from more infrastructures for experimentation. Biocontrol solutions are being developed such as sexual confusion on Monbazillac, clays (repellents against green leafhoppers in organic farming). The preservation of auxiliaries and the implementation of agro-ecological infrastructures are developing. We can cite the example of predation of pests by bats, or the realization of landscape diagnosis in Pécharmant, a project carried out by the federation of wine growers, with the CAUE (Conseil d'Architecture, d'Urbanisme et de l'Environnement), the LPO (Ligue de Protection des Oiseaux) and the chamber of agriculture. In the future, the stakes for the vineyard related to health and societal expectations should increase. Other future issues include the impact of climate change on the future of the Bergerac Duras vineyard (Ollat *et al.*, 2016), the economic issues of vineyard profitability (Aouadi *et al.*, 2020), and varietal selection (resistant varieties, adapted to climate change, indigenous varieties).

Figure 4-25: Evolution of the surfaces under organic farming conversion in Dordogne (in green: surfaces certified organic in brown: surfaces under organic conversion)



Source: Interprofession des Vins du Bergerac et Duras (IVBD), 2021

Main trends identified in the Bergerac Duras value chain

The Bergerac Duras vineyard produced 520,187 hl in 2021, or 65 million-bottle equivalent (IVBD, 2021). The range of wines is much diversified, including dry whites, reds for aging, rosés. The wine 'à reste de sucre' (sweet wine) represents more than 50% of the production (Monbazillac, Saussignac, MontRavel, Cotes de Bergerac). Seventeen wines are produced in AOC (controlled designation of origin), and three in IGP (protected geographical indication). Bottled wine represents 35%, bulk 65%. These products are recognized as authentic, local, quality and typical products (IVBD, 2021). Historically, white wines constituted the vast majority of sales (70% white and sweet white). Since the 1980s, red wines have increased and currently there is a reverse trend. The wine cooperative cellars vinify the production of their members, contributing to one third of Bergerac wines, and more than half of Duras wines (INSEE, 2018). About half of the producers are independent winegrowers, and half are grouped in cooperatives. The trade is mainly cooperative (e.g. the cooperative colors of Aquitaine). The industry is well organized with a federation (e.g. Fédération des Vins du Bergerac et Duras, FVBD) and a trade association (e.g. *Interprofession des Vins du Bergerac et Duras,* IVBD). The wines are mainly distributed in large and medium-sized supermarkets, but also by the CHR (coffees, hotels, restaurants) network, on the national market. The export represents less than 10% of the market and is stable (INSEE, 2018).

Main trends identified on agroequipment and digital tools

Equipment, tools for working and maintaining the soil have developed very strongly (weed control) over the last few years. Crop protection treatment tools (confined spraying) are very expensive and are not always adapted to hillside vineyards. Moreover, they require qualified drivers. Today, winegrowers use harvesting machines and decision support tools (DSS) such as Decitrait[19].

Future developments concern the pooling of robot-type equipment within cooperatives. A robotic equipment is currently being tested in the Monbazillac vineyard, an electric weeding robot[20]. Decision-making tools should develop strongly: DSS tools that allow the evaluation of mildew, powdery mildew and black rot risks. These DSS are very interesting for wine growers. DSS on pests are currently being developed.

Planting density can have impact on agroequipment and digital tool. Planting density is a very important criterion to find the balance between quantity and quality. It also has an impact on water requirements and pest population. This density dropped in the 1950s, then returned to a higher density since 2000, even if it remains much lower than in other vineyards (density described in the specifications of the Bergerac appellation, JORF 2021).

Main trends identified on the Bergerac Duras wine farms

The average size of the farms is 15 ha (IVBD, 2021). These are mostly family farms, which call on service companies for labour, particularly during the harvest. It appears to be increasingly difficult to find qualified (tractor drivers) as well as unskilled labour. The issue of availability and training of the workforce will be critical in the future. Half of these farms are grouped in the form of cooperatives and CUMAs (Coopératives d'Utilisation de Matériel Agricole, service co-operatives for collective investment and joint use of machinery for tasks directly linked to production cycle). We anticipate an increase in the presence of cooperatives in the future, particularly because of the benefits they bring to the trade.

These farms are specialized in viticulture, even if polyculture is in the majority in Duras (plum trees, cereals, some livestock). In the future, this tendency to return to diversification could increase, to take into account climatic and geopolitical hazards.

[19] https://gironde.chambre-agriculture.fr/outils-daide-a-la-decision/decitrait/

[20] https://www.reussir.fr/vigne/monbazillac-un-projet-collectif-pour-tester-un-robot

Two notable evolutionary trends have been identified. The first one concerns the enlargement of the farms and the ageing of the winegrowers, which poses the problem of the transmission, with different possible evolution hypotheses: resumption by young people, repurchase by other properties, resumption by new rural people. The second one concerns the will of the wine growers to better valorize their productions and thus to develop the wine in bottle at the expense of the bulk.

4.2.6.3. Scenario of chemical pesticide-free wine production in Bergerac Duras in 2050

Choice of the desirable scenario from the European scenarios

The local coordinators chose the European scenario "**Territorial and regional coordination, complex and diversified landscapes for one health food systems**" (S3). The reasons for this choice are based on the trends identified in the retrospective analysis, such as the implementation of agro-ecological infrastructures, the landscape diagnoses carried out on the Pécharmant vineyard, in particular. Moreover, the sector is very well structured at the territorial level via the trade association, and very dynamic. Collective and participative approaches are already in place, and winegrowers are used to working collectively within the framework of cooperatives, CUMAs, etc.

Once the European scenario was chosen, a collective brainstorming session allowed to translate the hypotheses of the European scenario of agriculture without chemical pesticides "Territorial and regional coordination, complex and diversified landscapes for one health food systems" into hypotheses specific to the Bergerac Duras case study. This was done during the regionalization meeting, where participants generated hypotheses of wine production in 2050 in Bergerac Duras, translating the European hypotheses.

Regionalised scenario

The regionalised scenario was built from the hypotheses generated during the regionalisation meeting, for each of the components. The complete scenario is in Appendix 4-1; a shorter narrative and a summary table of hypotheses is presented below (Table 4-5).

Scenario for chemical pesticide free wine production in Bergerac Duras in 2050 (short narrative)

The Bergerac Duras wine industry has succeeded in its agro-ecological transition by mobilizing all the stakeholders in the region to design a sector that preserves the health of humans and the environment, in which ecological processes at the landscape level are favoured and the vineyard is valued for its gustatory and environmental qualities and as an element of cultural heritage.

In 2050, the Bergerac and Duras wines are known for their taste qualities, the viticulture know-how and also environmental performance of the territory, particularly with regards to the preservation of water, soil and biodiversity. The Bergerac Duras vineyard is totally integrated into its territory. The vineyard landscape has been redesigned to promote biological regulation and protect the vines without the use of synthetic chemical pesticides. Natural resources - water, soil, air - are preserved in quality and quantity, and mosaics of crops are associated with semi-natural habitats, with the aim of creating a resilient winegrowing system. The size of the plots has been reduced, as well as the interventions on the vine and the use of inputs. The vineyard landscape is composed of rows of vines associated with other crops such as fruit trees that provide complementary production. The vineyards are bordered by hedges, meadows for grazing, cereal crops and woods. Winegrowers and researchers in vitiforestry have developed knowledge and know-how in the development of synergies between crops. The density of plantation is thought to ensure a fair balance between quantity and quality of grapes and a preservation of water resources. The grape varieties used are genetically diversified from one plot to another in order to promote resilience: they include indigenous varieties, better adapted to climate change, guaranteeing the typicality of the wines of the designations of origin, as well as varieties that are resistant to the main diseases, including new pests and diseases.

The landscapes are designed at the scale of the territory, involving wine growers but also the other actors involved in these landscapes. New participatory governance structures have appeared, integrating farmers, companies, local authorities, local residents' associations, etc. A social contract for the territory links winegrowers and inhabitants in order to preserve local biodiversity and natural resources, and reward them for the ecosystem services. A whole landscape monitoring system that integrates a multiplicity of data analyses the state of biological regulation within the landscape. Thus, winegrowers can use decision support tools based on observation data and their history, anticipating the dynamics of pests and proposing appropriate prevention measures.

The equipment used by the winegrowers is adapted to the diversity of the landscape and are designed according to the needs and specificities of the territory. They are created with manufacturers and suppliers of agricultural equipment to be adapted to the landscape, to pest management, and to meet the challenges of technological and energy sobriety. Indeed, there is now a social responsibility for agricultural equipment firms, which must develop ethical innovations taking into account social and environmental impacts.

Winegrowing operations remain family-owned and managed by new generations of winegrowers trained in the agroecological transition and financially supported by the community. These winegrowers have organized themselves through cooperatives to share equipment, transportation, trading, monitoring tools, but also landscape design. On the territory, the diversity of farms is maintained. Alongside the cooperatives, there are independent winegrowers who act as ambassadors for the sector, and also neo-rural winegrowers who carry out experiments on smaller farms.

The agro-ecological practices are promoted to consumers. The Bergerac-Duras designations of origin - AOC, IGP - include criteria for contributing to the reinforcement of biodiversity in their specifications, and make them visible on the label of their products via the "biosphere reserve" label. The wines of Bergerac Duras are thus very well valued, sold at a fair price. The new agricultural productions linked to crops diversification- fruits, nuts, cereals, animal productions- also bear the "biosphere reserve" label and are sold to consumers via short chains.

The Bergerac Duras region is renowned for the quality of its wines, the beauty of its landscapes and its preservation of the environment and biodiversity. Wine tourism is very popular in the area, and tours are proposed to discover the agro-ecological transition of the vineyard. The range of Bergerac Duras wines is increasingly diversified, including its characteristic sweet white wines and also red wines for ageing or even wines without sulfites to meet the expectations of certain consumers. This approach to preserving the terroir and its environment opens up new distribution channels for Bergerac Duras wines.

Table 4-5: Summary of hypotheses

Cropping system	Mosaics of crops (vines, fruit trees, hazelnut trees, cereals, pastures) and semi-natural habitats (copses, flowering strips, ponds, branches, etc.) create complex, resilient landscapes, where pests are regulated without the use of synthetic chemical pesticides. These landscapes are totally integrated into the Bergerac Duras territory. The interventions on the vine are reduced to a minimum. The grape varieties used are diversified.
Agroequipment and digital technologies	Equipment adapted to these complex landscapes are co-created with suppliers, researchers and winegrowers, and fulfils with the social and environmental criteria of the designations of origin specifications. They are shared between neighbouring winegrowers, as are the tools and monitoring data (climate, bio-aggressors, morphology) of the landscape. They facilitate the work of the winegrowers and reduce the risks for the users.
Value chain	The wines of Bergerac Duras and the new agricultural productions resulting from diversification are acknowledged by consumers for their taste and environmental qualities and their contribution to the cultural heritage of the region thanks to the UNESCO "biosphere reserve" label. They are well promoted to consumers through short chains, the bars, restaurants and cafés (CHR) network and specialised distribution channels.
Farm structures	A social contract bonds together the actors of Bergerac Duras - winegrowers, wine producers, cooperatives, local authorities, local residents' associations, industrialists, etc. - around the same territorial project in which the winegrowers are paid for the ecosystem services they provide. The farms are family-owned. The diversity of winegrowing operations is maintained on the territory with independent winegrowers and cooperatives.

Comments on the scenario

The regionalised scenario prepared by the local coordinators and the foresight team was presented to the participants of the workshop, who discussed it around on four questions: *What are the key words from the scenario? What are the main challenges around the scenario? How clear is the scenario on a scale from 1 to 5? What can be added to make it more explicit?*

The participants emphasized **cooperation between the actors of the territory and the sector** as a major element of the scenario. They highlighted the **social contract**, uniting these actors around a common project. They also mentioned **responsibility** as a key word in the scenario. The participants also quoted **diversity** and **biodiversity**, at different scales - vineyard, landscape, productions. They also spoke about **recognition**, of **a new image for the wine making work**, associated with the **ecosystem services** provided to the territory, and which creates a source of income.

This first sequence gave the opportunity to discuss two subjects related to the scenario: the definition of chemical pesticides and its application to viticulture, and the place of viticulture in the territory in 2050.

On the definition and scope of "chemical pesticides"

The discussion dealt in particular with sulphur and copper, used in viticulture as fungicides, against in particular the development of mildew and powdery mildew. Will these pesticides still be used in 2050 in chemical pesticide-free viticulture? Copper has an impact on the environment, which depends on the conditions of use (doses, frequency, etc.). In the context of foresight as synthetic pesticides, we want to suppress them because of their impact on environment. It seems difficult to the participants with the current knowledge to develop viticulture without those two chemical pesticides. However in 2050, new technologies based for example on microorganisms could be developed, and could help to suppress theses pesticides.

On the question of the place of viticulture in the studied territory

The scenario foresees a diversification of crops, which opens up the possibility of considering a reduction in the areas planted with vines, and therefore in the share of viticulture in the territory. This raises questions about the crops that could replace the vine, given the quality of the soil. It also raises questions about the evolution of the profession of winegrower.

The scenario is considered clear by the participants (rated 3.5 and 4 out of 5).

Participants suggested that the scenario should address the issue of **risk management**, at several levels: risks of pesticides for human health, the environment, how to ensure the health of crops without chemical pesticides, but also the management of risks related to hazards, unforeseen events (including climate). In addition, the **issue of land** could be further developed, as well as the **governance structures** that will be in place. The scenario creates new activities and requires a reallocation of professional activities; it would therefore be interesting to describe more precisely what **the job description of the winegrower will be in 2050**, what the labour needs will be, the working conditions of agricultural workers (remuneration, training, etc.), the transmission of agricultural know-how, etc.

The participants also suggested clarifying the **place of technology in the 2050 scenario**: will viticulture be a heavy user of equipment and robots, or on the contrary, will it be oriented towards technological sobriety? Finally, they recommended describing the **place of civil society**, of the citizen, in 2050.

4.2.6.4. Building the transition pathway towards chemical pesticide-free wine production in Bergerac Duras by 2050

Milestones and actions necessary to achieve the transition

After the presentation and discussion on the scenario, participants to the foresight workshop followed the backcasting process. In two groups, they identified first the milestones – intermediary steps required to achieve the desirable scenario. Then, they identified actions that will lead to these milestones. Table A.4-3-4 in Appendix 4-3 lists the selected milestones and actions for the transition towards chemical pesticide free wine production in Bergerac Duras by 2050. They are commented below.

Setting up new forms of governance

Several milestones relate to the implementation of new forms of governance around the actors of the territory. As a prerequisite, there is a need to gather the actors around the construction of the territory's project in order to develop resilience. Throughout the transition, there is a strong need for coordination to deploy the project.

Different milestones are therefore linked to the evolution of governance within the territory:

- An intervention structure bringing together the actors to coordinate the transition;
- A steering committee (cooperative) that drew the new landscapes;
- A territorial SCOP (Société Coopérative de Production);
- A cooperative for the sharing of equipment.

In order to create these new governance bodies, in particular the territorial SCOP, for a shared management of the territory, of the agricultural land, with a dedicated legal structure, several actions are proposed:

- Gather a citizen convention on the territory, with invited experts, to build a common project;
- Give it a legal status;
- Collectively define the purpose of the SCOP;
- Invent new forms of farming that integrate criteria of soil quality, biodiversity, etc.;
- An entity that brings together associative groups, state services, private actors, etc.

Some new forms of governance allow for the pooling of tools, data, and funding.

Sharing data, tools, funds

Mutualisation of several assets are necessary for the transition. This means first, sharing of agricultural tools: to manage the problem of specialized tools that must be used at the same time. The tools would be modular in order to be able to switch from one crop to another, or to fulfil several functions at once. Pooling also relates to landscape monitoring data, via collection tools shared between actors (pooling cooperative). Sharing also happens at the financial level: creating a monetary fund to finance the transition of the sector.

Evolution of certification systems

Certification has an important place in the transition. The existing specifications governing the designations of origin need to be revised, with the contribution of the INAO (Institut National de l'Origine et de la Qualité, institution which manage the French label), to take into account environmental criteria. Two milestones deal with this evolution of the specifications:

- Create a territorial specification for all actors involved in the transition, winegrowers, cooperatives, equipment suppliers, communities, etc. for the design of innovative agroequipment and the development of crop systems adapted for the transition;

- The specifications of the appellations of origin have evolved to take into account environmental criteria, landscape, protection of biodiversity, etc.

The certification leads to the Biosphere Reserve label delivered by UNESCO.

Evolution of the Bergerac Duras wine range

It is necessary to define, quite early in the transition, the range of products/wines of the territory desired in 2050, by linking them to changes in practices and consumer expectations. This will notably influence the research work on varietal choices.

According to the scenario, in 2050, the grape varieties used will be genetically diversified in order to promote resilience. They will include indigenous varieties that are better adapted to climate change, guaranteeing the typicality of the wines of the appellations, as well as varieties that are resistant to the main diseases, including the increased pest pressure especially from fungi, as a result of climate change (Brugière *et al.*, 2016).

In order to validate the varieties used, it will be necessary to carry out tests on the production of wines with the selected resistant varieties, as well as tests with consumers to verify the acceptability of the wines produced. It will also be necessary to adapt the management systems according to the selected grape varieties.

The range of Bergerac Duras wines must appeal to consumers and evolve with their expectations. First of all, it is necessary to define the product ranges to be developed according to the desired positioning, the consumers' expectations and taking into account the evolution of the planted varieties. This action could be the result of collaboration between economic research teams and the inter-profession. Then, to reach the milestone "The consumer is ready to pay a fair and ethical price for the qualities of Bergerac Duras wines and their environmental services", it will be necessary to carry out communication actions with consumers, via campaigns carried out by the interbranch organisation and the region's tourist offices. Winegrower ambassadors or personalities from the region will be able to promote the "biosphere reserve" label (the quality and environmental preservation of the sector). Lastly, communication actions aimed at professionals in the sector and its markets will be carried out via trade shows and social networks to highlight the label and the qualities of the wines.

An important milestone is linked to contracting with distributors: working with them on purchase price agreements for wines without chemical pesticides, but also seeking new distribution markets for Bergerac Duras wines.

Evolution of vineyard management systems for the agroecological transition

In a context of revision of the vineyard protection approach without using chemical pesticides, different milestones and actions are proposed.

The transition relies heavily on experimentation, co-construction, and making the results available to the greatest number of people:

- Bringing together the actors to identify the actions that already exist in order to carry out an inventory of the territory and to mobilize them (inventory of the "forces at work");
- Pooling funds - each participant brings his or her expertise, opinion, experience;
- Experiment - on the basis of the CAUE[21] study carried out in Pécharmant or other pilot sites, widen the experimentation approach to other sites (make land available for experimentation, and allow for a change of scale: move from experimental sites to a territorial network);
- Collect the results;
- Disseminate via existing networks: DEPHY, VitiREV and other field relays;

[21] CAUE: Conseil d'Architecture, d'Urbanisme et de l'Environnement - Council for Architecture, Urbanism and Environment

- Create fablabs to build solutions along the way;
- Train and motivate operators based on the good results obtained;
- Incentives through public subsidies;
- Change of scale: generalization of practices, maintenance.

Research organizations have a major role to play in the transition, to accompany experimentation and to transfer knowledge. It seems important for the success of the transition to highlight good practices, to make visible the actors who innovate, the solutions that work, etc. Many actions are proposed in this way. They include:

- Technology monitoring carried out by all the actors on the basis of a common watch method;
- Mapping of the actors, inventory of existing studies on the territory;
- Resource centre - low tech lab' which lists the tools / low tech solutions that the wine growers can use - open source sharing;
- Create tutorials to allow the reproduction of solutions that work (self-build equipment for example);
- Create 3D printing workshops;
- Farmers’ workshops

Biocontrol solutions are one of the tools of the transition. They are made available to winegrowers through research support, experimentation, and support for marketing authorization.

In the end, few technical solutions - or needs for technical solutions - were identified during the workshop. It is mainly organizational solutions, training, transfer, support for the transition, and value distribution that were proposed by the group.

Actions around the training of actors

Training is very important in the transition, for winegrowers, farm employees, equipment suppliers, and all actors in the territory.

One milestone is the creation of the "school of the transition": a training program that delivers a specialized "biodiversity" certificate for viticulture. It is a school opened to agricultural high schools, experimenters, consumers and local residents. The training is compulsory for winegrowers and vineyard workers; it leads to a certification and also allows the validation of acquired knowledge.

Participants imagined a "viticulture civic service" to facilitate the arrival of actors on the territory, who would be trained in agro ecological practices and would then become ambassadors.

Later on in the transition, a winegrower's job reference system, linked to the biosphere reserve label, is created.

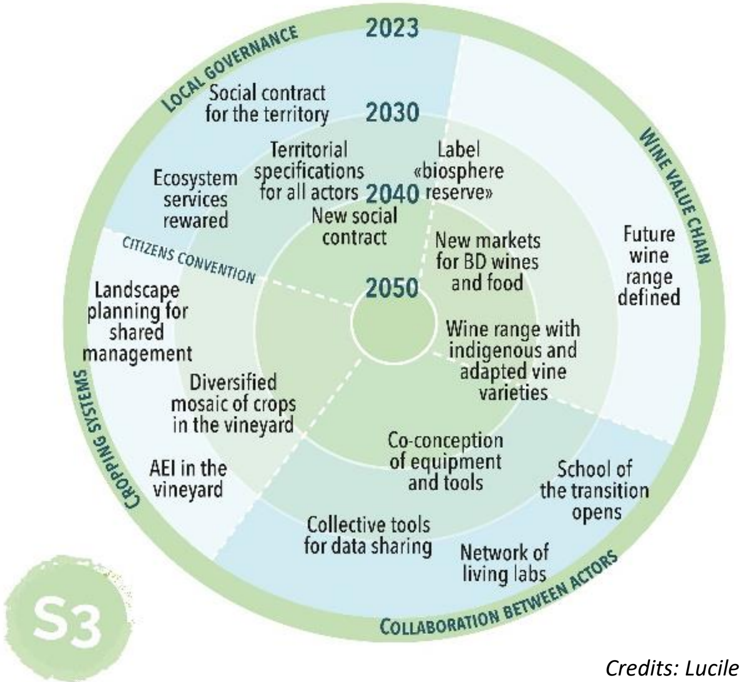
Transition pathway

The last session of the workshop was dedicated to the building of the transition pathway, meaning connecting and articulating milestones and actions logically and chronologically. After the workshop, the transition pathway was translated and transcripted on an excel document (version 1 of the transition pathway). Then, this version was studied by the foresight team, considering the logic, and coherence with the scenario. This allowed to build a second version of the pathway, which was discussed with the local coordinators and participants to the workshop, in a meeting on September 27th.

The final version of the transition pathway is presented in Figure 4-27, with a simplified version in a form of a target diagram (Figure 4-26). A narrative has also been prepared to further describe the transition, as follows.

Figure 4-26: Target diagram summarising the transition pathway towards chemical pesticide-free wine production in Bergerac-Duras by 2050

AEI : agro-ecological infrastructure ; BD : Bergerac Duras



Credits: Lucile WARGNIEZ

Narrative describing the transition pathway

The transition began with the validation of the agro-ecological transition project and the obtaining of the "biosphere reserve" label by the professional actors and the local authority, in response to the concerns expressed by local residents about the risks associated with the use of chemical pesticides. This was followed by a first phase in the transition, dedicated to the establishment of a new governance system and the carrying out of various diagnostics. An inter-communal structure was created, bringing together the actors of the transition, and a decision-making body. A semi-public company (SEM) is created at the initiative of the inter-communal structure and built by a citizen convention. It will pilot the transition, organise the shared management of the territory and finance the transformation of the landscapes.

At the same time, the actors of the Grand Bergeracois are organizing a survey of existing studies, of solutions developed on the territory, of actors involved in the transition. The Chamber of Agriculture, the CAUE and the LPO are mapping the Bergerac Duras landscape in order to identify resilient natural ecosystems and to identify where to install agro-ecological infrastructures. In 2026, we have a landscape diagnosis on the whole territory, and we also know the needs in monitoring sensor networks.

A transition school has been opened, financed by the region and by the ministry of agriculture. This school is open to all and provides various training courses, conferences and workshops on the agro-ecological transition in Bergerac Duras. A "wine and biodiversity" certification is offered to winegrowers, winemakers and farm workers.

Finally, the ODG, the interbranch organisation of Bergerac Duras wines and the merchants define the range and typology desired for Bergerac Duras wines, according to consumer expectations and the agro-ecological project of the territory. To do this, they conduct consumer studies and work with experts in marketing, experimental economics and oenology.

In 2028, at the end of this first phase, the Bergerac Duras has a mixed economy company for the shared management of the territory, a monetary fund that finances the transition. The landscape actors share a tool for collecting and pooling biodiversity monitoring data. Winegrowers use a collective OAD, based on data collected within the territory. A land-use plan is in place.

In the second phase of the transition, the territory is preparing to obtain the "biosphere reserve" label. For this purpose, a self-diagnosis of current practices with regard to the requirements of the label is carried out by the wine industry, with the support of the Chamber of Agriculture. On this basis, territorial specifications are drawn up, bringing together all the criteria required to obtain the label (diversity of varieties, management of plots including the non-use of chemical pesticides, wine characteristics, etc.). It gathers criteria on viticulture, but also on other trades such as construction and supply of equipment (environmental, energy, social criteria, etc.). These specifications are built with the INAO, the ODG, INRAE, the French Institute of Vine and Wine. Once developed, the specifications are included in the application for the "biosphere reserve" label, submitted to UNESCO by the IVBD and the inter-communal structure. The adoption of these new specifications is supported by the payment of the ecosystem services rendered by the wine growers and by the actors of the territory. The calculation and payment mechanisms are based on research and economic studies conducted by researchers and the interbranch organisation.

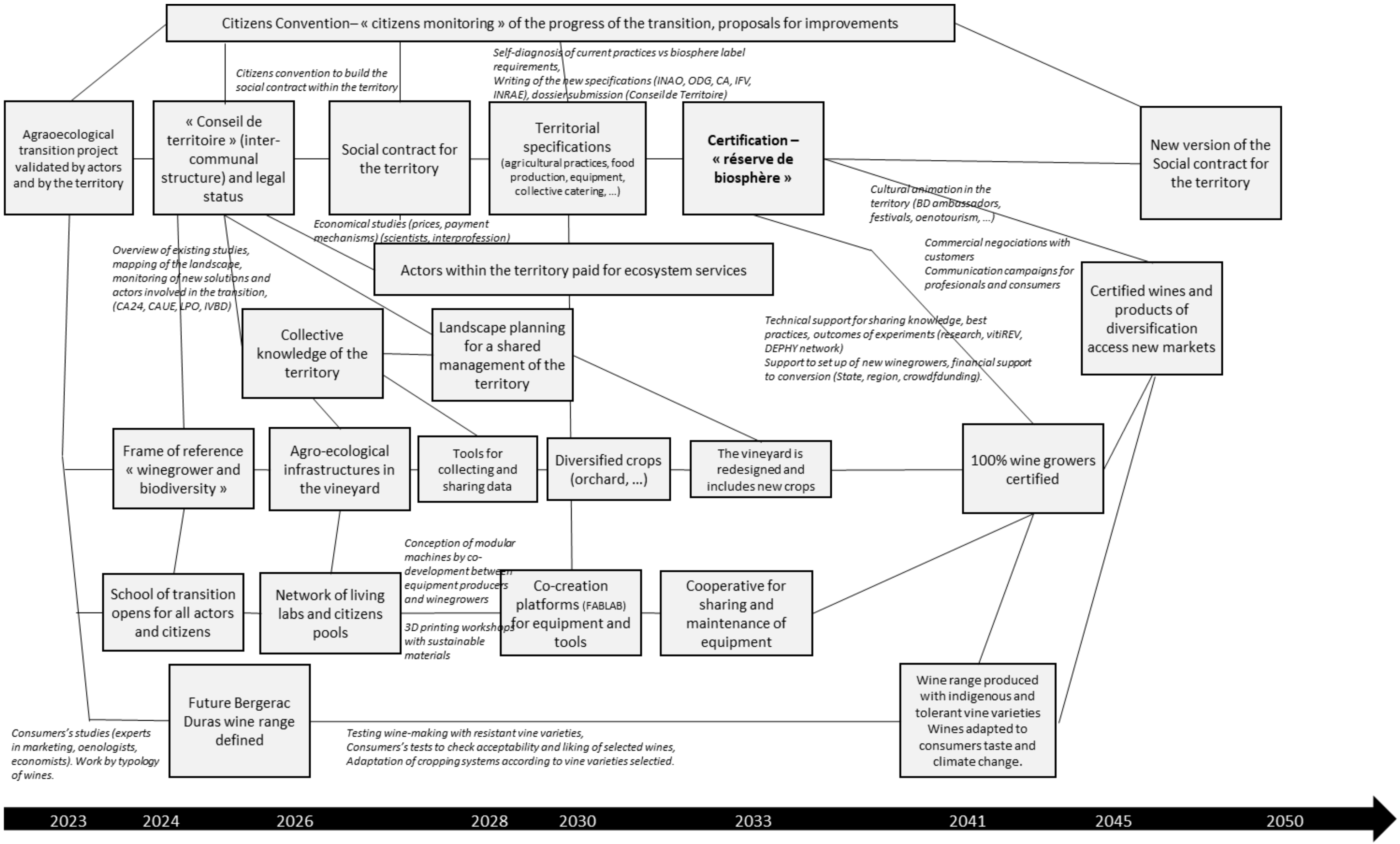
To meet the requirements of the territorial specifications, a Fab Lab has been created, in which the tools necessary for vineyard management operations are designed collectively. A collective management of equipment allows these tools to be shared, and to benefit from mechanics for their maintenance, as well as a resource centre to share best practices.

In 2033, Bergerac Duras obtained the "biosphere reserve" label issued by UNESCO. We are now entering the third phase of the transition, which consists of deploying this certification and promoting the label. To do this, commercial negotiations are taking place with the distributors of Bergerac Duras wines, in order to promote the "biosphere reserve" label. A whole cultural program is set up around this certification, via targeted and multi-channel communication campaigns aimed at professionals and consumers.

The deployment of the certification involves the creation of a "winegrower and biodiversity" reference system. The government and the region provide financial support for the conversion and installation of new winegrowers. Research organizations and networks (DEPHY, VitiREV) share knowledge on experimentally validated systems and support winegrowers in their conversion. In 2041, Bergerac and Duras appellation wines will be produced using resistant, indigenous grape varieties that respect biodiversity in the region, and in 2045, 100% of winegrowers will be certified "wine and biodiversity". Any new winegrowing or business installation is subject to compliance with the territorial specifications.

In 2050, the social contract of the territory evolves again and enters a new version, co-constructed with all the actors of the territory.

Figure 4-27: Final transition pathway towards chemical pesticide-free wine production in Bergerac Duras by 2050



4.2.7. Insights from the four case studies

4.2.7.1. The case studies illustrate the European scenarios

The case studies illustrate the European scenarios, by giving examples of how they translate for a specific region and for a specific crop. They provide detailed information about the 2050 hypotheses, notably on the cropping systems and pests' management.

For example, the 2050 scenario in Tuscany describes the main pests for durum wheat, and how they will be managed:

- **Against fungi**, a combination of solutions are available to farmers, in order to strengthen the immune defences of durum wheat plants. Genetic control is used to select cultivated varieties that are resistant and tolerant to rust, and plants are selected to produce plant defence stimulators for increased allelopathic effects. Seeds are coated with biostimulants for better crop rooting and establishment, or with beneficial microorganisms to induce resistance to fungal diseases caused by *Fusarium* species. Different varieties of wheat are sown together in order to form composite crops, more resistant to fungi. Beneficial micro-organisms are spread as biocontrol solutions at various stages of its development, and competitive non-harmful fungi species are sprayed to compete with the species causing diseases. Biostimulants are also sprayed to make durum wheat stronger and more competitive with diseases;
- **Weed management** measures to limit their development include longer crop rotation to break disease and pest cycles and inter cropping selection. Different sowing machines and techniques and highly efficient mechanical weeding equipment can solve the issue of weed-wheat competition. Mechanical control tools are used to destroy weeds and avoid them to go to seed.

The scenarios from the case studies also give more details about the value chain in 2050 to store – transform – distribute products, according to the specificities of the crop studied and the region. For example, in the case study for Romania and vegetables, the value chain is very detailed, as it is an important element of the 2050 scenario: different scales of value chains are used by vegetable producers. They range from short food supply chains and local food systems to more sophisticated value chains:

- Farmers leverage **short chain distribution channels** to build trust and conveys information directly to the consumers. Vegetables are sold directly to consumers in farmers markets or cooperative's local outlets, to regional restaurants, local schools, local nurseries, etc.
- Vegetables are also sold outside the production region by valorising the quality and region identity of the vegetables. **Vegetable producers' cooperatives**, acting as commercial organizations (including certification, packaging, branding to ensure premium organic prices), **are regular suppliers of major retailers**, via contracts, and also open premium cooperative's market outlets (ex: cabbage, onions, broccoli, mushrooms).
- Some specialty vegetables and premium quality products are distributed **in national and international markets via a cooperative-oriented approach**. They focus on blockchain, data integration, data traceability, collective agreements in order to enhance food quality along the value chain. Every vegetable has a pedigree, including social farm aspects, so that consumers get access to information about the farmer producing it.
- Vegetables distribution channels take several forms: vegetable stock exchange, specialized department of cooperatives distribute on a specific map of consumers, specialized transport companies develop special department for food transport directly to consumer, "supermarket" (specialized shops) for retail.

The scenarios from the case studies, especially those based on European scenario “Territorial and regional coordination, complex and diversified landscapes for one health food systems“ also provide details about the relations between professional actors and inhabitants. Indeed, for example the Bergerac Duras scenario describes:

- New **participatory governance structures** in place, integrating farmers, companies, local authorities, local residents’ associations, etc.
- **A social contract for the territory**, connecting winegrowers and inhabitants in order to preserve local biodiversity and natural resources.

The actions identified during the participatory workshop for each of the case studies also provide detailed information about the actors involved in the transition. These actors are specific to the region; for example the Finnish institute for natural resources (LUKES), the Direction for county agriculture in Romania, the wine trade organization (IVBD) in Bergerac Duras.

In each pathway, interactions between actors are necessary to achieve the transition. These interactions however take several forms and involve different actors. In Bergerac Duras strong collaboration takes place between actors of the wine value chain, the local authorities, the citizens through a social contract within the territory. In South Finland, putting in place and progressively developing collaboration between farmers is key to achieve the transition. In South South East Romania, collaboration takes form through organizations of farmers and the vegetable supply chain at various scales. In Tuscany, the interactions happen between the various actors of the durum wheat sector, up to the integration of the food chain.

4.2.7.2. The transition pathways built in the case studies put out some specific milestones or actions

The transition pathways built in each of the case studies can be compared with their European versions, which were developed by other groups of experts, and afterwards.

In all cases, there were no contradictions between the transition pathway built in the case study and its European version. On the contrary, there were a lot of similarities between the European and regional pathways. For example, in the Bergerac Duras transition pathway towards chemical pesticide-free wine growing, the **set-up of territorial cross-sectoral governance, the development of semi-natural habitat and the diversification of permanent crops are** key in the transition, as it is in the European transition pathway. In the Tuscany transition pathway towards chemical pesticide free durum wheat production, the three first milestones identified are similar to the ones in the European transition pathway. There are: **contracting between farmers and food processors** or retailers on the basis of private production standards, **digitalization of the farms**, and the **organization of AKIS** around precision farming and bio-inputs use. In the South South-East Romanian transition pathway, the transition of the vegetable cropping system starts with **crop diversification**, then **use of biological solutions including micro-organisms**, and buil**ding of soils based on soil – plant microbiome monitoring**. The corresponding European transition pathway follows exactly the same path.

Moreover, there are **specificities in the transition pathway** for each of the case studies, with some milestones and actions that are **adapted to the local/regional situation**, or to the **crops studied**. The Table 4-6 lists the main specificities taken from the transition pathways for each case studies. Some specificities are linked to the sector studies; for example, the specifications for the designations of origin in wine production, the evolution of controlled environment agriculture systems for vegetable production, the non-use of chemical pesticides during grain storage. Other specificities are more linked to the context in the region studied, like in South South-East Romania the organization of the vegetable supply chain, or in Finland the identification of future pests' challenges due to climate change.

Table 4-6: Specific milestones and actions identified in each of the case studies

Specific milestones or actions in Tuscany transition pathway	Specific milestones or actions in SSE Romania transition pathway	Specific milestones or actions in South Finland transition pathway	Specific milestones or actions in the Bergerac Duras transition pathway
• Substitution with organic fertilizers • Crop residue management • Increased soil organic matter • Network of pilot farms and farms • Grain storage without pesticides • National agriculture plan to finance the transition in terms of breeding program and digitalization of farms • Biodiversity protection and enhancement planning	• Organization of the supply chain (logistics, warehouses, short chain, etc.) • Development of Controlled Environment Agriculture and new forms of horticulture • Consumers education on healthy diets • Water preservation measures • Microfarms • Periurban markets	• Foresight study on future pests due to climate change and alternative crop protection methods to anticipate future pests • Mechanical weeding development in cereal fields • Increased share of organic food in retail and in food services • Agroecological symbiosis • Carbon neutrality	• Evolution of the wine range according to consumers expectations • Evolution of the specifications for designations of origin • Certification label "biosphere reserve" • New markets opened for Bergerac Duras wines • Social contract within the territory • Attractiveness of the territory (eco-tourism)

A key difference between the European and regional transition pathways is the scale of public policies. Logically, the transition pathways in the regional case studies include public policies implemented at local / regional or even national levels. European public policies are not listed as actions in the transition pathway of the case studies, since they are not in the remit of the regions or territories. However, the consequences of the European public policies – such as incentives, subsidies coming from EU funds – are listed in the actions supporting the transition.

4.2.7.3. The participatory backcasting methodology as a tool to build transition pathways for chemical pesticide free agriculture by 2050

The method based on the backcasting approach works successfully and is well rated by participants

Participatory backcasting is well described in the literature as a process to develop pathway connecting a desirable future to the present (see for example Bengston *et al.*, 2020; Dreborg *et al.*, 1993; van de Kerkhof and Wieckzorek, 2005). Participatory backcasting exercises are conducted to build transition pathways in diverse areas including on sustainability (Okada *et al.*, 2020), forests (Toivonen *et al.*, 2021; Hines *et al.*, 2019; De Bruin *et al.*, 2017), agriculture and food (Manners *et al.*, 2020; Andreotti *et al.*, 2020; Kanter *et al.*, 2016), and water (Van vliet and Kok, 2015; Kok *et al.*, 2011).

In all four case studies the participatory and step by step methodology worked well and enabled the creation of a transition pathway at the end of the workshop day. The size of the group – between 14 and 20 participants – allowed to split participants into two sub-groups, each working on different components of the foresight system according to their expertise. There were strong engagement of participants in each of the groups, and intense discussions generated, especially around the milestones and actions.

Also, and although they were intense and lively discussions among the groups, there were no tensions nor strong disagreements within participants, mainly due to the rather long time horizon (2050), and normative process (the desirable scenario was set before the workshop).

After each workshop, a feedback was gathered from participants, through a questionnaire (in SSE Romania, in South Finland and in Bergerac Duras) and a roundtable (Tuscany). In each case studies, participants to the workshop gave very positive feedback in the post-workshop questionnaire they filled in. They rated the overall workshop between 4.5 and 4.75 (out of 5). The vast majority of the respondents found the workshop relevant and useful to their work, and believe that they will use the outcomes of the workshop in their work. The vast majority of them also stated that the objective of the workshop was clearly given, that the backcasting methodology helped to build the transition pathway, and that the participatory process succeeded in taking advantage of the different types of knowledge and expertise of the participants. However, more than half of the respondents considered that the time allocated to the discussion among the groups was not enough.

They overall presentation of the foresight and backcasting methodology, the identification of milestones and of actions were listed as the most interesting parts of the workshop.

Challenges with building transition pathways to a distant future

It was difficult for participants to identify milestones in a rather long timeframe: As a result, there were only few milestones and actions identified after 2040. On the contrary, there were a lot of milestones and actions at the beginning of the transition, starting from now. This could give the impression that the transition could be achieved sooner than 2050.

Also, when building the transition pathway, the participants positioned some of the milestones at different times in comparison to the previous sessions. Indeed, when articulating the milestones from different components together, they realized that the initial dates were not coherent for some milestones and had to rework the timings accordingly.

A necessarily iterative process

The sessions related to the milestones and to the actions generated a lot of ideas from the groups, which in turn could be challenging when building the transition pathways, with a lot of items to articulate and order. We tried to improve this situation by limiting the number of ideas per person, and by asking to select the six most important milestones per component. We also asked participants to work in pairs in order to list the actions. Nevertheless, the transition pathways generated during the workshop were quite complex, and required further work post-workshop.

A second version of the transition pathway was shared and discussed with the workshop participants, in order to get a final version of it. This **iterative process** was necessary to fully articulate the milestones together, to check the coherence with the scenario, and address some potential missing elements. It also allowed to build a storyline to accompany the transition pathway, making it clearer to understand for people not directly involved in the pathway building. Many participants suggested that the transition pathway is reviewed regularly (on an annual basis for example) in order to continue the discussions, check progress, and revisit it if needed.

The transition pathway as a tool to enable discussions on the transition within a territory or a region

By working together on building the transition pathway, participants had numerous opportunities to discuss, in rather small groups, about the intermediary steps, the actions and actors to involve to achieve the transition. The one-day workshop allowed to generate a first version of the transition pathway for every case study, thanks to the clear objective given from the start of the workshop, the succession of steps to build it, and the strong involvement of the facilitators. The follow up discussions – during the post-workshop meetings or by emails - were very interesting to challenge this first version, to analyze deeper some milestones, some actions, to identify missing elements in the transition.

The transition pathway – in its visual representation and its narrative - turned out to be a useful tool to generate discussions between actors. For example, in Bergerac Duras it allowed to discuss the role of citizens in the transition, and the articulation between the various actors involved – namely local policy makers, wine growers, citizens. In Finland, it allowed to discuss the role of organic growth to achieve chemical pesticide-free farming by 2050, and to think about how both organic farming and chemical pesticide-free farming could coexist in 2050.

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Section 4.2

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Appendix 4-1 – Full versions of the regional scenarios

Scenario of chemical pesticide-free durum wheat production in Tuscany in 2050

Generic scenario: Global and European food value chains for pesticide-free food markets

Tuscany exports its know-how and high quality, pesticide-free durum wheat products on the international food markets.

In Tuscany in 2050 durum wheat is produced without chemical pesticide, in compliance with market standard in place in Europe, and using cutting edge technologies. Durum wheat is used for producing semolina and pasta, delivered to national, European and international markets. Indeed, the high quality reputation of Tuscan durum wheat has spread beyond Italy, and durum wheat processed products are very popular. Export market of Tuscan pasta is very developed in Europe, America, and have reached Asia. In addition to the standard pasta, premium pasta ranges valorize local Tuscan production, with old traditional durum wheat varieties, top quality taste and product attributes. They are produced using re-fashioned old equipment in the pasta factories with simpler materials integrated in highly automatized and digitally controlled production lines.

The main quality assets consumers are looking for are: Tuscan origin, absence of pesticides all across the food chain, seeds varieties, know-how of the Tuscan farmers and of the Italian food chain, but also the worldwide renowned Tuscan quality of life and terroir. Thanks to the blockchain[22] technology, pasta products are fully traceable throughout the supply chains, from the crop to the fork, in a secured, unmodifiable and transparent way. Consumers get access to information including the origin of the durum wheat, seed varieties used (including the use of old varieties with a higher gluten digestibility), agricultural inputs, processing steps, composition of the end product including proof of absence of pesticides. Durum wheat storage facilities are equipped with preventive solutions to avoid development of pests - particularly insects - without using chemical biocides. These include proper cleaning of the facilities, ventilation to reduce grain temperature, or fumigation techniques. To deal with variable quality of durum wheat, production facilities are equipped with seeds sorters that can select the durum wheat grains according to quality criteria, and mix different varieties together.

Durum wheat production happens in large and specialized farms in Tuscan plains. They are equipped with cutting edge technologies that allow farmers to work at very large scale without too much labor forces and with a high working speed, resources optimization and control. The use of precision farming is spread and almost all the equipment used for the main operation, from sowing to mechanical weeding until harvesting, are satellite-guided (Isobus etc). Most of the agricultural area is under production even if the number of farms has decreased. Farms size and working capacity are higher.

Crops are protected from pests without using chemical pesticide. Against fungi, a combination of solutions are available to farmers, in order to strengthen the immune defenses of durum wheat plants. Genetic control is used to select cultivated varieties that are resistant and tolerant to rust, and plants are selected to produce plant defense stimulators for increased allelopathic effects. Seeds are coated with biostimulants for better crop rooting and establishment, or with beneficial microorganisms to induce resistance to fungal diseases caused by Fusarium species. Different varieties of wheat are sown together in order to form composite crops, more resistant to fungi. Beneficial micro-organisms are spread as biocontrol solutions at various stages of its development, and competitive non-harmful fungi species are sprayed to compete with the species causing diseases. Biostimulants are also sprayed to make durum wheat stronger and more competitive with diseases. Weeds management measures to limit their development include longer crop rotation to break disease and pest cycles and inter cropping selection. Different sowing machines and techniques and highly efficient mechanical weeding equipment can solve the issue of weed-wheat competition. Mechanical control tools are used to destroy weeds and avoid them to go to seed. Application of vermicompost in the plot enriches the soil with beneficial plant growth hormones, nutrients, and beneficial microbes acting against pests, and fill the gap of the lack of manure in many areas where animal husbandry almost disappeared. The use of mineral nitrogen is limited, especially the

[22] A blockchain is a distributed database of records in the form of encrypted blocks, or a public ledger of all transactions or digital events that have been executed and shared among participating parties and can be verified at any time in the future (Antonucci *et al*., 2019).

one produced from fossil fuels, and the use of organic and organic-mineral complex fertilizer are commonly used. Other fertilizers coming from different byproducts are used instead of the common mineral fertilizers.

Farmers use user-friendly technologies to monitor pest developments on the plots and get advice on crop management options. They remain the decision makers, and are helped in their choices by the use of Decision Support System (DSS) tool services. They trust these tools as reliable source of advice on seeding time, fertilizers application time, pests development and use of biocontrol solution. These tools build upon artificial intelligence based on years of observations, and predictive modelling. They are connected with drones, sensors for real time detection of pests, analyse the relationship between pests, potential crop damage, and the efficacy of control measures. The precise application of targeted control decided by the farmer is executed with small autonomously navigating robots. Farmers remain the decision maker through a centralized station connected to the other equipment. These tools are co-developed and supported by different actors in living labs that gather farmers, researchers, digital tools developers, agroequipment providers, pasta producers. The use of remote platforms to communicate with farmers help the advisors to give real-time information to solve problems occurring in the fields. Laws regulate the property and use of these data to ensure proper ownership, access and use.

Scenario of chemical pesticide-free vegetable production in South South-East Romania in 2050

Generic scenario - European and regional food systems, soil and food microbiomes for healthy food and healthy diets

South east Romanian organizations of farmers leverage good soil conditions and maintain strong microbiome interactions from the soil to the plant, to produce pesticide-free vegetables that are major contributors to healthy Romanian diets.

In 2050 in south east of Romania vegetables are grown without chemical pesticides, and provide the local and national consumers with highly nutritious products, that are major contributors to their healthy diets. Vegetables are produced in family farms that are grouped together at regional level, in order to share storage facilities, develop brand, marketing and selling strategies. Farmers have access to several modes of action in order to avoid the use of chemical pesticides in their cropping system. These are based on 4 main levers : the management of the microbiomes, from soil to the vegetables, the monitoring of the soil and pests, diversification of crops, and fertilisation practices. Vegetables production is diversified and include tomatoes, cucumbers, eggplants, melon, onions, broccoli, etc. Vegetables are grown in open fields and protective spaces (greenhouses, solars, etc). They are mostly sold fresh, directly from farm to consumers, in regional storage facilities that are owned by the regional cooperative. They can also be sold in local and peri-urban markets. There are processing units, owned by the farmers's organizations, where vegetables are dried, or frozen, or canned, and sold to the local, regional and national markets, and even internationally in the case of quality labelled vegetables.

Romanian consumers pay lot of attention to the healthiness of their diets. The impacts of chemical pesticides on human health are well known to consumers and public health authorities, who have decided to ban their uses. Healthy diet means to them consuming a diversity of food products, seasonal, in majority cooked at home, little processed, produced with “like home” recipes. Food products are of high nutritional value, and pesticide free. Vegetables are key parts of their diet as they bring micronutrients (vitamins, minerals) and also polyphenols, dietary fibre that exert prebiotic functions, contributors to healthy gut microbiome. Consumers are well aware of the benefits of well-balanced gut microbiome on various functions (gut health, brain health, immunity, etc.) and overall health Diets rich in vegetables are encouraged as a way to balance the gut microbiome and prevent development of non-communicable diseases. Vegetables are accessible to all since they are considered priority products, and therefore are supported and promoted by the health authorities in the Romanian government. Nutritional information of food is provided to consumers, through labels or digital platforms.

Consumers live and feel close to the farms. They contribute to the vegetable production by helping with the picking, buying vegetables directly from the farmers. Different scales of value chains are used by vegetable producers. They range from short food supply chains and local food systems to more sophisticated value chains. Farmers leverage short chain distribution channels to build trust and conveys information directly to the consumers. Vegetables are sold directly to consumers in farmers markets or cooperative’s local outlets, to regional restaurants, local schools, local nurseries, etc. They are also sold outside the production region by valorising the quality and region identity of the vegetables. Vegetable producers’ cooperatives, acting as commercial organizations (including certification, packaging, branding to ensure premium organic prices), are regular suppliers of major retailers, via contracts, and also open premium cooperative’s market outlets (ex: cabbage, onions, broccoli, mushrooms). Some specialty vegetables and premium quality products are distributed in national and international markets via a cooperative-oriented approach. They focus on blockchain, data integration, data traceability, collective agreements in order to enhance food quality along the value chain. Every vegetable has a pedigree, including social farm aspects, so that consumers get access to information about the farmer producing it. Vegetables distribution channels take several forms : vegetable stock exchange, specialized department of cooperatives distribute on a specific map of consumers, specialized transport companies develop special department for food transport directly to consumer, ”supermarket” (specialized shops) for retail, etc.

Average farms size has increased but there remains diversity of farm sizes in the region. They are mainly owned by families working together with the support of neighbours. Young farmers get access to education and trainings. They are encouraged to adopt innovations on crop protection.

Vegetables crops are protected from pests without the use of chemical pesticide. Beneficial organism are integrated in the farm ecosystem. An important lever for protecting vegetables from pests is the management of the holobiont, from the soil to the plant. By analyzing the soil microbiome composition, farmers better understand reservoirs of microbial diversity (soil, air, weeds and water). Strong epidemiological services, sensors and other digital technologies companies provide tools to measure soil health indicators (DNA profiling, enzymatic activity, etc.), but also weeds, and plant microbiota composition, and pests dynamics. Technology is strongly applied in farms, with different sensors, imagistics (satelittes, drones, etc), applications for farms with Decision support systems (including all managements tasks). These data are shared within the cooperative among farmers. Farmers can then modulate microbiomes using biocontrol solutions through innoculation of micro-organisms such as *Trichoderma sp, Bacillus sp*. that are applied on farms soils. Also, vegetable varieties are selected in the Romanian genes bank, to be adapted to local agro and pedoclimatic conditions, and soil microbiome. Crops and cover crops are chosen in order to raise the soil organic matter and boost the plants immune system. Precise and non chemical fertilisation is preferred in order to reinforce the recruitment capacities of cultivated plants and reduce pest virulence. Organic fertilisation or Pellet-shape organic fertilizer is provided, especially by livestosck cows, sheeps and goats, and smart methods of fermentation compost fertilization are used. Agroecological solutions for crop protection also include the choice of association of crops to limit the development of pests, by associating together vegetables, cereals, legumes, aromatic plants (basil, mint). Alfalfa and clover are intercroped. For example, squash (pumpkin) and corn can be associated, for combining respectively soil covering and shade. Carrots are associated with onions, garlic, whose odors repel carrot rust flies. *Tagetes sp*., *Calendula* and *Centaurea* are used as companion plants with different vegetable species.

This cropping system requires strong cooperation between actors: farmers within the cooperatives, that provide tools, data on and biofertilizing solutions. There is also a strong network with researchers who provide advice, planning and prevention support, and with ICT (information and communication technologies) companies. All these actors are partners in the entire food chain.

Scenario of chemical pesticide-free cereals and oilseed production in South Finland in 2050

Generic scenario – Territorial and regional coordination, complex and diversified landscapes for a one health food system

Finnish cereals and oilseed sector produces sustainably healthy milling and vegetable oil products, and delivers ecosystem services to local consumers & citizens who are concerned about environmental and human health preservation.

In Southern and Western Finland, in 2050, cereals and oilseeds are produced without chemical pesticide, in order to answer Finnish consumers's demand for food preserving human and environmental health. Consumers look for food with a high nutritional value and that are little processed. Finnish people are very concerned about environmental protection, preservation of rural areas, and about food sovereignty. In 2050, Finland is self-sufficient in producing protein rich plant crops for animal feed as livestock production has reduced and mainly switched to organic dairy and for biogas. Finnish society acknowledges the ecosystem services of agriculture, and farmers' environmental protection services are explicitly targeted by public subsidies. Healthy and environmental friendly food are affordable to all thanks to targeted public subsidies.

Cereal cropping systems are diversified and represent maximum 3/5 of the crop rotation. Other crops include legumes for plant protein, feed nutrition, but also to contribute to healthy soils. Green manure is used as a source of fertilization and also to strengthen soil microbiome. The seeds selected are local, adapted to the specific climate conditions in Northern Europe, and also to pests and diseases. They are heat-treated to prevent seedborne diseases and increasing risk of mycotoxins along the humid weather conditions. Crop protection is ensured through biological regulations by complexification of landscape including forests, crop diversification, with field strips and buffer zones to maintain beneficial arthropods and other biodiversity, beetle banks and flowering zones around the plots, honey bees and wild pollinators for oilseed crops pollination. In 2050, conservation biological control is favored, the landscape is reconfigured as a mosaic of areas including lakes, rivers, forests, connected together to reinforce populations of beneficial insects and avoid isolated populations of pests. Non-chemical solutions, such as late sowing are used for some specific pests such as *Phyllotreta spp*. on oil crops. Crop diversification and complex landscape are also very important to strengthen the resilience of cropping systems to extreme climatic events that are now more frequent because of climate change. Circular economy if favored and supported by the bioeconomy finnish strategy. Farms aim to closing the cycles of inputs and outputs, e.g. by local production of biogas and return of nutrients into the soil via biogas digestates.

Cooperation between farmers, advisory organisations, and other actors at territorial level is in place in order to monitor efficiently the weather but also the state of ecosystem and the dynamics of animal pests, weeds and diseases. IT monitoring systems based on diverse remote sensing data and crowdsourcing of information are available, accessible to farmers, and allow online and collective book keeping to base decisions.

Farms remain family based in terms of ownership, capital and work, but have grown in size. Farmers are concerned about sustainability. They are highly educated and regularly trained on agroecology and the use of digital tools. They are supported by independent advisory organisations. They cooperate at territorial level to share machinery (collective organization, co-owning), knowledge, monitoring. They have reduced their dependence on input retailers and also reduced their level of specialization through diversification of crop. Non-farm activities have developed (part-time farming) such as advisory services, own baking productions, research, etc. Participatory research and development through Living labs have increased the co-development of innovative solutions by gathering researchers, farmers and machinery companies. Virtual education and continuous trainings are provided to farmers in order to give them access and knowledge to redesign their own cropping systems.

Plant productions are transformed locally into milling products that are very diverse, little processed, of high nutritional value thanks to the use of wholemeal cereal flours, legumes flours that are rich in plant proteins, fibre, and micronutrients. Milling and bakery industries remain local small and medium size entreprises (SMEs). They provide diversified cereal products and traditional varieties of bread in different parts of Finland. Pulses are also valorized in animal nutrition, improving Finnish self-sufficiency for feed.

Consumers buy these free-pesticide products from a diversity of food chains: big/national retailers, local food markets, and direct distribution channels allowing them to be in direct contact with farmers through digital platforms. Community supported agriculture, improving the link between consumers and farmers, is very popular. Big retailers have seen an interest in selling healthy food products. Food chains "free from" is very developed on shelves, to fulfill demand regarding diverse diets (gluten free, vegan, fat free, etc.). Responsibility, sustainability claims (such as organic label) and certificates are checked and approved by public authorities before being used on food labels. This public verification of environment and health claims has reinforced consumers trust in Finnish products. All across the value chain, the traceability of the whole food chain is ensured for consumers and data about the nutritional composition, the origin, processing steps, environmental footprint are made available to consumers through easy-to-use digital applications. There is a share of knowledge between consumers and farmers about the health and environmental properties of food. Food chain have reduced the transport of food from long distance, and food packaging is fully recyclable and leverage the bio-based resources materials from forests.

Scenario of chemical pesticide-free wine production in Bergerac Duras in 2050

Generic scenario – Territorial and regional coordination, complex and diversified landscapes for a one health food system

The Bergerac Duras wine industry has succeeded in its agro-ecological transition by mobilizing all the stakeholders in the region to design a sector that preserves the health of humans and the environment, in which ecological processes at the landscape level are favoured and the vineyard is valued for its gustatory and environmental qualities and as an element of cultural heritage.

In 2050, the Bergerac and Duras wines are known for their taste qualities, the viticulture know-how and also environmental performance of the territory, particularly with regards to the preservation of water, soil and biodiversity. The Bergerac Duras vineyard is totally integrated into its territory. The vineyard landscape has been redesigned to promote biological regulation and protect the vines without the use of synthetic chemical pesticides. Natural resources - water, soil, air - are preserved in quality and quantity, and mosaics of crops are associated with semi-natural habitats, with the aim of creating a resilient winegrowing system. The size of the plots has been reduced, as well as the interventions on the vine and the use of inputs. The vineyard landscape is composed of rows of vines associated with other crops such as fruit trees that provide complementary production. The vineyards are bordered by hedges, meadows for grazing, cereal crops and woods. Winegrowers and researchers in vitiforestry have developed knowledge and know-how in the development of synergies between crops. The density of plantation is thought to ensure a fair balance between quantity and quality of grapes and a preservation of water resources. The grape varieties used are genetically diversified from one plot to another in order to promote resilience: they include indigenous varieties, better adapted to climate change, guaranteeing the typicality of the wines of the designations of origin, as well as varieties that are resistant to the main diseases, including new pests and diseases.

The landscapes are designed at the scale of the territory, involving wine growers but also the other actors involved in these landscapes. New participatory governance structures have appeared, integrating farmers, companies, local authorities, local residents' associations, etc. A social contract for the territory links winegrowers and inhabitants in order to preserve local biodiversity and natural resources, and reward them for the ecosystem services. A whole landscape monitoring system that integrates a multiplicity of data analyses the state of biological regulation within the landscape. Thus, winegrowers can use decision support tools based on observation data and their history, anticipating the dynamics of pests and proposing appropriate prevention measures.

The equipment used by the winegrowers is adapted to the diversity of the landscape and are designed according to the needs and specificities of the territory. They are created with manufacturers and suppliers of agricultural equipment to be adapted to the landscape, to pest management, and to meet the challenges of technological and energy sobriety. Indeed, there is now a social responsibility for agricultural equipment firms, which must develop ethical innovations taking into account social and environmental impacts.

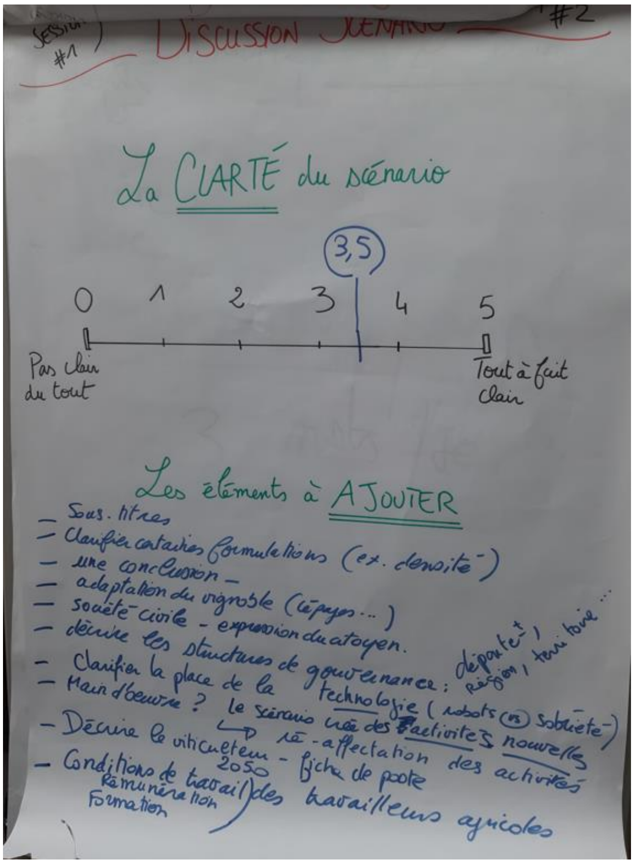
Winegrowing operations remain family-owned and managed by new generations of winegrowers trained in the agroecological transition and financially supported by the community. These winegrowers have organized themselves through cooperatives to share equipment, transportation, trading, monitoring tools, but also landscape design. On the territory, the diversity of farms is maintained. Alongside the cooperatives, there are independent winegrowers who act as ambassadors for the sector, and also neo-rural winegrowers who carry out experiments on smaller farms.

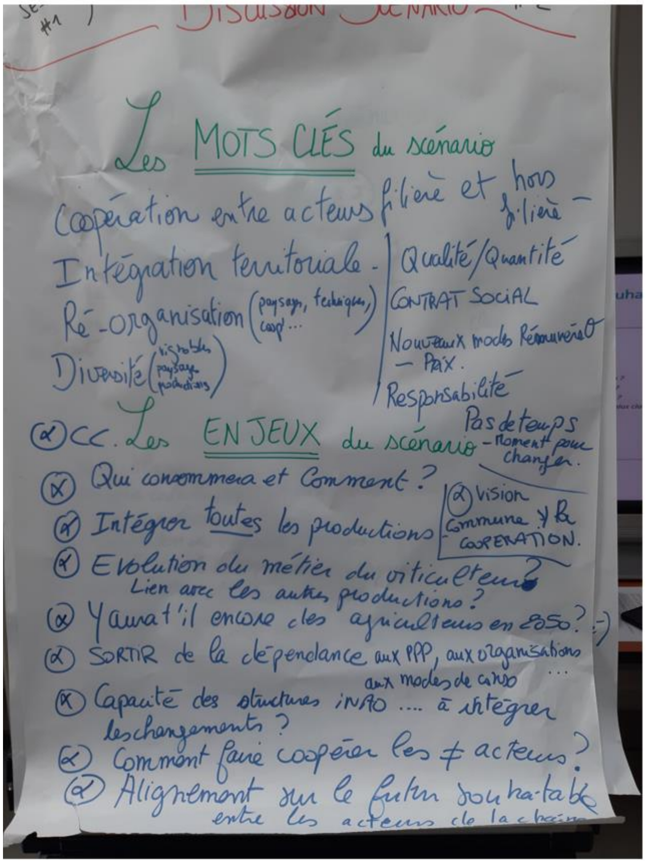
The agro-ecological practices are promoted to consumers. The Bergerac-Duras designations of origin - AOC, IGP - include criteria for contributing to the reinforcement of biodiversity in their specifications, and make them visible on the label of their products via the "biosphere reserve" label. The wines of Bergerac Duras are thus very well valued, sold at a fair price. The new agricultural productions linked to crops diversification- fruits, nuts, cereals, animal productions- also bear the "biosphere reserve" label and are sold to consumers via short chains.

The Bergerac Duras region is renowned for the quality of its wines, the beauty of its landscapes and its preservation of the environment and biodiversity. Wine tourism is very popular in the area, and tours are proposed to discover the agro-ecological transition of the vineyard. The range of Bergerac Duras wines is increasingly diversified, including its characteristic sweet white wines and also red wines for ageing or even wines without sulfites to meet the expectations of certain consumers. This approach to preserving the terroir and its environment opens up new distribution channels for Bergerac Duras wines.

Appendix 4-2 – Some pictures from the workshops

Discussion on the scenario in the Bergerac Duras workshop (group 1)

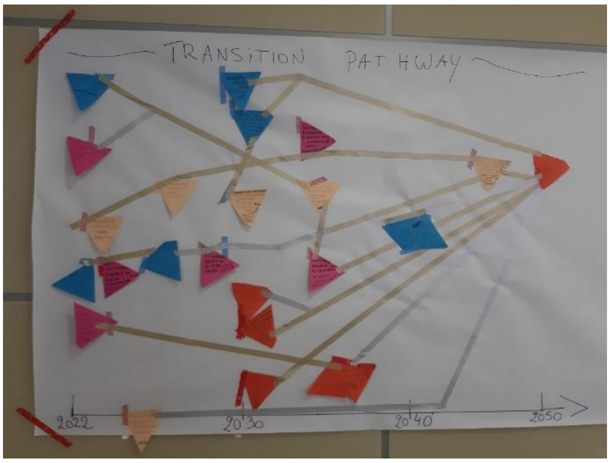




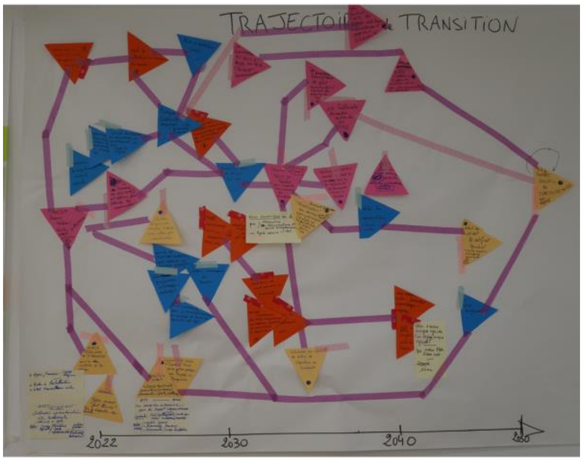
Milestones, obstacles and opportunities generated during the workshop in Finland

List of milestones and actions generated in Tuscany

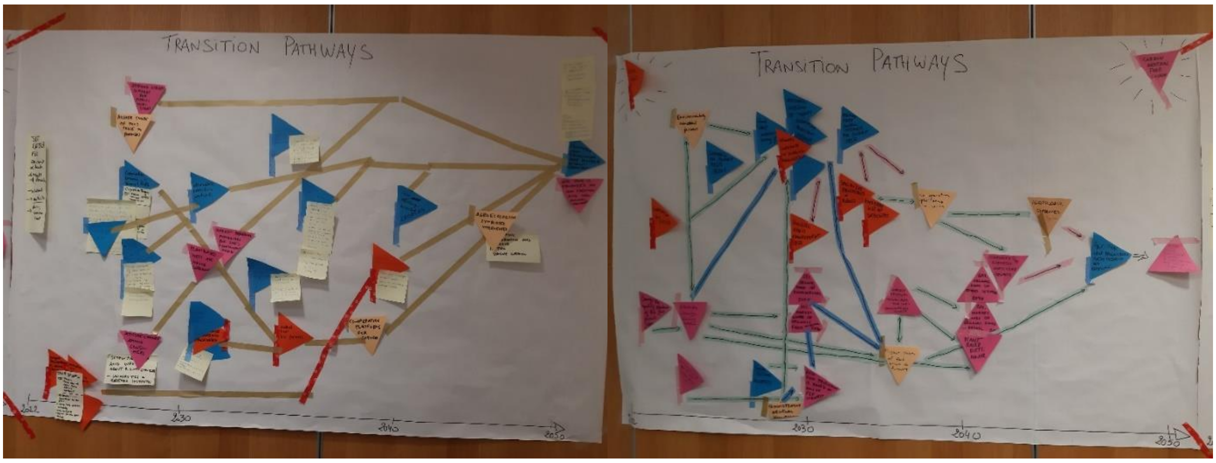
Transition pathway generated during the workshop in Romania



Transition pathway generated during the workshop in Bergerac Duras



Transition pathways generated during the workshop in Finland



Transition pathway generated during the workshop in Tuscany

Appendix 4-3 – Tables of milestones and actions

Table A.4-3-1 Case study – Tuscany and durum wheat: milestones and actions generated during the workshop (translated from Italian) – *milestones in bold, connected actions below, actors in italics*

Durum wheat cropping system	Durum wheat value chain	Farm structures	Agroequipment and digital tools
2050 **+1 point in rate of organic soil matter**	**2040** **Logistic models using artificial intelligence**	**2045** **Export marketing plan (regional)**	**2050** **New professional role of the farmer**
University to do research and give long-term data for solid scientific databases to help the policy makers. *Regional government* to write CAP Measures easier to be implemented and more rentable and liked by the farmers. *EU and Ministry of Agriculture* to write laws to promote the circularity/easiness of making the farming systems smarter.	Creating investments to promote a better internet network (*EU and Italian government*). *Italian government and Ministry of Education and Agriculture* to plan new technical school at the pace with the newest digital technologies in agriculture	Starting from the schools (public schools' canteens with local products). *EU and Regional government* to give funding (Operational groups and others) for food value chains integration and to promote the multi-actor approach	Create new roles of "innovation brokers" (agronomists, farmers, technicians) to deliver the innovations. *University and farmers' unions* to promote training and to spread the innovations. *EU* to finance and create these new figures
2040 **50% of organic fertilizers (non-chemical origin)**	**2035** **The food value chain from producers to retailers is strengthened and locally planned**	**2040** **-Farms' digitalization**	**2040** **50% arable land with precision farming**
Building a better law system and a lighter bureaucracy to stimulate the organic fertilisers market, with the aim of building a strong and rich circular fertilisers value chain good for all the actors. *Ministry of Agriculture and Ministry of Environment* to write better laws.	Logistic platforms with the help of digitalization built with a bottom-up approach (starting from the farmers' needs and involving the consumers too)		Collective organisation of innovative machineries trials, to let every type of farm to have access to the cutting edge technologies. Agronomists' professional organisation to do training among agronomists who spread the digitalisation in the farms. Banks to give access to loans for young farmers. Cooperatives/farms' networks to buy, to lend or to have free trials of innovative machineries
2040 **Cover crops availability for different pedo-climatic contexts**	**2030** **Certification and control labelling**	**2040** **Farmers generational turnover**	**2030** **Simpler and integrated DSS (common language, common platforms)**
Promote the research and the innovation transfer on the cover crops. *University* to study and test on the long term, *farms networks and agronomists* to spread the innovation and to implement the innovations	A set of rules for the production to be set by the *Regional government*. Volunteer certification to ensure the revenues (*food industry and farmers*)	Building politics for setting a higher life standard in the rural areas (services, attractivity and so on). *EU and Italian government* to write laws and set rules related to rural areas.	Connecting software specialists and specialists in agriculture. *EU* has to give funding to digitalisation projects. *Agronomists professional organisation* to do training among agronomists who spread the digitalisation in the farms
2040 **Crop residue management***	**2028** **No use of insecticides in grains storage***		**2036- Robots acting on each plant under farmers management***
2038 **-80% use of chemical pesticides***			
Biocontrol solutions available (biostimulants, micro-organisms)*			**2032** **Farmers mobilize technologies to manage the fields***
2030 **Promoting biodiversity protection and enhancement planning: longer crop rotations, intercropping, agroforestry, cover crops and other measures**	**2025** **Creation of a participative network on innovation**	**2035** **Cooperative and networks structures for farms**	**2025** **Network of pilot farms and networks of farms for knowledge transfer**
Building a long-term and ambitious "national agriculture plan" to give fundings for research and for "innovation brokerage" to transfer the innovations. At Regional scale, farms networks (*Regional government*). *All the actors to be involved in the process*	Creating a national AKIS system, free and public (*Italian government*). *University, Regional government and farmers (producers)* to organize a common innovation platform, built with collective contracts, incentives, de-taxations and so on. Creating a public office to organize the AKIS system.	Building a reduced number of cooperatives not to leave the farmers alone to trade (aggregate the offer to have a higher commercial power). *Italian government* to write rules to promote the creation of these cooperatives, *farmers* to accept these new structures and make them effective	Networks of farms to be built in a mix of public and private funding. Selection of the farms (*farmers' unions*), funding from the *Regional policy makers*, *farms* who want to be involved in
2020 **Breeding (from now to 2050 in a continuous process)**	**2022** **Contracts for risk compensation and dedicated financial tools**		**2025** **Incentives with de-taxation of equipment, input, technology**
Promote the research and the innovation transfer through a long-term and ambitious "national agriculture plan".	CAP reform in 2028-2035-2042 (*EU and Italian government*) with the aim of protecting the durum wheat production (e.g. Durum wheat common market organization with the model of wine). Aggregate offer, production planning (*from the industry to the farmers with the help of National and Regional governments*)		Funding to the research (*University*) to set the standards; writing laws to promote investments in equipment (*Ministry of agriculture*)

*Milestones added after the workshop

Table A.4-3-2: Case study South South East Romania and vegetable production: milestones and actions generated during the workshop (translated from Romanian) – *milestones in bold, connected actions below, actors in italics***.**

Vegetable cropping systems	Vegetable value chain	Farms structures	Agroequipment and digital technologies
2040 **New forms of CEA implemented (modern greenhouses, vertical farming, etc.)**	**2035** **Defining short chain and local farms in legislation (implementation)**	**2045** **Making turnkey microfarms in the vicinity of cities to be used by those who do not own land and want to grow organically**	**2050** **Elimination of chemical pesticides**
Urban farming (Local government, building owners, owners' associations). Resistant varieties, Politics + research (Farmers). Machine learning algorithm (Software companies). Easy to use system.	1. Development of digital platforms with short chains and local markets, dedicated financing (Legislation). 2. Creating a favorable (favorable) legislative framework, providing fiscal and financing facilities (Legislative). 3. Stimulation of functional associations (clusters, producer groups, cooperatives, etc.), Provision of fiscal and financing facilities (Legislative)	1. Creating functional models (universities, legislative framework). 2. Land identification (public / private), land conversion, infrastructure construction - roads, fencing, utilities, plots (DAJ, local councils). 3. Identification of applicants (associative organization of applicants) (DAJ, NGO). 4. Organization of operations (funding, inputs) (Applicants' associations)	Legislative regulations - directives (MADR). Replacement of chemical pesticides with organic products (Farmers)
2033 **Water preserving methods applied in 35% farms***			
2030 **CEA (Controlled Environmental Agriculture) (greenhouses) Close control environment agriculture, vertical farming**	**2035** **Legislation of eco-food education in schools (curriculum, food acquisition / purchase)**	**2035** **Specialists in farms and or outsourcing services (the "heavy" ones)**	**2035** **Blockchain technology for traceability of the final products**
1. Interior design (Real estate). 2. New companies in the agricultural sector. 3. Implementation of modular greenhouses (retailers in Romania). 4. HORECA - modular greenhouses. State subsidy.	How to educate children on the production and consumption of eco-food (Ministry of Education, MADR)	Creating and supporting courses for farmers. Creation of programs aimed at knowledge exchange (agricultural directorates, town halls, certification and control bodies, farmers)	Collaboration between key actors (farmers and software developers) to facilitate access to such easily usable and implementable technology. Communicating the benefits of such technology to the end consumer through PR & Marketing companies
2030 **Building up soils**	**2030** **Digital platform. Digitization. Creating informative HUBs (info about who, where, which products)**	**2030** **Sustainable diversification, Smart crops with perennial vegetables and green manures**	**2035** **Crop monitoring in the production areas - field, greenhouses, solariums Specialized training for farmers in the use of new equipment.**
Soil: crop rotation - diversification. Inclusion of green crops / protection. List (product catalog). Amendment. Windbreaks. Reforestation (Actors - farms + MADR).	IT team co-op (Ministry Department). Data collection, Organization of farmers' information campaigns, Organization of consumer information campaigns (MADR, DEJ, AFIR, Certification companies, Social media)	Law / Agricultural policy for the obligation to diversify on farms (2025-MADR). Organization of demonstration fields + technology transfer in each region (2027 - Universities, experimental stations, technology). Awareness campaigns (MADR + universities + input companies).	Research. Training. Technical solution. Financing (EU, banks, etc.). Private IT companies - equipment suppliers. Farmers who have already been advised how to use the equipment. Agricultural high schools and universities in the field + researchers from different fields.
2030 **Increasing biodiversity in horticultural crops in order to reduce the incidence of diseases and pests (Plant Association)**	**2028** **Price policy vegetables affordable to all***	**2028** **Family farms organized in a cooperative system**	**2030** **Biological control as a standard in plant protection**
1. Carrying out viable cultivation plans that take into account all specific factors (eg allelopathic effects) by introducing new species that do not have the same specific pests (horticultural engineer). 2. Obtaining a varied assortment and identifying the sales market and consumer education (PR & Marketing). 3. Collaboration with research centres and introduction in the culture plan of acclimatized / developed species inside them (researchers / research centres). 4. Use of repellent species with multiple functions (horticultural engineer).		1. Financial support for the development of production through local programs (European Commission, MADR). 2. Financial support for infrastructure provision (logistics storage facilities, protected cultural areas) (European Commission, MADR, ADR)	Biological control: bringing natural enemies into the culture. Use of beneficial bacteria. Educating / informing farmers.
2025 **Farmers education programs are in place**	**2025** **Providing logistics locally**		**2030** **50% reduction in chemical pesticides. Monitoring of the concentration of nutrients and soil microecosystems**
Information by organizing workshops, demo lots (university staff, academics, research, local council, town halls, associations, agricultural agencies). The obligation by legislative means for a majority of the culture to be achieved in an ecological system. Providing free specialist advice for organic crops (researchers, engineers, teachers). Promoting through the media the nutritional benefits due to the consumption of organically grown vegetables (Ministry of Health, MADR, MEC, Media Institutions). Financing.	Association of farmers in various forms, Creation of warehouses (Farmers, local authorities, central authorities)		Carrying out periodic inspections by taking soil and fruit samples (Agencies with specific activity). Cultivation of varieties and hybrids with resistance / tolerance to the attack of pathogens (Farmers, producers, research). Implementation of biofertilization programs (Research). Improving the range of ecological control products (Research, farmers). Cultivation of varieties / hybrids adapted to super-intensive ecological crops (Farmers, research and academia)
2025 **New production spaces with specific monitoring. Construction of renewable energy modules for new equipment**	**2023** **Food education programs in schools run by volunteers with the school teaching staff***		
2022 **National and regional organization to coordinate, monitor the transition and secure fundings**			

*Milestones added post-workshop

List of acronyms: ADR = Agentie de Dezvoltare Regionala = Agency of Regional Development; AFIR = Agentia pentru Finantarea Investitiilor Rurale = Agency for Rural investiment financing; DAJ = Directia pentru Agricultura Judeteana = Direction for county agriculture; DEJ = Directia economica Judeteana = Direction for County economics; MADR = Ministry of Agriculture and Rural development; MEC = Ministerul Educatiei si Cercetarii = Ministry of Education and Research

Table A.4-3-3: Case study cereals and oilseeds production in South Finland: milestones and actions generated during the workshop – *milestones in bold, connected actions below, actors in italics*.

Cropping systems	Food value chain	Farm structures	Agroequipment and digital technologies
2048 **Profitable crop production made possible without the use of chemicals**	**2045** **Community Supported Agriculture is very popular among Finish people**	**2048** **Agroecological symbioses (farmers, food processors, energy providers)**	**2050** **Farming collaboration platform**
Bigger share of food prices go to farmers. *Food industries, groceries*. Research on non-chemical pest management. *Government funding, public research bodies*.	Creation of a "social" label, providing information about the social footprint (share of price among the food chain, ethical values, etc.) of the food product. Creation of a manual on how to do CSA in Finland. *Union of farmers*.	Development of cooperation and dialogue in the whole value chain. *Farmers, retailers, food processors, energy providers*.	Build trust on technologies and people developing the tools. *Research, farmers' community*. Regulate data access and use. *Regulators*.
2042 **Alternative protection methods are available**	**2040** **Plant based diets are major contributors to Finnish diets**	**2041** **Higher share of food prices for farmers**	**2040** **Farming execution system FES**
More research on non-chemical pest management (*researchers, government funded).* R&D development of new plant protection solutions (biocontrol). *biocontrol companies*	Plant breeding on pulses to improve their nutritional, taste qualities. *Research*. New processing technologies developed by R*&D of private companies* to manage the digestion issues (digestive tolerance) of pulses.	Price recommendations allowed for producers (farmers). *Ministry.*	Creation of business need for farmers' appearance of highly automated machines and collaboration models. *Agtech companies.*
2040 **Varieties healthy and resistant to pests**	**2040** **60% share of organic food in food services, 20% market share of organic food in retail**	**2040** **Collective landscape planning***	**2037** **Holistic farm management DSS**
Breeding program that take into account lack of herbicides (roots, shading ppties, etc.). *Ministry of agriculture, food sector.* Benchmark and learn from successes. *Farmer advisors*.	Innovation - R&D developments in food new recipes including organic and plant-based products. *R&D companies.* Cooking lessons and trainings to consumers and professional kitchens to introduce more organic and plant based products. *Food companies.* Sharing information about the organic food label (communication campaign). Farm to fork: new agri-food policy at EU level. *EU & MS*.	Research in landscaping, Education of farmers and society, Public policies & funds (EU biodiversity strategy)	Input from cropping systems needs information on future farming systems.
2040 **Pesticide free control methods for future pests risks are identified**	**2040** **100% food produced is based on the principles of organic production (or agroecology) even if not all certified organic**	**2035** **Cooperation platforms among farmers are well established**	**2037** **Machines available for mechanical weed management**
Learn from all available and successful control methods already available among farmers (farmers have huge amount of knowledge that cannot be found in books). *Farmers, advisors, koneyrittajat*, etc.	Regulation states the new organic standards. *EU commission*	Pro agria : name of the cooperation platform created by the finnish government to exchange between farmers	Piloting and testing of machines -> demovideos shared with farmers to convince them of efficacy (results in farms visible). *agroequipment companies*
2037 **Crop rotation on 100% farms**	**2035** **Carbon neutral food chain**	**2030** **Administration services have been renewed in order to be able to measure, value ecosystem services delivered by farmers**	**2030** **Cooperation on fields to change fields and introduce crop rotation**
Development of rotation models, option 1, option 2, etc. Supporting force to face to face advising of farmers. Training of advisers and of farmers. Rules / mandatory by law. e-college of regenerative farming. *Farmers, advisors, officials and politicians (for subsidies*).	Carbon sequestration in soils. *Farmers*. Research funding. *Public policy makers.* Support from administration (subsidies to farmers), food industry (CdC) and consumers towards nutrient resource recycling efficiency.		

Table A.4-3-3 (continued): Case study cereals and oilseeds production in South Finland: milestones and actions generated during the workshop – *milestones in bold, connected actions below, actors in italics*.

Cropping systems	Food value chain	Farm structures	Agroequipment and digital technologies
2037 **Field usage collaboration models in place**	**2035** **Market of food products sold in Finland is renewed - includes more diversified foodstuffs, has evolved to answer changes in consumption habits, open new opportunities for SMEs**		**2030** **Autoguide in every farm**
Experimentation between farmers coordinated by local farmers' organizations. Dissemination of results and experiences through *advisors and farmers organizations.*	Preference shopping service: digital application that recommends + delivers food products according to preferences (nutritional, environmental, social). *retailers, cooperation with SMEs*		Research program to develop the autoguides. Discussion on the price /mass purchase. Training to help adoption. Incentive for 1st purchase. *Farmers, selling companies, advisors, public policy makers.*
2035 **Mechanical weeding technologies are available and used by farmers**	**2030** **25% share of organic in food services** **10% market share of organic food in retail**		**2028** **Specialized equipment and robots to manage diversity of crops**
Best practices put in action (knowledge transfer). *Finnish institute for natural resources (LUKES), advisory services.*	Canteens: Using the EU school scheme to increase the share of sustainable products in schools. *Schools canteens owners, local authorities.* Dissemination of policy tools to support growing of organic (CAP subsidies).		Experimentation and demonstration by Ag tech companies and through pilot farms
2035 **Foresight and scenarios available regarding future pests risks in Finland due to climate change**	**2030** **Food production follows F2F objectives**		**2028** **Growers cooperate to share machinery**
Northern European research project "the most probable pests (insects, diseases, weeds) in nordic countries and their potential effects on cereals and oilseed crop production." *nordic council of ministers, H2025, Luke, Nibio, Ahrus, SLU, advisory companies, central & southern EU partners.*			Creation of growers' cooperation systems that provide planning platforms, communication methods, information from demo farms. *Advisors, research, farmers*.
2030 **The use of low risk substances including microbiological solutions) is widespread**	**2025** **Consumers's attitude has changed - they are very concerned about environment and biodiversity**		**2023** **Specialized DSS**
Companies develop new products (innovation investments). Testing for these substances conducted in several countries including Finland, also in farms (not only labs). Authorization of low risk substances facilitated in the regulation (*policy makers).*	Selection of criteria and simplified data about right food choices - nutritional and environmental. *Universities and research institutes*. Price policies to influence food behaviors changes. *Regulators, food chain.* **Creation of a label for food based on nutrition and environment**. *EU.* Prices recommendations allowed for producers. *Ministry*.		Common acceptance of technology as a useful tool for farming. *Governance steering regulators and Ag Tech companies*. Support to farmers for adoption. A*dvisory services and research*.
2028 **50% of fields have multiple crop rotations => diversification of crop rotation (legumes + grasses + cereals)**			
Establishment of "demonetwork" for crop rotations and facilitation of transfer of organic farmers' knowledge to conventional farmers.			
2025 **Cooperation between farmers**			
Models of cooperation are promoted through communication campaigns. Contracts of collaboration are developed. Operational support provided to accompany the cooperation through starter projects, money (subsidies). *Farmers, advisers, example actors (ambassadors), research*.			

*milestones added after the workshop

Table A.4-3-4: Case study wine production in Bergerac Duras: milestones and actions generated during the workshop – *milestones in bold, connected actions below, actors in italics (translated from French)*

Cropping systems for wine production	Wine value chain	Farm structures	Agroequipment and digital technologies
2045 **A territorial specification is in place**	**2048** **Wines of Bergerac and Duras designations of origin are produced using resistant and autochthonous grape varieties, preserving the biodiversity of the territory**	**2050** **Version 3 of the social contract of the territory is adopted**	**2045** **Territorial specifications are created for equipment manufacturers and suppliers, listing environmental, social and energy-saving criteria.**
Research programs to develop reconstruction of generic components, and verify the feasibility of implementing the concepts. *Research community.*			
2035 **Vineyards have been redesigned and now includes new crops**	**2040** **A new market promotes wines from the Bergerac Duras Biosphere Reserve**	**2040** **Ecosystem services delivered by wine growers and landowners are "monetized" (there is a value assigned to each service rendered)**	**2040** **Participatory workshops allow the assembly and adjustment of equipment**
	Multi-channel communication campaign (trade shows, social networks, magazines, etc.). *IVBD*. Targeted and concerted communication actions between producers and traders to highlight the label.	Carry out economic studies on prices and payment mechanisms for ecosystem services. *Researchers, (vitiREV research agenda, trade organizations).*	
2035 **Field experiments and models are validated**	**2040** **Taste ambassadors promote Bergerac Duras wines and their qualities**	**2037** **100% of winegrowers have obtained the "biodiversity" certification. Any new set up or creation of a company is conditioned to this certification.**	**2035** **A FAB LAB is created for participatory design of the necessary tools and sharing good practices**
Technical support and provision of land for field experiments. *Research organizations, DEPHY network, vitiREV, innovative research.*	Identification of one or several ambassadors: famous people within the Bergerac Duras territory. *IVBD, in connection with the ambassador winegrowers*.	Financial support for conversion from ministry of agriculture, Nouvelle Aquitaine region. Support for the set-up of new winegrowers. VAE for farm workers.	R&D: design modular machines so that the same machine can be used for several types of farms. *Co-development between agricultural equipment manufacturers and wine growers*. Set up 3D printing workshops (with sustainable materials, not plastic). *Agroequipment suppliers*.
2030 **A land use planning scheme is in place**	**2038** **Consumers are informed about the actions conducted to protect biodiversity on the territory**	**2035** **A new legal status, the territorial SCOP, gathers producers, communities, schools, residents, for the shared management of the Bergerac Duras area**	**2033** **Territorial network of collectively managed equipment, including mechanics available to farmers**
	label on the wines, and detailed explanations made available to them (digital)	A citizen convention within the territory to build together the territorial SCOP. State, communities, trade organization, associations, citizens, private actors. Define the statutes of the SCOP. Mechanisms for access to land.	Creation of a resource centre that proposes kits for low-tech equipment, easily repairable, etc. and that lists similar initiatives to share them with the largest number. *Agricultural advisors, low tech experts, etc.*
2030 **A steering committee (participatory) designed the new landscapes.**	**2035** **A whole range of cultural activities is in place around the territory**	**2032** **The "Winegrower & Biodiversity" trade standard is validated**	**2032** **a maintenance service is in place to maintain the equipment and provide after-sales service**
	Festivals, wine tourism and biodiversity, cultural mediation, live shows, etc. T*ourism offices, trade association.*		
2030 **The specifications of the designation of origin criteria have evolved to take into account environmental criteria, landscape, protection of biodiversity, etc.**	**2032** **The territory obtains the 'biosphere reserve' label certification**	**2028** **Creation of the SEM for the shared management of the Bergerac Duras landscape**	**2030** **A cooperative for the sharing of equipment is in place**
	Submission of the application for the biosphere reserve certification. *IVBD, territory.*		

Table A.4-3-4 (continued): Case study wine production in Bergerac Duras: milestones and actions generated during the workshop – *milestones in bold, connected actions below, actors in italics (translated from French)*

Cropping systems for wine production	Wine value chain	Farm structures	Agroequipment and digital technologies
2028 **Scientific results on the impact of biodiversity in agriculture are available, and we know where to install the agro ecological infrastructures**	**2030** **Trade agreements with wine distributors (cafés, restaurants, etc.) to promote the environmental actions of local actors**	**2023** **Opening of the school for transition, for winegrowers and other actors (agri workers, etc.) including residents.**	**2028** **An unit for the design of future tools is created, where workshops allow assemblies, adjustments**
	Discussions and negotiations with wine distributors	Funding of the school and its operation by the ministry of agriculture and the Nouvelle Aquitaine region. Implementation of a specialized certification "wine & biodiversity" for wine growers, winemakers, agricultural workers. School also opened to citizens. Interregional and international dimension. *Agricultural high schools, professional trainers, socio-economical researchers*.	Creation of a farming civic service
2028 **Cultivation practices follow the specifications (no chemical pesticides, preservation of biodiversity)**	**2028** **The specifications of the wine designations of origin have been revised to integrate the preservation of biodiversity, the adaptation to climate change**	**2023** **An organization - intervention structure bringing together the actors to coordinate the transition is created.**	**2028** **A tool for collecting and sharing data on the landscape, pests, solutions implemented, etc. is available for actors**
	Self-diagnosis of current practices / specifications vs the requirements of the "biosphere reserve" label by the *trade organization, CA24, winegrowers*, to submit of the application for the "biosphere reserve" label. Writing of new specifications including the diversity of varieties, the adaptations of the cultivation methods (including the non-use of chemical pesticides), the criteria 'biosphere reserve', the characteristics of the wines (typicity, identity). *INAO, ODG, CA, IFV, INRAE.*		Set up a monitoring on solutions developed by other actors in other territories. Create a mapping of networks of actors also working on the transition.
2025 **Natural resilient ecosystems have been identified**	**2025** **The range of BD wines is defined according to consumers' expectations and the vision of the territory**		**2024** **Sensors are in place on a pilot structure**
	Consumer studies conducted with experts in marketing, experimental economics, BSE oenology, to analyze and understand consumer expectations (taste, price, environment, label, willingness to pay). Then, leverage these expectations by typology of the elaborated wines. *ODG, trade organization, traders*.		
2024 **Diagnosis/landscape study on the whole territory and a knowledge of the soil are available**	**2024** **"Convention citoyenne" created to monitor the transition***		**2022** **Needs for monitoring sensor network have been identified**
Bring together all "Pays du Grand Bergeracois" actors to identify existing studies, mobilize and organize governance and budget. Carry out an inventory - mapping of the landscape (extension of the Pécharmant approach). *CAUE, LPO, CA24*.			
2023 **All stakeholders agree on the "no chemical pesticide" standard**	**2022** **The project of agro-ecological transition and label "biosphere reserve" certification is validated by the professional actors and the territorial authority**		

*milestones added after the workshop

List of acronyms: CA24: Chambre d'Agriculture de Dordogne – Chamber of Agriculture of Dordogne; CAUE: Conseil d'Architecture, d'Urbanisme et de l'Environnement - Council for Architecture, Urbanism and Environment; IFV: Institut français du vin – French wine institute; INAO: Institut National de l'Origine et de la Qualité - National Institute of origin and quality; LPO: Ligue de Protection des Oiseaux – French league for the protection of birds; IVBD: Interprofession des Vins de Bergerac Duras – Bergerac Duras wine trade organization; ODG: Organisme de Défense et de Gestion – Organism in charge of writing the specifications of the designations of origins; SCOP: Société Coopérative de Production.

European Chemical Pesticide-Free Agriculture in 2050

Chapter 5

Quantitative assessment of the scenarios

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Table of contents

Introduction

This Chapter reports the quantitative assessment of scenarios, which was carried out in addition to the scenario building process, as part of our coupled approach. Scenarios are simulated with the AE2050 version of the GlobAgri model, named GlobAgri-AE2050 (Tibi *et al.*, 2020). The first step of the work is to translate the qualitative assumptions of the narrative of each scenario and its related transition pathway into quantitative model inputs. The second step is to simulate the scenarios and their eventual variants. The third step is to analyse simulation results and deduce the main insights. The three steps of the work were conducted with experts, through individual interviews, a workshop and a webinar (Box 1).

For ease of comparison and in order to calibrate what happens in the rest of the world, we first define a so-called reference scenario. Then, the three scenarios of the foresight and their variants are simulated considering no change in the rest of the world. All scenarios provide a picture of the 2050 situation in Europe and in the rest of the world, under different assumptions of change in Europe. The reference scenario provides a picture of the 2050 situation if current trends in Europe and in the rest of the world are maintained. Therefore, comparing each scenario and its variants to the reference scenario allows to assess the impacts in 2050 of assumed changes in Europe.

The Chapter is organised as follows. Section 5.1 describes briefly the GlobAgri-AE2050 and its functioning. Section 5.2 presents the reference scenario and its simulation results. The scenarios of the foresight and their simulation results are the focus of Section 5.3. Section 5.4 deals with several variants of these scenarios and their simulation results, with the aim of putting emphasis on the key role of some assumptions. Finally, Section 5.5 concludes by reporting the main insights and the main limits of this quantitative assessment.

Box 1: Strategy for the quantitative assessment and contribution of experts

Step 1. Translation of the qualitative assumptions of scenarios and pathways into quantitative model inputs	
Individual interviews	Food diets: E. Kesse-Guyot (INRAE, nutritionist); F. De Clerck (CGIAR France and SRC Sweden, Eat Lancet commission) Trade: S. Jean (CNAM and CEPII, economist); A. Cheptea and C. Gaigné (INRAE, economists) Cultivable areas: K. Helming (Zalf, Germany, soil scientist) Crop yields and cropping intensities: N. Guilpart (AgroParisTech, agronomist)
Steps 2. and 3. Simulation, results analysis, back and forth between assumptions and results	
Workshop (July, 4th 2022)	Crop yields and cropping intensities and preliminary simulation results: J.N. Aubertot (INRAE, agronomist); J. Barreiro-Hurle (JRC, Spain, economist); C. Bartoli-Kautsky (INRAE, biologist); H. Mitter (BOKU, Austria, economist); A. Mosnier (FABLE, IIASA, Austria, economist)[1]; N. Munier-Jolain (INRAE, agronomist)
Webinar (September 30th 2022)	Simulation results of scenarios: J. Barreiro-Hurle (JRC, Spain, economist); A. Mosnier (FABLE, IIASA, Austria, economist); N. Munier-Jolain (INRAE, agronomist)

[1] Member of the European expert committee of the foresight.

5.1. The GlobAgri-AE2050 model

The GlobAgri platform has been developed by CIRAD and INRAE to generate consistent databases and biomass balance models using data from FAOStat and from a few other sources. The databases generated are balanced and account for the links between products (through animal feed or oilseed crushing for instance). Biomass balance models provide a balance equation between resources (domestic production plus imports minus exports) and utilization (food, feed, other uses, waste) for each region and each agri-food product. Feed use of vegetal products is a linear combination of outputs of animal products (through feed to output ratios). In each equation, imports depend linearly on the total domestic use of the product (through import coefficients), while exports are a linear function of the world market size (through export market shares). To preserve the global coherence in the model, two constraints are introduced: the first one ensures that at the world level, for each agri-food product the sum of all imports equals the sum of all exports; the second one imposes a maximum cultivable land area for each region that cannot be surpassed.

GlobAgri aims at simulating the impacts of scenarios of change in agri-food systems on agricultural resource-use balances, land use and greenhouse gas (GHG) emissions at both global and regional level. Table 5-1 reports the input variables and parameters of the model. These are these variables and parameters that the modeller can change to depict the scenario to be simulated. For instance, the scenario may involve a change in the food diet and in agricultural production systems in one region. This would translate into a change in the food consumption levels of agri-food products as well as in crop yield and livestock productivity levels relative to the initial situation in the considered region. The levels of imports, exports, and domestic production would then adjust to restore equilibrium between resource availability and resource use. As imports of the considered region are produced abroad while exports replace production abroad, balances in other regions are adjusting as well. Therefore, land area needs change in all regions.

When no region reaches its maximum cultivable area, adjustments stop and a new global equilibrium is achieved. In that case, import coefficients and export shares remain exogenous. When one or some regions need more cultivated area than their maximum cultivable, additional adjustments are required to restore equilibrium. In regions where the limit on cultivable land area is reached, equilibrium is achieved by reducing exports (via a decrease in the region’s export shares) and/or increasing imports (via an increase in import coefficients). More specifically, for a region exceeding its maximum cultivable land area, export shares are decreased equi-proportionnally for all products. If even with zero exports, the region still needs more cultivated area than its maximum cultivable area, then the region starts increasing its imports (through increases in import coefficients). In other words, the region increases the share of its food needs which is covered by imports in order to reduce the required rise in domestic production and save some cultivated area. As initial import coefficients of regions vary widely across products, we defined intervals of initial levels upon which the coefficients are increased evenly, allowing for differentiating the level of increase by band. The GlobAgri database and model are fully described in Le Mouël *et al.* (2018) and Mora *et al.* (2020).

The GlobAgri platform has been used to generate a database and a biomass balance model specifically customised for the AE2050 study (European agriculture in 2050, see Tibi *et al.*, 2020). The resulting tool is named GlobAgri-AE2050. It encompasses 38 aggregates of agri-food products (Table 5-2) and covers 21 broad regions, including 6 European sub-regions (Table 5-3). Globagri-AE2050 is fully described in Tibi *et al.* (2020). The initial situation is the base year "2010" corresponding to the 2009-2011 average.

Table 5-1: The input variables and parameters of GlobAgri

Input variables	**Definition**	**Examples of quantitative hypotheses of simulated scenarios**
$\boldsymbol{Food_{ij}}$	Food consumption of product *i* in region *j*	Population change in region *j* Food diet change in region *j*
$\boldsymbol{Oth_{ij}}$	Other uses of product *i* in region *j*	Change in non-food use of agricultural biomass in region *j*
$\boldsymbol{\overline{Surf_j}}$	Maximum cultivable land area in region *j*	Land degradation or land restoration in region *j* Expansion or reduction of irrigated land area in region *j* Impact of climate change in region *j*
$\boldsymbol{Y_{vj}}$	Per-hectare yield of crop *v* in region *j*	Technical change and/or change in cropping systems in region *j* Expansion or reduction of irrigated land area in region *j* Impact of climate change in region *j*
Parameters		
$\boldsymbol{\beta_{iaj}}$	Feed-to-output coefficient for feed product *i* and animal product *a* in region *j*	Technical change and/or livestock system change in region *j*
$\boldsymbol{e_j}$	Ratio of total cultivated area over total harvested area in region *j*	Change in cropping intensity in region *j* Change in fallow land in region *j*
$\boldsymbol{\alpha_{ij}}^*$	Import dependence coefficient for product *i* in region *j*	Change in trade policy in region *j*
$\boldsymbol{\sigma_{ij}}^*$	World export market share of region *j* for product *i*	Change in trade policy in region *j*

Table 5-2: Composition of the 38 agri-food aggregates of GlobAgri-AE2050

Aggregates	Composition
Aquatic animals	Freshwater Fish, Demersal Fish, Pelagic Fish, Marine Fish Other, Crustaceans, Cephalopods, Molluscs, Aquatic Mammals, Aquatic Animals Others
Bovine meat	Bovine Meat
Dairy	FAO aggregate: Milk excluding butter*
Eggs	Eggs
Pork meat	Pork Meat
Poultry meat	Poultry Meat
Small ruminant meat	Mutton and Goat Meat
Fibres etc.	Jute, Jute-Like Fibres, Soft-Fibres Other, Sisal, Abaca, Hard Fibres Other, Tobacco, Rubber, Seed Cotton
Fruit and vegetables	Tomatoes, Onions, Vegetables Other, Oranges, Mandarins, Lemons, Limes, Grapefruit, Citrus Other, Bananas, Plantains, Apples, Pineapples, Dates, Grapes, Fruits Other
Other plant products	Nuts, Coffee, Cocoa Beans, Tea, Pepper, Pimento, Cloves, Spices, Other
Other products	Meat Other, Offals Edible, Fats Animals Raw, Honey, Meat Meal, Aquatic Plants
Pulses	Beans, Peas, Pulses Other
Roots and tuber	Potatoes, Cassava, Sweet Potatoes, Roots Other, Yams
Maize	Maize
Other cereals	Barley, Rye, Oats, Millet, Sorghum, Cereals Other
Rice	Rice (Paddy equivalent)
Wheat	Wheat
Sugar plants and products	Sugar Cane, Sugar Beet
Other oilcrops	Groundnuts (Shelled Eq), Coconuts - including Copra, Sesame seed, Olives, Oilcrops Other
Cake other oilcrops	Cake of other oilcrops (see above)
Oil other oilcrops	Oil of other oilcrops (see above)
Oilpalm fruit	Oilpalm Fruit
Palm product oil	Palm Oil, Palm Kernel Oil
Palm kernel cake	Palm Kernel Cake
Rape and mustard seeds	Rape and Mustard Seeds
Rape and mustard cake	Rape and Mustard Cake
Rape and mustard oil	Rape and Mustard Oil
Soyabeans	Soyabeans
Soyabean cake	Soyabean Cake
Soyabean oil	Soyabean Oil
Sunflower seeds	Sunflower Seeds
Sunflower seed cake	Sunflower Seed Cake
Sunflower seed oil	Sunflower Seed Oil
Grass	Permanent grassland grazing and silage
Grass-like forages	Temporary meadows and pastures (mix and ray-grass)
Other forages	Alfalfa, clover, other cultivated forages (beets, legumes, sorgho, corn, pulses, etc.)
Occasionals	Food waste, occasional feeds, etc.
Crop residues	Straw, stalks, residues

Table 5-3: Composition of the 21 regions of GlobAgri-AE2050

Countries/Regions	Composition
France	France
Germany	Germany
United Kingdom	United Kingdom
Poland	Poland
South Europe	Albania, Bosnia and Herzegovina, Croatia, The former Yugoslav Republic of Macedonia, Montenegro, Andorra, Cyprus, Gibraltar, Greece, Holy See, Italy, Malta, Monaco, Portugal, San Marino, Slovenia, Spain
East Europe	Serbia, Bulgaria, Hungary, Romania
Central Europe	Switzerland, Austria, Czechia, Slovakia
Rest of Europe	Norway, Denmark, Sweden, Finland, Estonia, Ireland, Latvia, Liechtenstein, Lithuania, Netherlands, Belgium, Luxembourg
Canada/USA	Canada, USA
Brazil/Argentina	Brazil, Argentina
Rest of America	Antigua and Barbuda, Bahamas, Barbados, Bermuda, Bolivia (Plurinational State of), Aruba, Belize, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela (Bolivarian Republic of), British Virgin Islands, United States Virgin Islands, Anguilla, Falkland Islands (Malvinas), French Guiana, Guadeloupe, Martinique
Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
China	China
India	India
Rest of Asia	Afghanistan, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei Darussalam, Myanmar, Sri Lanka, Cook Islands, Indonesia, Japan, Cambodia, Democratic People's Republic of Korea, Republic of Korea, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Nepal, Pakistan, Philippines, Timor-Leste, Singapore, Thailand, Viet Nam
Near and Middle East	Israel, Jordan, Lebanon, Syrian Arab Republic, Occupied Palestinian Territory, Bahrain, Iran (Islamic Republic of), Iraq, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Yemen, Western Sahara
North Africa	Algeria, Egypt, Libya, Morocco, Tunisia
West Africa	Cabo Verde, Benin, Gambia, Guinea-Bissau, Guinea, Côte d'Ivoire, Mali, Niger, Senegal, Togo, Burkina Faso, Ghana, Liberia, Nigeria, Sierra Leone
ECS (Eastern, Central, South) Africa	Angola, Botswana, Burundi, Cameroon, Central African Republic, Chad, Comoros, Congo, Equatorial Guinea, Djibouti, Gabon, Kenya, Lesotho, Madagascar, Malawi, Mauritanie, Mauritius, Mozambique, Namibia, Eritrea, Zimbabwe, Rwanda, Saint Helena, Ascension and Tristan da Cunha, Sao Tome and Principe, Seychelles, Somalia, South Africa, Swaziland, United Republic of Tanzania, Uganda, Ethiopia, Democratic Republic of the Congo, Zambia, Mayotte, Sudan, South Sudan
Oceania	American Samoa, Australia, Solomon Islands, Christmas Island, Cocos (Keeling) Islands, Fiji, French Polynesia, Kiribati, Guam, Marshall Islands, Micronesia (Federated States of), Nauru, New Caledonia, Vanuatu, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Papua New Guinea, Pitcairn Islands, Palau, Tokelau, Tonga, Tuvalu, Wake Island, Wallis and Futuna Islands, Samoa
Rest of the world	French Southern and Antarctic Territories, Iceland, Republic of Moldova, Faroe Islands, Greenland, Saint Pierre and Miquelon, Channel Islands, Svalbard and Jan Mayen Islands, Isle of Man

5.2. The reference scenario

Introduction

With the reference scenario, we wish to depict the situation in 2050 in Europe and in the rest of the world, in terms of agricultural resource-use balances, land use and GHG emissions, if the current trends in agri-food systems are maintained all over the world.

Our reference scenario is inspired from the scenario "Trend Diets x Low Yields" of the AE2050 study (Tibi *et al.*, 2020). Most of our assumptions are taken from this AE2050 scenario. However, we adopted different hypotheses for the food diet in Europe and for the cropping intensities all over the world.

5.2.1. Underlying assumptions

5.2.1.1. Population growth

We assume that population in the various parts of the world will change according to the median projection of the United Nations World Population Prospect (2017). This results in the population changes from the base year "2010" to 2050 as reported in Table 5-4 for the 21 regions of GlobAgri-AE2050.

The world population would grow with almost +40% between "2010" and 2050. In the GlobArgi-AE2050 model this induces a world population of almost 9.5 billion inhabitants in 2050. Very high growth rates are observed for some regions, especially for West and ECS Africa (+163% and +152% respectively) but also for North Africa and Near and Middle East (+64% and +63% respectively). Other regions would observe lesser growth in their populations and a stabilization would occur notably for China (+0.4%) and the Former Soviet Union (+4%).

The European population would also stabilize between "2010" and 2050 at around 535 million habitants, although very large differences can be observed between the European sub-regions. Several sub-regions would see their population decline (East Europe: – 20%, Poland: -15%; South Europe: -8% and Germany: -2%). These evolutions would be compensated by growth in other European sub-regions or countries (United Kingdom: +19%, France: +12%, Rest of Europe: +12%).

From "2010" to 2050, the significant population increase in India, Rest of Asia, Near and Middle East (NME), North Africa, West Africa and ECS Africa will have a positive impact on food needs in these regions.

Table 5-4: Population growth as projected in the 21 Globagri-AE2050 regions between "2010" and 2050

	Population "2010" (Mhab) (FAOStat)[1]	Share in world population in 2010 (%)	*Percent change between "2010" and 2050 (%)*	*Variation between "2010" and 2050 (Mhab)*	Population 2050 (Mhab)	Share in world population in 2050 (%)
France	63.0	0.9	*12.0*	*+7.6*	70.6	0.7
Germany	80.9	1.2	*-2.1*	*-1.7*	79.2	0.8
UK	63.3	0.9	*19.1*	*+12.1*	75.4	0.8
Poland	38.3	0.6	*-15.5*	*-5.9*	32.4	0.3
South Europe	145.8	2.1	*-8.1*	*-11.8*	133.9	1.4
East Europe	46.8	0.7	*-19.8*	*-9.3*	37.5	0.4
Central Europe	32.2	0.5	*5.0*	*+1.6*	33.8	0.4
Rest of Europe	64.5	0.9	*12.0*	*+7.8*	72.3	0.8
TOTAL Europe	534.8	7.9	*0.1*	*+0.3*	535.2	5.7
Canada, USA	342.8	5.0	*26.8*	*+91.8*	434.5	4.6
Brazil, Argentina	238.0	3.5	*21.0*	*+49.9*	287.9	3.0
Rest Amer.	354.3	5.2	*36.8*	*+130.4*	484.7	5.1
FSU	277.8	4.1	*4.1*	*+11.5*	289.3	3.1
China	1 390.4	20.4	*0.4*	*+5.9*	1 396.4	14.8
India	1 230.8	18.1	*34.8*	*+428.1*	1 659.0	17.5
Rest Asia	1 196.9	17.6	*34.4*	*+412.3*	1 609.2	17.0
NME	262.0	3.8	*62.7*	*+164.2*	426.3	4.5
North Africa	163.4	2.4	*64.3*	*+105.1*	268.4	2.8
West Africa	304.2	4.5	*163.2*	*+496.5*	800.7	8.5
ECS Africa	483.0	7.1	*151.5*	*+731.6*	1 214.6	12.8
Oceania	28.9	0.4	*56.0*	*+16.2*	45.1	0.5
ROW	4.4	0.1	*-14.3*	*-0.6*	3.8	0.0
TOTAL World	6 811.7	100.0	*38.8*	*+2 643.3*	9 455.1	100.0

[1] In the initial base year situation, the GlobAgri model uses the FAOStat figures to be consistent with its agricultural data. However the lack of data for some countries in FAOStat, that are included in the United Nation prospects, induces a difference between the world population in FAOStat/GlobAgri-AE2050 and in the United Nations initial situation « 2010 » (2 % in the world and less than 0,06 % in Europe-AE2050). The use of the median growth projection thus induces a world population of 9.46 bn habitants in 2050 instead of around 9.77 in the UN's 2017 projections.

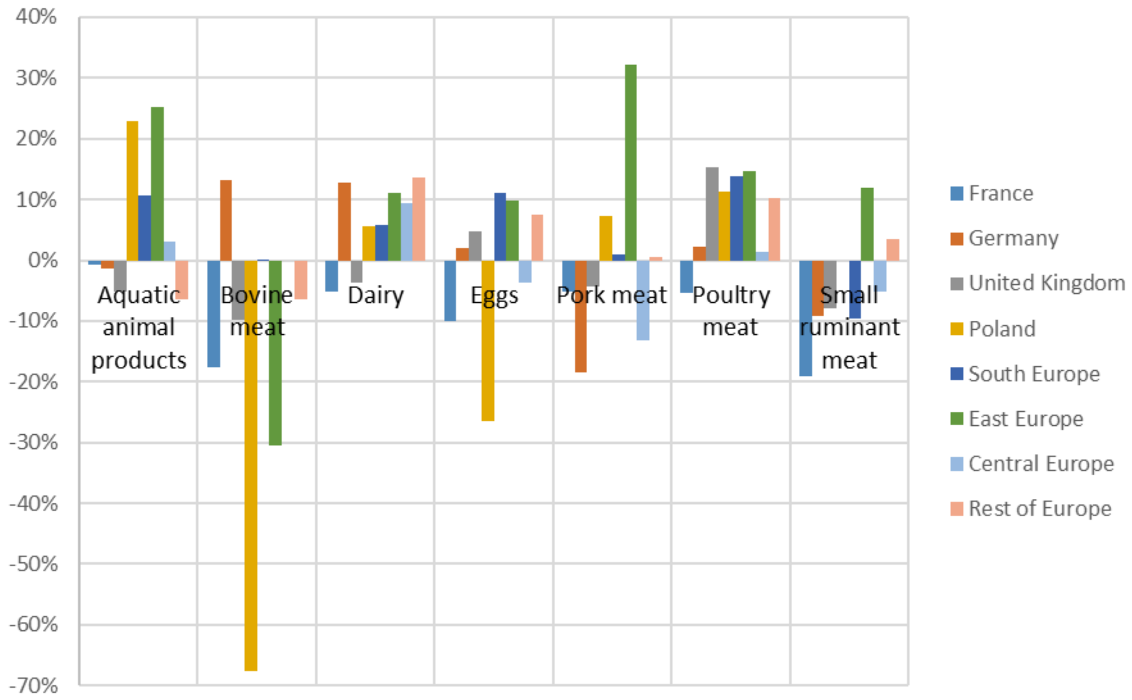
5.2.1.2. Diets

The AE2050 study assumed that food diets in the various parts of the world would change according to the projections by Alexandratos and Bruinsma (2012). We updated this assumption by using the proposed food diets in the Business As Usual (BAU) scenario of a more recent FAO study (FAO, 2018). Such more recent projections assume a lower growth in the consumption per capita of animal products outside Europe, notably in Asia (especially in China), compared to Alexandratos and Bruisman (2012). This seems more in line with the observed evolution over the last years.

According to the BAU projections of the FAO (2018) study, food diet changes between "2010" and 2050 are very significant in developing regions (All African regions, a large part of Rest of America, India and a large part of Rest of Asia), with a rise in energy content and changing patterns towards more animal products, vegetable oils and sugar plant and products, and less cereals and roots and tuber. Changes are similar but less marked in emerging regions (e.g., Brazil/Argentina, China) and significantly less marked in developed regions (e.g., Canada/USA) (Figure A.5-1 in Appendix).

For Europe however, the BAU scenario of the FAO (2018) study implies an increasing consumption per capita of animal products until 2050. This is in contradiction with observed trends over the last years in Europe, where consumption per capita of most animal products is rather stagnating or decreasing (notably ruminant meat), even if observed changes are not homogenous across European sub-regions (Figure 5-1).

Figure 5-1: Observed percentage changes in food consumption of animal products between 2010-2011 average and 2018-2019 average, in kcal per habitant and per day, for different European sub-regions



Source: FAOStat, new food balance sheets.

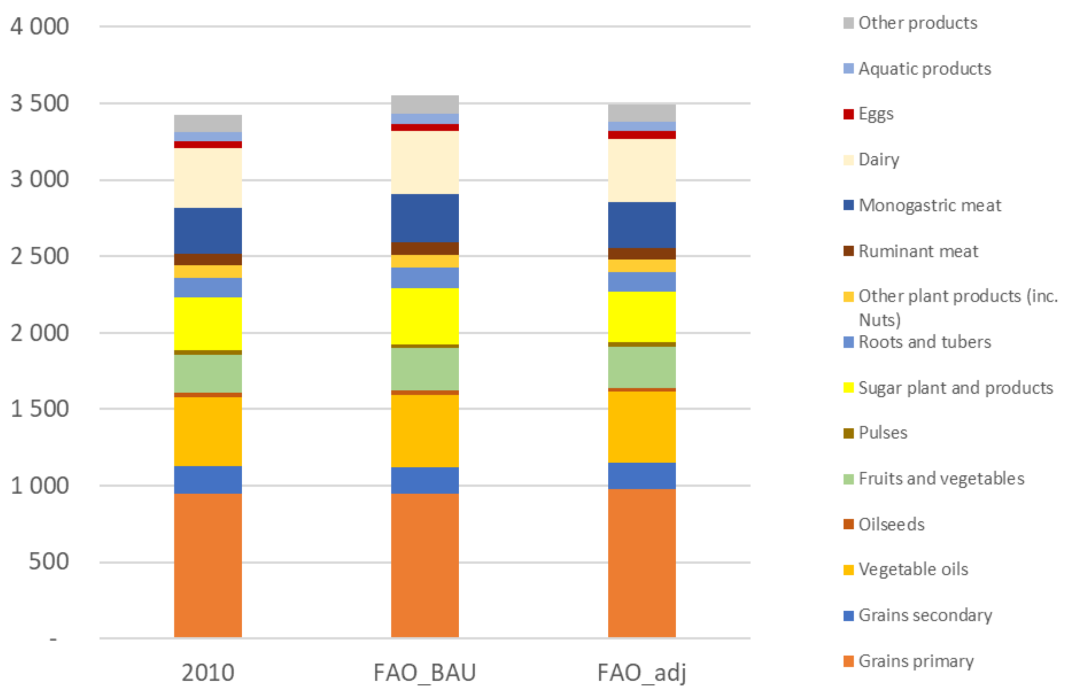
Based on FAOStat data, Figure 5-1 reveals that between 2010-11 and 2018-19, consumption per capita of ruminant meat, pork meat, small ruminant meat and eggs is stagnating or decreasing in most European sub-regions. At reverse, consumption per capita of dairy products, poultry meat and aquatic animal products is stagnating or increasing in most European sub-regions.

Hence, in order to take into account these recent trends in European food consumption, we replaced the FAO BAU projections of consumption per capita of all products by our own projections for our European sub-regions. We based our own projections on the observed changes in food diets in European sub-regions from the average 2010-2011 to the average 2017-18-19 year (the three latest years with available consolidated data in FAOStat). Then, we assumed no additional change until 2050.

As shown by Figure 5-2, the average European food diet in 2050 according to our projections (FAO_adj) is slightly different from the average European diet in 2050 according to the BAU projections in FAO (2018) (FAO_BAU), with mainly slightly lower energy content (-2%); lower bovine meat (-10%), pork meat (-7%) and small ruminant meat (-13%). Compared to the "2010" base year food diet, our 2050 projected diet is richer in energy, with relatively stable patterns.[1]

[1] Corresponding food diets for each of our European sub-regions are provided in Appendix, Figure A.5-2.

Figure 5-2: Average European food diet in the "2010" base year, and in 2050 according to FAO BAU projections (FAO_BAU) and according to our own projections (FAO_adj) (in kcal/cap/day)



Source: Own calculation, based on FAOStat data and FAO (2018).

Note: One may notice that our food diets are the so-called food availability per capita and per day as provided by FAOStat. Therefore, they include waste at the distribution and consumption level.

Change in total food consumption between "2010" and 2050 in each broad region results from both change in population and change in food diets. According to our assumptions, world food consumption will be driven mainly by increase and changing patterns in food consumption in developing regions, where assumed population increase and westernization of food diets are the most significant.

5.2.1.3. Crop yields

In the reference scenario, changes in crop yields from "2010" to 2050 are those assumed in the "Low yield" hypothesis in the AE2050 study (Tibi *et al.*, 2020). This "Low yield" hypothesis builds on:

- Technical progress assumption as in the BAU scenario in FAO (2018);
- Climate change impact in 2050 evaluated based on Makowski *et al.* (2020), in the case where the potential impacts of CO_2 fertilization on plant productivity is not taken into account[2], for the RCP 6.0 scenario.

For a complete description of the methodology used, please refer to Forslund *et al.* (2020).

[2] The BAU technical progress projections in FAO (2018) can be seen as more pessimistic for crop yields compared to previous ones (notably those in the FAO report authored by Alexandratos and Bruisnma, 2012). On the other hand, crops need the most favourable conditions to be able to exploit the CO_2 fertilization impact. We thus considered that the pessimistic technical progress assumption was more consistent with the exclusion of the CO_2 fertilization effect. In the AE2050 study, the High yield hypothesis is based on a more optimistic technical progress assumption and accounts for the CO_2 fertilization effect on plant productivity. In that case, it is assumed that under higher technical progress, better adapted seeds through varietal selection, more efficient fertilizers and water management, etc, would provide favourable conditions for the plant to be able to exploit the CO_2 fertilization effect.

According to Tibi *et al.* (2020), the technical progress assumption in the BAU scenario of the FAO (2018) study is rather conservative. Like many other studies, FAO (2018) assumes that crop yields will continue to increase in most parts of the world, but significantly less rapidly than during previous decades. In addition, FAO (2018) technical progress assumption in the BAU scenario is significantly less optimistic than the one underlying previous projections by Alexandratos and Bruinsma (2012). On the other hand, with no CO_2 fertilization effect, climate change would affect negatively crop yields (in average, from -1% to -5% for C3 crops and -4% to -7.5% for C4 crops, depending on countries/regions).

Table 5-5 reports the crop yield changes over the 2010-2050 period for the various crops in average for Europe and for the whole world according to our assumptions. Under our assumptions, crop yields would continue to increase for all crop types in world average and in Europe. The only exception is grass from permanent pasture which projected yield is slightly decreasing. FAO (2018) does not provide yield projection for grass and the potential of yield increase due to technical progress is very uncertain in existing literature. Hence, for grass we considered that no technical progress would arise over the period, so that only the negative impact of climate change is acting here.[3] For all other crops, crop yield projected increases are significantly higher in world average than in Europe.

Table 5-5: Changes in crop yields from "2010" to 2050 in average in Europe and in the world as a whole for different groups of vegetal products (%)

	Europe	World	Europe	World
	Change 2010-2050		Per year	
Cereals	16%	29%	0.37%	0.63%
Oilseeds	18%	25%	0.42%	0.57%
Fruits and vegetables	26%	37%	0.59%	0.80%
Other plant products	27%	35%	0.60%	0.74%
Pulses	19%	33%	0.43%	0.72%
Roots and Tuber	19%	27%	0.44%	0.60%
Sugar plants and products	19%	25%	0.44%	0.56%
Fibers etc.	14%	37%	0.32%	0.79%
Grass	-3%	-3%	-0.07%	-0.07%
Grass-like forage	11%	24%	0.27%	0.53%
Other forages	13%	29%	0.31%	0.64%

Source: Based on Tibi *et al.* (2020).

Crop yields in "2010" and in 2050 for the European sub-regions are provided in Appendix (Table A.5-1). Figure A.5-3 in Appendix reports observed crop yield evolution from 1975 to 2017 and then crop yields projected to 2050 under different assumptions (including the "Low yield" hypothesis of our reference scenario), for main crops in the European sub-regions. Overall, our assumptions result in crop yields increasing for most crop types in most European sub-regions. Figure A.5-3 suggests however that our projected yields are rather conservative relative to those obtained under alternative projection assumptions.

Nevertheless, according to the experts we consulted, some crops in some European sub-regions exhibit yields which are plateau-ing yet since several years. Therefore they doubt that for these crops in these sub-regions we could see yields increasing even slightly from now to 2050. As shown by Figure A.5-3,

[3] As the initial calculated grass yields seem very low for West, ECS Africa and China, we made exception to this assumption and considered that some technical progress would arise until 2050 and contribute to increase yield in the same extent than the average increase of all other crops in these regions, that is +40% for the two sub-Saharan regions and +30% for China.

main concerned crops are: wheat in France, UK and Rest of Europe; other cereals in France and UK; rapeseed in France; sunflower in Germany; soyabean in South of Europe; sugar plant and products in France. For these crops in these sub-regions, experts advised us to explore further the potential of yield increase. Thus, we collected data on yield gaps (from Schils *et al.*, 2018, and the Global Yield Gap Atlas https://www.yieldgap.org/) and harvested area shares (from FAOStat) and decided that if the yield gap is low while the harvested area share is high, then the potential of yield increase is likely to be low and the corresponding crop yield is assumed to continue to plateau-ing at current level until 2050. In all other cases, and especially when the yield gap is high, we consider that there is still some potential for yield increase and we keep the corresponding crop yield at its initial projection level in 2050. Applying these rules, only a few crops in a few sub-regions would be assumed to continue plateau-ing. In addition, the current plateau levels are most often close to the yield levels initially projected in 2050 (starting from the base year "2010" where yield levels are lower than the current ones). Therefore, such plateau-ing assumption would have nearly no effect on simulation results and we decided to keep initial projections for all crops in all European sub-regions.

5.2.1.4. Animal feed efficiencies

For each animal product, the global animal feed efficiency is the coefficient linking the total quantity of output produced to the total quantity of feed inputs.[4] This coefficient measures the efficiency of the animal in transforming the feed ration into produced output. This coefficient changes over time as a result of technical progress (genetics of the animal and production practices) and climate change (animal health and digestibility of the feed ration). Therefore, projecting global animal feed efficiencies up to 2050 requires adopting assumptions on technical progress in the livestock production systems and on climate change impacts on animal and on feed resources.

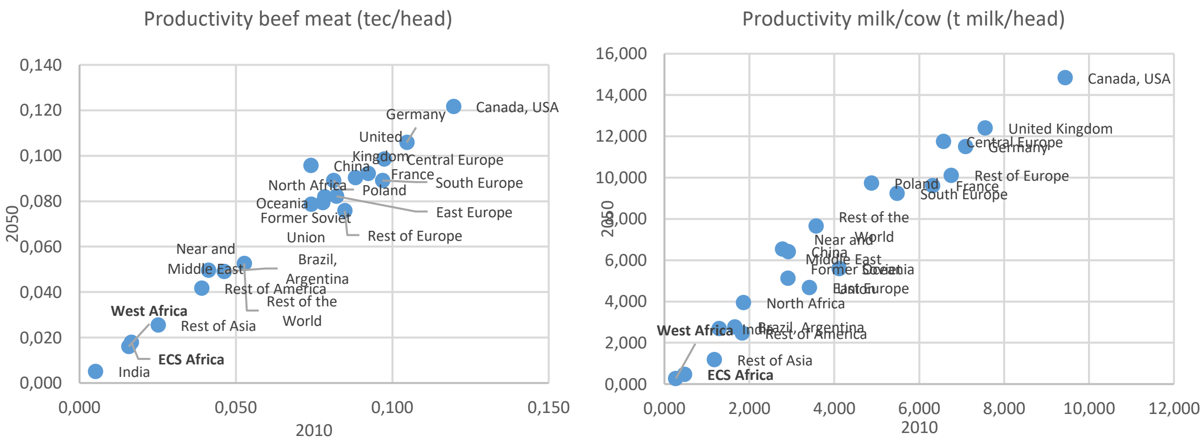
In this foresight we use the projections of animal feed efficiencies from the AE2050 study. The methodology is described in detail in Tibi *et al.* (2020). It is important to notice that these projections rely on a rather conservative assumption in terms of technical progress. Regarding climate change, only the potential impact on feed digestibility is accounted for. Globally, this results in significant improvement of animal feed efficiencies for milk production, slight improvement or stagnation for monogastric production and rather deterioration or stagnation for ruminant meat production, all over the world (improvements being greater in developing and emerging regions than in developed regions).

As shown in Figure 5-3, initial productivity of animals for milk and bovine meat production is very low for the two African regions. Furthermore, according to Tibi et al's assumptions, this productivity would at best stagnate in both regions. We thought it was too conservative and assumed instead that some rupture could arise in bovine production systems in Africa, making it possible to double productivity of animals. Thus, we assumed a doubling of animal productivity in milk and bovine meat production systems in West Africa and in ECS Africa from "2010" to 2050. This implies a significant improvement of corresponding global animal feed efficiencies: -44% for milk and -42% for bovine meat in West Africa; -43% for milk and -39% for bovine meat in ECS Africa, relative to the AE2050 study.[5]

[4] Let's notice that the animal feed efficiencies are the coefficients, which are used in the model. Each coefficient links the output quantity of an animal product to the quantity used of a specific feed ingredient. The animal feed efficiencies are thus different from the global animal efficiency. However, both types of coefficients are closely linked and the projection up to 2050 of the animal feed efficiencies (the parameters of the model) are based on the projection up to 2050 of the corresponding global animal feed efficiencies (for more details, see Tibi *et al.*, 2020).

[5] This also results in an adjustment of related GHG emission factors: emission factors increase per head, but decrease per produced unit, by approximately the same order as global animal feed efficiencies.

Figure 5-3: Ruminant meat and milk productivity in GlobAgri regions, in "2010" and 2050 according to the projections of the AE2050 study (t/head)



Source: Tibi *et al.* (2020).

5.2.1.5. Cropping Intensity

The cropping intensity for each GlobAgri-AE2050 region for the base year "2010" is calculated by dividing each region's total harvested area (including areas for grass-like and other forages) by the area for "Arable Land and permanent crops", both variables from FAO data and the average 2009-11 years.

Therefore cropping intensity coefficients compare harvested to cultivated areas. When the coefficient is greater than one, the reported harvested area in one region is greater than its reported cultivated area, meaning that the same hectare is, on average, harvested more than one time a year (e.g., multi-cropping). When the coefficient is lesser than one, the reported harvested area in one region is lower than the reported cultivated area, meaning that some hectares are left fallow (since fallow is included into cultivated area, but of course is not harvested) or that some hectares have been planted but not harvested (due to climatic event, pest attack or conflicts, etc.).

Table 5-6 reports the cropping intensity coefficient of each GlobAgri-AE2050 region calculated for "2010". In Europe, cropping intensity is close to one in Germany and Poland. It is lower than one for the other European sub-regions (suggesting larger cultivated than harvested land areas). In the rest of the world, cropping intensities are most often lesser than one, except in Asia, where several harvests a year are possible, notably for rice. Cropping intensities are particularly high in China and India and particularly low in FSU and Oceania, which is in line with other studies (e.g., Ray and Foley, 2013).

Existing literature shows an increasing trend in cropping intensity on average at the world level over the two last decades (e.g., Ray and Foley, 2013; Wu *et al.*, 2018; Waha *et al.*, 2020). They also evaluate the extent to which cropping intensity could potentially increase in the various parts of the world. They find that cropping intensity could increase significantly in Latin America, Africa and Asia, while Europe and North America face very limited potential gains. However, the most recent study is far less optimistic than the both previous ones: Waha *et al.* (2020) estimate that harvesting current single-cropping area a second time a year where it is possible all over the world would result in +395 million additional hectares (Mha) of global cropland, under the most optimistic scenario. This is 41–46% less than the +666 Mha to +736 Mha maximum area increase estimated previously by Ray and Foley (2013) and Wu *et al.* (2018).

The FAO (2018) study also considered an increasing trend in cropping intensity all over the world up to 2050, in all scenarios (+6% in world average in the BAU scenario). The AE2050 study adopted the BAU assumption of the FAO (2018) study (Table 5-6). In this foresight we considered that it was a too optimistic assumption for our reference scenario, for at least three reasons. Firstly, our reference scenario assumes no significant changes in cropping systems, making it difficult to realise the potential of the cropping intensity increase, as mentioned by Waha *et al.* (2020). Secondly existing estimates are likely to be too optimistic since they do not take into account that the potential of increasing cropping intensity might be limited by soil degradation, biotic stress, availability and access to inputs, etc. Lastly, the extent of the potential of increasing cropping intensity is very different from one study to another.

Thus, we decided to keep cropping intensities constant from "2010" to 2050 in our reference scenario (Table 5-6).

Table 5-6: Cropping intensity in "2010" and in 2050 under our reference scenario and in the AE2050 study

	CI "2010"	CI 2050 (our reference scenario)	CI 2050 (AE2050 study)
France	0,83	0,83	0,90
Germany	0,97	0,97	1,05
UK	0,88	0,88	0,95
Poland	0,98	0,98	1,07
South Europe	0,77	0,77	0,84
East Europe	0,90	0,90	0,97
Central Europe	0,83	0,83	0,90
Rest of Europe	0,81	0,81	0,88
Canada, USA	0,77	0,77	0,88
Brazil, Argentina	0,87	0,87	0,88
Rest of America	0,85	0,85	0,87
FSU	0,65	0,65	0,71
China	1,43	1,43	1,43
India	1,31	1,31	1,36
Rest of Asia	1,02	1,02	1,05
NME	0,75	0,75	0,74
North Africa	0,78	0,78	0,77
West Africa	0,98	0,98	1,02
ECS Africa	0,81	0,81	0,83
Oceania	0,62	0,62	0,63

Source: Own calculation based on FAOStat data and Tibi *et al.* (2020).

5.2.1.6. Maximum cultivable area

We define the maximum cultivable area per region as the maximum potential cropland per region. In other words, this is the maximum area where the current cropland area (sometimes called the current cultivated area) could expand if necessary. We calculate regional maximum cultivable areas in "2010" and in 2050 under our reference scenario using data from GAEZ (*Global Agro-Ecological Zones*) version 4.0 (Fischer *et al*., 2021).

The GAEZ data portal classifies land according to their agro-ecological potential independently from their current use (arable or permanent crops, grassland, shrubland, forest, protected area or partly urbanized, etc.). The agro-ecological potential of land is assessed through the « Suitability Index » (SI) (for more details, see Fisher, 2021). In GAEZ.v4, the SI is calculated for 51 different crops, two levels of inputs (High, Low), two types of water supply (Irrigated, Rainfed), for past years and three future time horizons (2020, 2050 and 2080) under four climate change (CC) scenarios (RCPs 2.6, 4.5, 6.0 and 8.5). Table 5-7 reports the various options we retained for SI computation in "2010" and in 2050.

The SI comprises 0 to 100 % and is divided into six classes of soil quality: not suitable if SI is between 0 and 5 %; very marginally suitable if SI is between 5 and 20 %; marginally suitable if it is between 20 and 40 %; moderately suitable if it is between 40 and 60 %; suitable if it is between 60 and 80 % and very suitable if it is greater than 80 % (FAO, 1996). Land area with an SI superior to 40% is often aggregated and presented as potentially cultivable land (Fischer *et al.*, 2002, 2012), while land with SI lesser than 40% is also aggregated and considered as marginal land, not suitable for agriculture. For our reference scenario we follow usual assumption and consider land with SI greater than 40% as potentially cultivable land.

Table 5-7: Options retained for computing the suitability index from GAEZ data for "2010" and 2050 under the reference scenario

	Base year "2010"	2050 under our reference scenario
Simulation period	Average 1981-2010	2050
Climate scenario	Historical climate	Scenario RCP 6.0 ("trend" scenario)
Climate model	HadGEM2[1]	
Suitability index	>40	
Water assumption	Rainfed	
Input level	High	
CO_2 fertilization	Yes[2]	

[1] The results from the HadGEM2 model were used in order to be consistent with the AE2050 study (the same family as Hadley CM3 that was used in the AE2050 study) and because this model, which is European, is very complete on all components that allow to represent all interactions of the systems (atmosphere, aerosol, land surface, ocean etc. cf. Annexe 9.A in the evaluation report of climate models from IPCC, 2013).

[2] This option is not a choice. The impact of CO_2 fertilization is considered automatically for historical data and in future scenarios as of the increase in CO_2 atmospheric concentration.

As already mentioned, cultivable land for each GAEZ country is given for 51 different crops. As the GlobAgri model does not need one land constraint per crop but one land constraint per GlobAgri-AE2050 region, we must develop a method to aggregate cultivable land per crop and cultivable land per country. First, we choose the potentially cultivable land area of the crop for which the land with SI>40 is the utmost (biggest). Thus the aggregation of areas per GlobAgri-AE2050 region is as follows:

$$Surf(r,t,s) = \sum_{p=1}^{n} \max\big(i, Surf(i,p,t)\big)$$

Where *r* is the GlobAgri-AE2050 region composed of *n* countries *p*, *i* the GAEZ crops and *t* the considered time period. For reasons of credibility in terms of cropland expansion possibilities and for being able to estimate easily greenhouse gas emissions from land use, we applied the following rules to calculate the final set of data used in the model:

- We choose land with SI >40 for all types of land covers (water, urban, shrubland land, forest, grassland, etc.);
- Cultivable land corresponds to the area of the crop which gives the highest cultivable area of all crops (as detailed above);

- Of this total aggregated cultivable land, we deduct land that is currently under:
  - (1) sparsely vegetated land, snow glacier, bare land, water, urban (set of data "forest included");
  - (2) = (1) - Tree-covered land & Mangroves (set of data "forest excluded");
  - (3) = (2) – Shrubland (set of data "orest and shrubland excluded").

Table 5-8 reports the maximum cultivable land area per GlobAgri-AE2050 regions for the 3 sets of data defined above.

Table 5-8: Cropland in "2010" and maximum cultivable land in 2050 (1000 ha)

Regions	Cropland in 2010	Cultivable.land with.forests in 2050 (1)	Cultivable.land without.forests in 2050 (2)	Cultivable.land without.forests & shrubs in 2050 (3)	Cropland expansion margin (3)-(1)
France	19 292	44 559	31 092	30 674	11 382
Germany	12 088	31 832	19 986	19 946	7 858
United Kingdom	6 072	19 353	17 537	16 152	10 080
Poland	11 715	28 617	16 968	16 966	5 251
South Europe	35 972	56 903	41 289	37 753	1 781
East Europe	20 260	38 798	27 007	27 002	6 742
Central Europe	6 517	15 203	8 360	8 354	1 837
Rest of Europe	15 175	101 338	37 207	36 834	21 659
Europe	127 092	336 603	199 447	193 681	66 589
Canada, USA	193 234	921 320	496 907	415 280	222 046
Brasil, Argentina	116 143	803 133	359 559	206 917	90 774
Rest of America	68 767	477 856	188 575	152 857	84 090
FSU	201 947	866 499	380 190	352 168	150 221
China	122 537	247 919	176 017	157 215	34 678
India	169 442	213 300	191 087	178 835	9 393
Rest of Asia	171 957	297 773	172 773	155 680	-16 277
NME	57 183	61 195	51 738	41 158	-16 025
North Africa	28 283	15 421	13 741	12 457	-15 826
West Africa	98 490	251 507	181 625	130 050	31 560
ECS Africa	134 134	1 120 463	617 794	354 146	220 012
Oceania	47 919	157 077	72 162	68 245	20 326
Rest of World	2 273	3 418	2 922	2 671	398
Total	1 539 399	5 773 485	3 104 537	2 421 360	881 961

Source: Own calculation based on FAOStat data for "2010" and on GAEZ data for 2050.

In our reference scenario, we consider the third set (3) as the maximum cultivable land area. In other words, we allow cropland to expand on cultivable permanent pastures only.

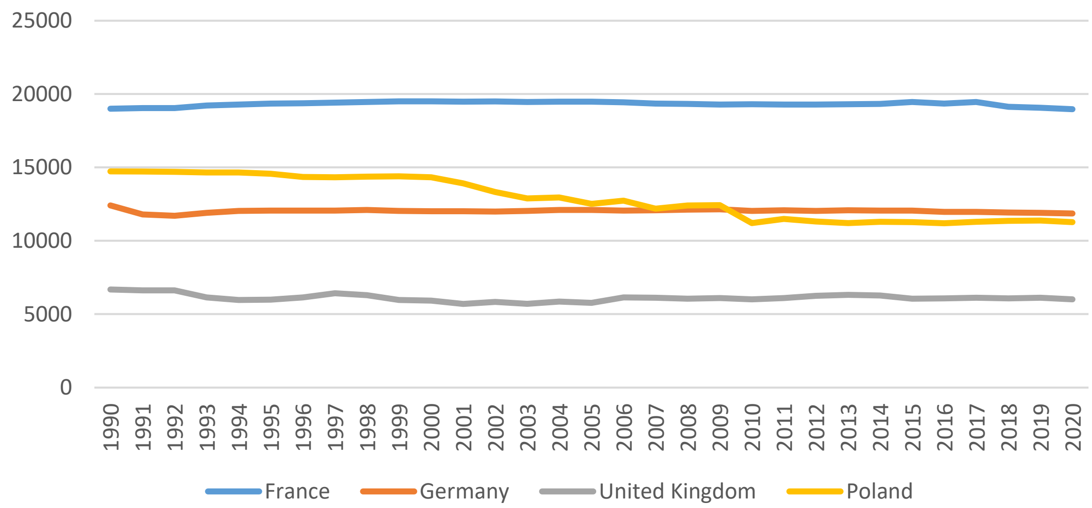
As shown in Table 5-8, under this assumption, three regions already reached their land constraint in "2010": Rest of Asia, Near and Middle East and North Africa. Indeed, in these regions the cropland in "2010" is already greater than the maximum cultivable land without forest and shrublands. For these three regions we consider that the maximum cultivable area is the observed cropland in "2010", meaning that their cropland cannot expand at all.

Following discussions with experts, we decided to limit the possibilities of cropland expansion in Europe. According to experts, due to water, soil and biodiversity protection purposes, there are Common Agricultural Policy (CAP) measures and various other regulations and laws (e.g., protected areas) that are currently in force in Europe, with the aim of preserving permanent pasture areas. Therefore, the possibility of expanding cropland on pastureland is limited in Europe. Furthermore, in the last 25 years, cropland has been either stable, or decreasing in our European sub-regions (Figure 5-4).

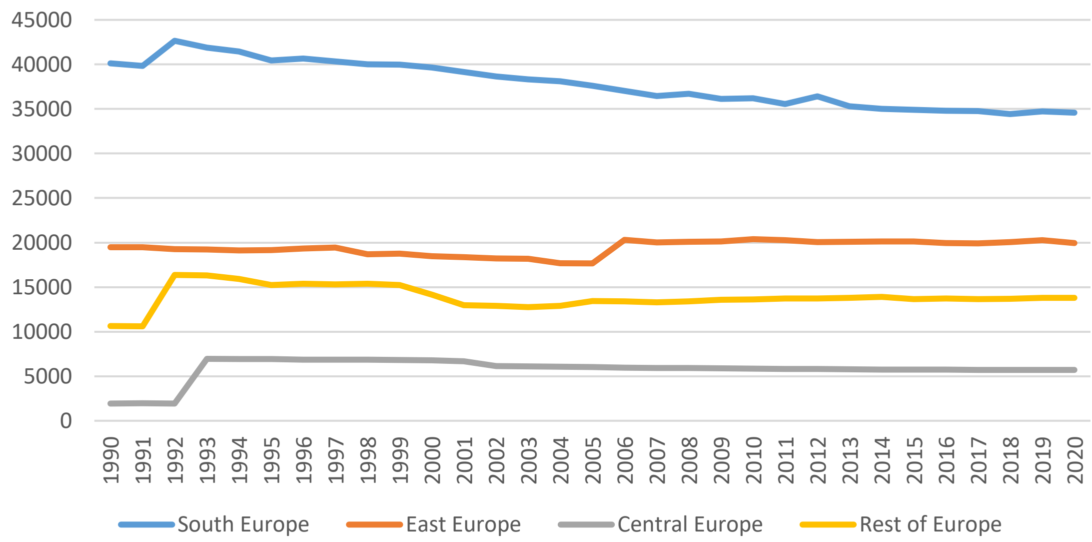
Finally, in our reference scenario we decided to set the maximum cultivable land area to the level of the cropland in "2010" for European sub-regions as well. Thus, cropland area in Europe is not allowed to expand. This is a crucial assumption. For instance, Röös *et al.* (2022) allow no, +20% or +70% cropland expansion, depending on scenarios. But they do not specify the foundations of their cropland expansion limits. In Section 5.4, we conduct a sensitivity analysis on this assumption, as a variant of our scenarios of pesticide-free agriculture in Europe in 2050.

Figure 5-4: Cropland area from 1990 to 2020 in the various European sub-regions (1000 ha)

a) France, Germany, United Kingdom and Poland



b) South, East, Central and Rest of Europe



Source: FAOStat (August, 2022)

5.2.1.7. Trade parameters

In the reference scenario we consider that trade parameters (import coefficients and export shares) are constant between "2010" and 2050. The underlying assumption is that there is no significant change in trade regimes and in competitive positions of countries over the simulation period. Thus, current trade patterns are maintained.

We made one exception for China. Pasture area expansion was quite large in China during simulation tests. This was not the case in the AE2050 study because, according to GAEZ v3 data, China already reached its maximum cultivable area in the base year "2010" and domestic production, including ruminant livestock production (and related pastureland area), could not increase. When we updated data using the new GAEZ v4, we realised that there was a quite large discrepancy between the China's maximum cultivable area according to the both versions of GAEZ: with v3 the maximum cultivable area in China amounted to 98 million hectares when forest only was excluded while in v4 it was about 157 Mha when both forest and shrubland were deduced.

As the extent of pastureland expansion possibilities in China are quite uncertain, we decided to limit the Chinese pastureland area increase in the reference scenario. For that purpose, we adjusted up Chinese import coefficients for some animal products, meaning that for meeting its increasing needs of these products China relied more on imports and less on domestic production. We increased Chinese import coefficients for bovine meat, small ruminant meat and pork meat from a couple of percent up to 11% of their total domestic use (the 11% level corresponds to the average import dependency -imports/total domestic use in energy equivalent- of China in the reference scenario). Poultry meat and dairy products were already imported at a ratio of 11%.

5.2.1.8. Non-food use of agricultural products

Regarding non-food use of agricultural products we kept the AE2050 study's assumptions (Forslund *et al.*, 2020).

5.2.2. Simulation results

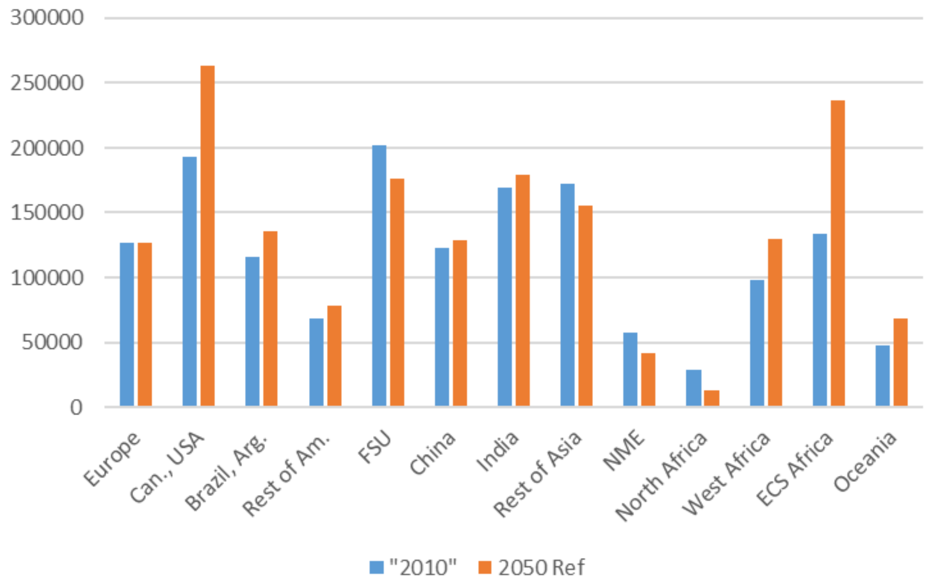
In the reference scenario, the land constraint is active in all European sub-regions, India, Rest of Asia, Near and Middle East, North Africa, West Africa and Oceania. This means that these regions must reduce their exports in order to be able to raise their domestic production for meeting their domestic food needs. In some regions (Near and Middle East, North Africa and West Africa), reducing exports is not sufficient and once they are reduced to zero, import coefficients must be adjusted up.

At the world level, decreased exports and increased imports in the constrained regions must be replaced by other sources of exports. Thus, export shares in other regions are increased until their domestic production runs up against their own maximum cultivable land area. This arises for Oceania only in the reference scenario.

5.2.2.1. Impacts of the reference scenario on cropland area

In our reference scenario, world cropland increases by +196 million ha (+13%) between "2010" and 2050. Cropland expansion arises mainly in ECS Africa (+103 million ha), where domestic production raises for meeting domestic needs, and in the Canada, USA region (+70 million ha), where domestic production increases for meeting world needs through exports. Meanwhile no cropland expansion takes place in Europe, so that European sub-regions cannot expand their exports as a response to increasing world food needs and thus loose export market shares to the benefit of Canada, USA (Figure 5-5).

Figure 5-5: Cropland (cultivated) area in "2010" and in 2050 under the reference scenario (1000 ha)



While total cropland area does not vary in Europe, the area devoted to each crop changes (Table 5-9). Total harvested area in Europe amounts to 108.3 Mha in the base year "2010". This differs from the total cropland area (127.1 Mha, Table 5-8) in "2010", which corresponds to the cultivated area, which is equal to the harvested area adjusted for the cropping intensity level. As the cropland area in Europe is assumed unchanged, as well as the cropping intensity, the total harvested area does not change from "2010" to 2050.

Table 5-9: Harvested areas (1000 ha), change (%) and shares in harvested areas (%) in "2010" and 2050 by crop aggregate in Europe

	Harvested areas (ha) "2010"	Harvested areas (ha) 2050	Change	Share in total ha "2010"	Share in total ha 2050
Cereals	60 925	55 345	-9%	56%	51%
Oilseeds	16 956	18 005	6%	16%	17%
Fruits and vegetables	9 452	8 813	-7%	9%	8%
Pulses	1 661	1 626	-2%	2%	2%
Roots and Tubers	2 200	3 584	6%	2%	3%
Sugar plants	1 712	1 456	-15%	2%	1%
Other crops	1 707	1 969	15%	2%	2%
Temporary pastures and meadows	8 457	10 828	28%	8%	10%
Remaining other forages	5 209	6 653	28%	5%	6%
Total Europe	108 279	108 279			

Source: Own calculation from FAOStat and Monfreda *et al.* (2008).

The reference scenario makes the share of cereals in European total harvested area to decrease from 56 to 51% (areas decrease for all cereals but rice). Shares of fruits and vegetable and sugar plants decrease slightly as well. At reverse, the shares of oilseeds and roots and tuber increase slightly. One may notice that the harvested area of quality forages raises significantly: +28% over the period, with the share of temporary pasture and meadows increasing from 8 to 10%. This is linked to the increased ruminant livestock production that Europe is mainly exporting to meet the significantly increasing world consumption.

5.2.2.2. Impacts of the reference scenario on pastureland area

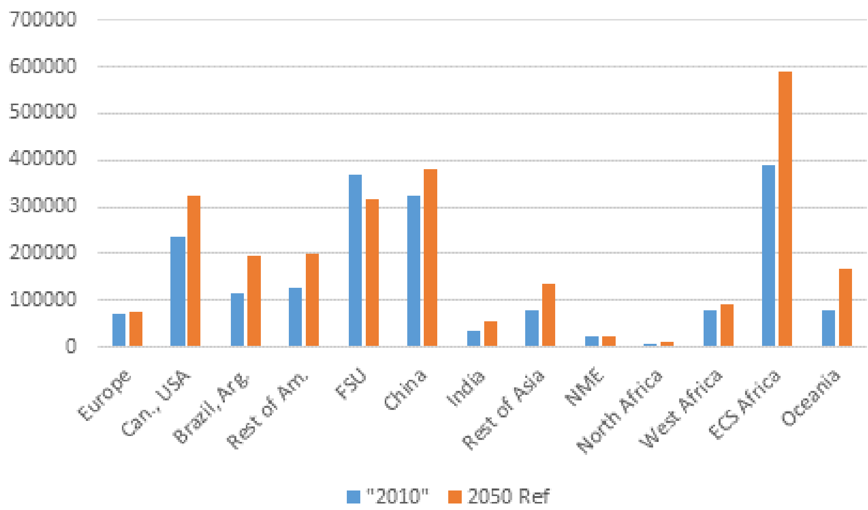
In the reference scenario, permanent pasture area (or pastureland area) increases by +636 million hectares (+33%) at the world level. The most impressive increase is observed in ECS Africa (+198 million ha, +51% of its initial permanent pasture area), due to the availability of cultivable land in this region which makes it possible to continue to enlarge the production of all products (including animal products) mainly for domestic use. Observed increases are also particularly significant in regions traditionally exporting ruminant animal products: Canada, USA (+90 Mha), Brazil, Argentina (+83 Mha) and Rest of America (+71 Mha) (Figure 5-6.a).

In Europe, the reference scenario makes the pastureland area to increase by only +2.2 million ha (+3%). This is due to the constraint on the European cropland area, which limits the possibilities of domestic production expansion, including livestock production and the related pastureland area expansion.

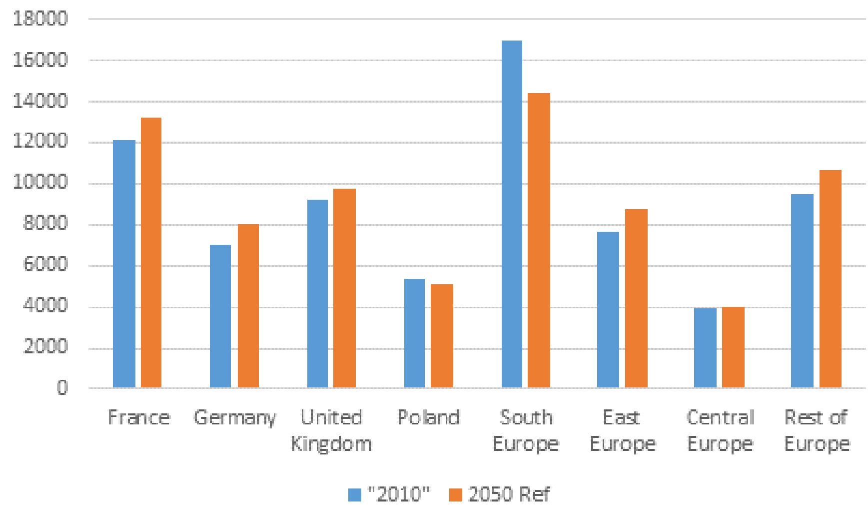
In Europe, the greatest increase in pastureland area is observed in the Rest of Europe (+1.3 Mha, +13% of its initial pastureland area) which is also the sub-region with the highest export shares of ruminant meat and dairy in Europe, and in France (+1.1 Mha, +9%). South Europe would see its pastureland area decrease between "2010" and 2050 (-2.6 Mha, -15%) due notably to decreased domestic demand for animal products (Figure 5-6.b).

Figure 5-6: Pastureland area in "2010" and in 2050 under the reference scenario (1000 ha)

a) World regions



b) European regions



5.2.2.3. Resulting land-use changes under the reference scenario

In each broad region, total agricultural area is the sum of the cropland and the pastureland areas and changes in total agricultural area result from changes in cropland area and in pastureland area. At the world level, the reference scenario induces +196 million hectares cropland area expansion and +636 million hectares pastureland area expansion. According to our assumptions, cropland expansion takes place on cultivable permanent pastures. As a result, the reference scenario leads to +832 million additional hectares requirement of pastureland (Table 5-10). These additional hectares of pastureland need to expand on other areas. According to our assumptions, pasture will first expand on shrubland, and then on forest land.

Table 5-10 suggests that at the world level, the +832 million hectares pastureland expansion splits on shrubland for nearly 715 million hectares and on forest land for the remaining 117 million hectares. Expansion of pastureland on forest land takes place mainly in Oceania, China, India and, to a lesser extent, Europe. In Europe, it is mainly East Europe which would see its forests land area decrease (slightly more than -1 million hectares) followed by Germany (nearly -1 million hectares).

Table 5-10: Land-use change induced by the reference scenario between "2010" and 2050 (1000 ha)

Change in	Cropland	Pastureland	Total Agricultural area	Cultivable pasture	Shrubland	Forest land
France	0	1 091	1 091	0	-973	-118
Germany	0	975	975	0	-58	-917
United Kingdom	0	504	504	0	-504	0
Poland	0	-259	-259	0	+259	0
South Europe	0	-2 577	-2 577	0	+2 577	0
East Europe	0	1 115	1 115	0	-112	-1 103
Central Europe	0	100	100	0	-100	0
Rest of Europe	0	1 266	1 266	0	- 1 266	0
Europe	**0**	**2 214**	**2 214**	**0**	**-176**	**-2 038**
Can., USA	70 406	90 423	160 829	-70 406	-160 829	0
Brazil, Arg.	19 096	82 562	101 659	-19 096	-101 659	0
Rest of Am.	9 802	71 102	80 904	-9 802	-80 904	0
FSU	-25 385	-48 945	-74 331	+25 385	+74 331	0
China	6 657	59 476	66 132	-6 657	-46 712	-19 421
India	9 393	19 610	29 002	-9 393	-21 109	-7 894
Rest of Asia	-16 277	53 422	37 145	+16 277	-37 145	0
NME	-16 024	-102	-16 127	+16 024	+16 127	0
North Africa	-15 825	6 035	-9 791	+15 825	+9 791	0
West Africa	31 560	11 869	43 429	-31 560	-43 429	0
ECS Africa	102 634	198 430	301 065	-102 634	-301 065	0
Oceania	20 326	90 447	110 773	-20 326	-22 942	-87 831
Rest of the World	-289	-563	-852	+289	-852	0
Total world	**196 072**	**635 979**	**832 052**	**-196 072**	**-714 868**	**-117 184**

5.2.2.4. Impacts of the reference scenario on trade

World trade increases by 58% in calorie equivalent between "2010" and 2050. In world regions, which are not constrained by their maximum cultivable areas, exports increase proportionally to the size of the world market (i.e., export shares are constant), while imports increase or decrease proportionally to their total domestic use (i.e., import coefficients are unchanged). In world regions, with area constrained by their maximum cultivable areas, exports may increase, but less than proportionally to the size of the world market, or even decrease (i.e., export shares decrease). Similarly, imports may increase proportionally or more than proportionally to their total domestic uses (i.e., import coefficients may be unchanged or increased).

As shown in Figure 5-7.a, these export and import adjustments lead net imports (imports minus exports) to increase dramatically in most constrained regions (West Africa: +717%, India: +253%, ECS Africa: +168%, North Africa: +133%, NME: +124%, Rest of Asia: more than thousand percent due to the very small base year level of net imports of this region).

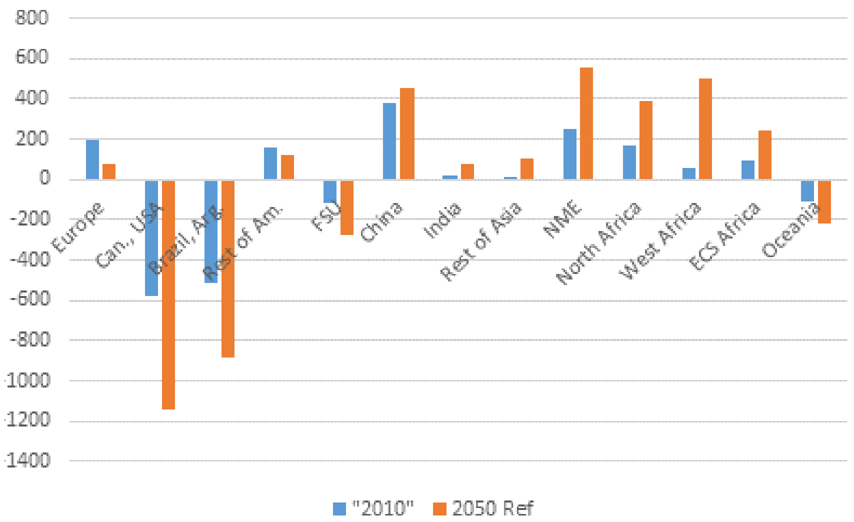
Generally, traditional net importers (China, India, Rest of Asia, NME and all African regions) and net exporters (Can-USA, Brazil-Argentina, FSU and Oceania) of agricultural products all exacerbate their trade position in the reference scenario: net importers increase their net imports while net exporters (with negative net imports on Figure 5-7) increase their net exports.

Europe and Rest of America are the only two regions that reduce their net importer position under the reference scenario. This means that in both regions exports increase more than imports. As far as Europe is concerned, one may notice that albeit the cropland area cannot expand, domestic production (in calorie equivalent) may increase because we assumed rising crop yields in the reference scenario. This additional domestic production may turn into additional exports if it is not entirely absorbed by domestic needs. As a result, European exports may increase even if European export shares are reduced due to the cropland constraint.

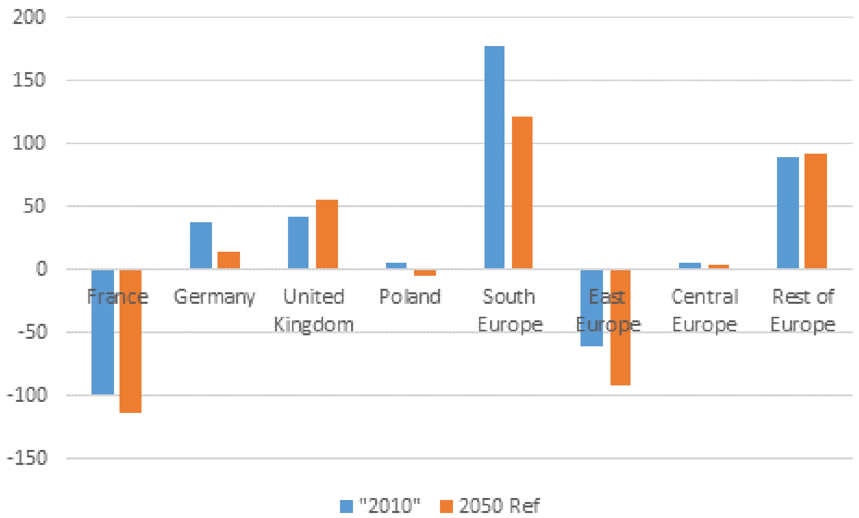
Figure 5-7.b shows that in Europe two sub-regions are already net exporters in "2010" and see their net exporting position to improve in 2050: France and East Europe. Germany, Poland, South Europe and Central Europe all improve their net importing position, Poland even becoming a slight net exporter in 2050. Inversely, United Kingdom and Rest of Europe register a worsening of their net importing position in 2050 compared to "2010".

Figure 5-7: Net imports in "2010" and in 2050 under the reference scenarios (in 10^{12} Kcal)

a) World regions



b) European regions



5.2.2.5. Impacts of the reference scenario on agricultural greenhouse gas emissions

Agricultural greenhouse gas (GHG) emissions in our model consist in the emissions related to agricultural production. They do not include the GHG emissions induced by land-use changes even if these land-use changes are closely linked to changes in agricultural production. Agricultural GHG emissions include emissions resulting from crop residues management, synthetic fertilizers application, pasture and soil emissions from organic fertilizers, rice production, enteric fermentation and manure management.

Under our reference scenario, world agricultural GHG emissions increase by 32% in 2050 compared to "2010". In Europe the increase is "only" +10%, due mostly to our no cropland expansion assumption, which restrains the domestic production increase (Table 5-11). World agricultural emissions thus amount to 7.2 Gt CO_2 equivalent in 2050 compared to 5.4 Gt in our base year, of which 468 million tonnes (Mt) in Europe in 2050 compared to 426 Mt in "2010".

Table 5-11: Changes in world and European agricultural GHG emissions between "2010" and 2050 under the reference scenario (%)

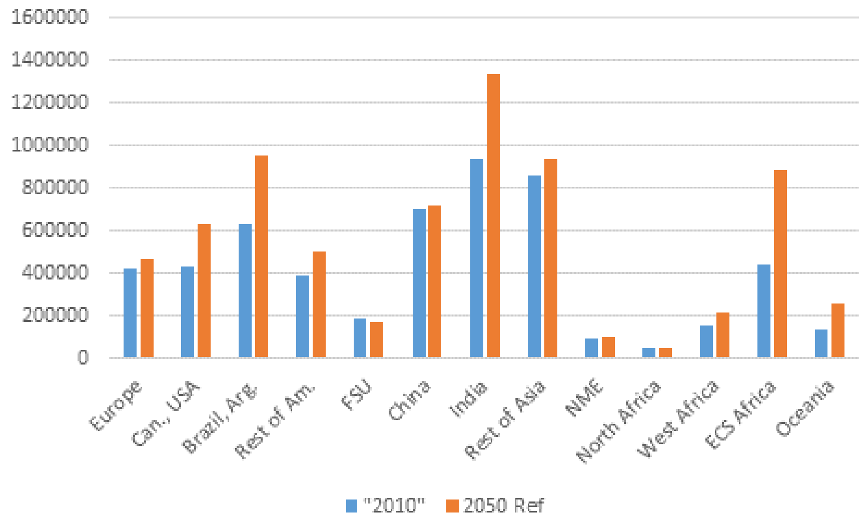
"2010"-2050 change	World	Europe
Total	+32%	+10%
Vegetal[1]	+27%	+11%
Animal[2]	+35%	+9%

[1] Burning of residues, crop residues, rice, synthetic fertilizers, pasture and soil emissions from organic fertilizers (in CO_2 equivalent)
[2] Enteric fermentation and manure management (in CO_2 equivalent).

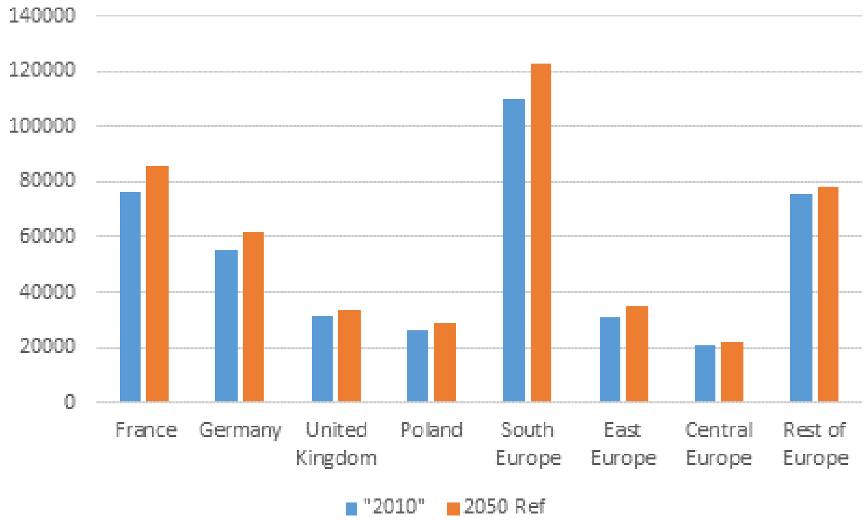
Large increases are observed for ECS Africa, India and Brazil-Argentina, but also in Canada-USA and Oceania due to important increases in domestic production and/or exports in these regions (Figure 5-8.a). In Europe the highest increase (in absolute value) is observed for South Europe. (Figure 5-8.b).

Figure 5-8: Total agricultural GHG emissions in "2010" and in 2050 under the reference scenario (1000 t CO_2 equivalent)

a) World regions



b) European regions



5.2.2.6. Impacts of the reference scenario on the land-use change emissions

According to our assumptions, the reference scenario results in land-use change emissions from soil and biomass amounting to 3129 Mt CO_2 equivalent per year in the world. These significant net positive emissions result from the +832 Mha of agricultural land area expansion in the world (of which +2.2 Mha of pasture in Europe). In Europe the reference scenario results in net sequestration of carbon of 6 Mt CO_2 equivalent per year.[6] Regional land-use change emissions are reported in Table A.5-4 in Appendix.

[6] Annual emissions calculated with 40 year amortization assumption.

5.2.2.7. Findings in the literature

Tables 5-12 and 5-13 report changes in world and European cropland and pastureland areas and GHG emissions, respectively, between base year and 2050, simulated by existing studies under BAU-like scenarios.

Our estimates of world and European cropland area changes in the reference scenario are in the range of other studies' results. As far as pastureland area is concerned, our estimate of change for the world as a whole is significantly greater than estimates by other studies, except Tibi *et al.* (2020). This suggests that our assumptions on future change of productive performance of ruminant livestock systems in the various parts of the world are likely to be significantly less optimistic than the ones used in other studies. Indeed we use the same assumptions as Tibi *et al.* (2020), which is the study with the largest estimate of world pastureland area expansion. Nevertheless, our estimate is significantly lower than in Tibi *et al.* (2020). Three main reasons explain the gap. First, initial pastureland areas are different in both studies, so are the initial grazing intensities, as a result of shifting from FAOStat data on permanent pasture areas to GAEZ.v4 data on grassland areas. Secondly, we decided to adjust up projected animal productivities for milk and bovine meat in both African regions. Lastly, we adjusted up Chinese import coefficients for ruminant (bovine and small ruminant) meat. All three reasons contribute to reducing the average pastureland area requirement per ton of ruminant output at the global level.

Few studies report estimates of pastureland area expansion in Europe. Our estimate is in the range of Tibi *et al.* (2020)'s estimates, albeit less marked as a result of our no cropland expansion assumption that was not in force in Tibi *et al.* (2020). Our estimate is not in line with the one of Röös *et al.* (2022) who find that pastureland area would decrease by -35% in Europe under their BAU scenario. Obviously, data, models and assumptions are different in both studies. In particular, we may guess that assumptions on productivity improvement in European ruminant livestock systems are more optimistic in Röös *et al.* (2022).

As suggested by Table 5-13 it is difficult to compare GHG emissions estimates between studies because reported results and underlying assumptions vary across studies. Nevertheless we can deduce from Table 5-13 that our estimates of agricultural GHG emissions are in the range of other studies for both the whole world and Europe.

Table 5-12: Estimates of world and European cropland and pastureland area expansion in various studies (Mha)

Study (year) **Scenario name** **Simulation period**	**Cropland area change (Mha)**	**Pastureland area change (Mha)**
This foresight study (2023) Reference scenario "2010"-2050	World: +196 (+13%) Europe: 0	World: +636 (+33%) Europe: +2.2 (+13%)
Röös *et al.* (2022) BAU scenario 2012-2050	Rest of the world: +9% Europe: -3%	Rest of the world: -13% Europe: -35%
AE2050 / Tibi *et al.* (2020) 4 reference scenarios combining assumptions on diets (2) and yield growth (2) "2010"-2050	World: from -51 (-3%) to +223 (+14.5%) Europe: from -4 (-3%) to -30 (-23%)	World: from +2 100 (+66%) to +2 900 (+88%) Europe: from +12 (+17%) to -16 (-22%)
FAO (2018) BAU scenario 2012-2050	World: +165 (+11%)	World: results non available
Le Mouël and Forslund (2017) Literature review	World: from 0 to +180 (+12%) depending on studies	World: results non available
Popp *et al.* (2017) IPCC-SSP2 scenario 2005-2100	World: +209 (+13.5%)[1]	World: +113 (+3.3%)[1]
Schmitz *et al.* (2014) IPCC-SSP2 scenario 2005-2050	World: from ~−140 to ~+415 depending on models; +193 (+12.1%) in average over all models	World: from -7% to +14% depending on models

[1] Figures for 2050

Table 5-13: Estimates of world and European GHG emissions in various studies

Study (year) **Scenario name** **Simulation period**	**From agricultural production (CO_2 eq)**	**Induced by land-use changes (CO_2 eq)**
This foresight study (2023) Reference scenario "2010"-2050	World: +32% (+1.77 Gt) Europe: +10% (+42 Mt)	World: 3.13 Gt CO_2 /year or 125 Gt cumulated Europe: -6 Mt CO_2 /year or -227 Mt cumulated
Röös *et al.* (2022) BAU scenario 2012-2050	World: +64% (+4.33 Gt) +37% with veg regrowth (+2.5 Gt) Europe: +13% (+66 M) -46% with veg regrowth (-308 Mt)	World: Vegetation regrowth on freed land enables carbon sequestration: 17% of emissions offset (from 11042 to 9212 Mt) Europe: Vegetation regrowth on freed land enables carbon sequestration: 52% of emissions offset (from 588 to 280 Mt)
FAO (2018) BAU scenario 2012-2050	World: +20%	World: not available
Popp *et al.* (2017) IPCC-SSP2 scenario 2005-2100	World: +38% (+2.08 Gt)[1]	World: 2.3 GT CO_2 /year in average over 2005-2100 or 219 Gt cumulated[1] (annual CO_2 emissions decrease steadily until the end of the century and are negative from 2080 onwards)

[1] Figures for 2100

5.3. European chemical pesticide-free agriculture in 2050: Three main scenarios

Introduction

As described previously, we defined three scenarios of chemical pesticide-free agriculture in Europe in 2050 as well as their respective transition pathways:

- Scenario and transition S1: Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market;
- Scenario and transition S2: European food systems based on plant holobiont, soil and food microbiomes for healthy foods and diets;
- Scenario and transition S3: Complex and diversified landscapes and regional food chains for one-health European food systems.

According to the general method of the foresight (cf. Chapter 1), the three scenarios are combinations of alternative hypotheses of change in 2050 of each component of the system. More specifically, the scenarios are combinations of hypotheses in 2050 for "Food value chains", "Farm structures", "Cropping systems" and "Agricultural equipment and digital technologies". Transition pathways associated to scenarios are based on hypotheses of change for "Public policies and trade", "Food diets" and "Education and Akis (agricultural knowledge and innovation systems)".

The quantitative assessment of the three scenarios with the GlobAgri-AE2050 model requires to translate each hypothesis of change of each component into quantitative values for 2050 of related input variables or parameters of the model. By definition, a model is a simplified representation of the actual considered system and only few model's input variables and parameters are available to account for the whole detailed hypotheses of change (Table 5-1). Therefore, some components and their hypotheses in 2050 are overlooked in the quantitative assessment because there are no input variables or parameters in the model that would allow to account for them. This is the case for the "Farm structures" component and its hypotheses of change. On the other hand, some other components can be considered only indirectly because some model's input variables or parameters can account for their evolution to 2050 but only implicitly and imperfectly. This is the case for "Food value chains" and "Agricultural equipment and digital technologies". Finally, only a few components and their hypotheses of change can be directly considered in the quantitative assessment because the model contains variables and parameters, which can explicitly account for them. Such components are "Cropping systems", trade regimes as part of "Public policies and trade" and "Food diets".

In the following, we explain how these three components and their hypotheses of change in 2050 have been translated into quantitative values of related input variables and parameters of the GlobAgri-AE2050 model. Then, simulation results of the three pesticide-free agriculture scenarios are detailed and discussed.

5.3.1. Underlying hypotheses

Table 5-14 provides an overview of assumptions adopted for the simulation of each scenario. Let's notice that some input variables and parameters that we mentioned when presenting the underlying hypotheses of the reference scenario, are absent from Table 5-14. This means that these variables and parameters keep the same 2050 projected values than in the reference scenario (this is the case for population growth, animal feed efficiencies, maximum cultivable area and non-food use of agricultural products notably). Furthermore, assumptions reported in Table 5-14 concern Europe only. Assumptions for other world regions are kept unchanged all along the simulation work.

Table 5-14: Overview of the quantitative hypotheses

	Scenario S1	**Scenario S2**	**Scenario S3**
	Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market	**European food systems based on plant holobiont, soil and food microbiomes for healthy foods and diets**	**Complex and diversified landscapes and regional food chains for one health food systems**
Diets	Trend diet [Source FAO, 2018 – BAU, adjusted] (same as in the reference scenario)	Healthy diet [Source Agrimonde-Terra (Le Mouël *et al.*, 2018) and AE2050 (Tibi *et al.*, 2020)] Including half reduction in food wastes	Healthy and environmental-friendly diet [Source EAT Lancet commission (Willett *et al.*, 2019) flexitarian] Including half reduction in food wastes
Crop yields	*Lower-bound* Reference yield 2050 – ½ Yield gap from de Ponti *et al.* (2012) *Upper-bound* Lower-bound yield 2050 + 50% Yield response to diversification	*Lower-bound* Reference yield 2050 – ½ Yield gap from de Ponti *et al.* (2012) *Upper-bound* Lower bound yield 2050 + 75% Yield response to diversification	*Lower-bound* Reference yield 2050 – ½ Yield gap from de Ponti *et al.* (2012) *Upper-bound* Lower-bound yield 2050 + 100% Yield response to diversification
Cropping intensity	+8% [Source FAO, 2018 – BAU]	+8% [Source FAO, 2018 – BAU]	+12% [Source FAO, 2018 – BAU +50%]
Max cultivable area	No cropland expansion	No cropland expansion	Cropland decreased in order to save space for semi-natural habitats (SNH) (> 20% land area, Garibaldi *et al.*, 2021)
Trade	Constant import coefficients Export shares: endogenous decrease	Import coefficients decreased for plant products used for food and for plant and animal products used for ultra-processed foods Decrease calibrated based on shares of extra-EU imports Export shares: endogenous decrease	Import coefficients decreased for all products Decrease calibrated based on shares of extra-EU imports Export shares: endogenous decrease

5.3.1.1 Hypotheses of change of food value chains and food diets and their quantitative translation

Change in diets and food value chains are closely linked. We developed three hypotheses for food value chains in 2050:

- Global value chains with pesticide-free food[7] as a food safety standard;
- Local, European and global value chains marketing healthy food for a healthy diet;

[7] Pesticide-free food means here food produced without pesticides. It does not mean food with zero pesticide residues content.

- Territorial and regional value chains marketing food preserving human and environmental health (biodiversity included) and contributing to diversified landscape.

Then, we imagined three hypotheses for food diets in 2050 corresponding to the three above hypotheses for food value chains:

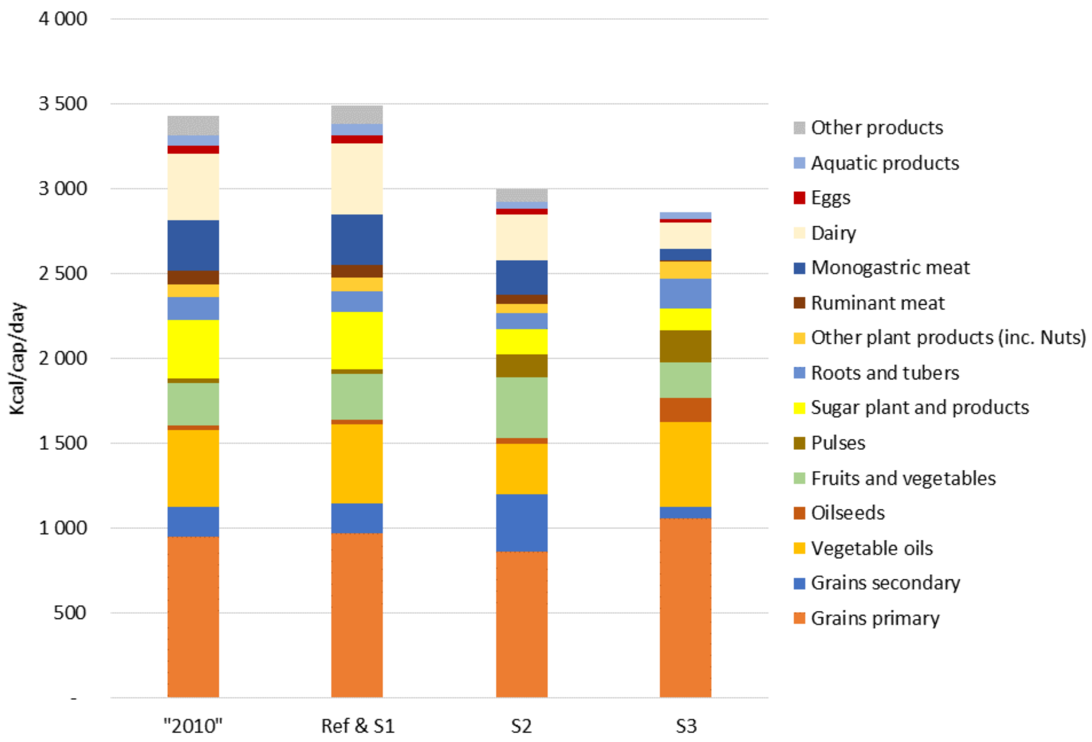
- With global value chains with pesticide-free food as a food safety standard, we suppose that food diets in Europe change according to current trends, with an emphasis on pesticide-free products. Therefore, European diets in 2050 are the same as those assumed in the reference scenario. However, the food products that enter the diets are pesticide-free, which was not the case in the reference scenario.
- With local, European and global value chains marketing healthy food for a healthy diet, we suppose that in addition to be based on pesticide-free food products, European food diets change towards healthy diets. Hence, diets in 2050 are the healthy diets of the AE2050 study (Tibi *et al.*, 2020), borrowed from the Agrimonde-Terra foresight (Le Mouël *et al.*, 2018).
- With territorial and regional value chains marketing food preserving human and environmental health, we suppose that in addition to be based on pesticide-free food products, European food diets change towards diets that are favourable to not only human health but also animal and environmental health. We selected the flexitarian diet proposed by the Eat Lancet commission, as this diet is supposed to be a healthy and environmentally sustainable diet (Willett *et al.* 2019).

The first hypothesis for food value chains and its associated trend diet is involved in our scenario S1: "*Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market*". Our scenario S2: "*European food systems based on plant holobiont, soil and food microbiomes for healthy foods and diets*" involves the second hypothesis for food value chains and its associated healthy diet. Our third scenario S3: "*Complex and diversified landscapes and regional food chains for one health food systems*" involves the third hypothesis for food value chains and the related healthy and sustainable food diet.

Figure 5-9 reports the average European diet in the initial "2010" situation and in 2050 under our three scenarios.[8] Compared to the food diet used in the reference scenario, the healthy diet used in scenario S2 has significant lower energy content (in line with World Health Organisation recommendations and as a result of reduced wastes) and is significantly more diversified. It is less rich in animal products, in vegetable oils and in sugar products. It is richer in secondary cereals, fruits and vegetables and pulses. The Eat Lancet flexitarian diet used in scenario S3 has even lower energy content. Its main specificity is to have a particularly low content in animal products compensated by a particularly high content in vegetal protein-based foods (pulses and oilseeds, i.e., soya-based foods). One may notice that the Eat Lancet flexitarian diet is also significantly richer in roots and tuber and in nuts than other diets. Finally, it is important to underline that in scenario S3 the territorial dimension is key. This implies that food products, which are involved in the various aggregates of the food diet in scenario S3 are likely to be different than food products involved in the same aggregates in the food diets of both other scenarios: for instance, in scenario S3 consumed fruits are exclusively fruits traditionally grown in each European sub-regions while in scenarios S2 and, especially, S1 consumed fruits may be all kinds of fruits, including exotic fruits.

[8] Corresponding food diets for each of our European sub-regions are provided in Appendix, Figure A.5-2. Product aggregates in the Eat Lancet commission diets are different from the ones used in GlobAgri. In addition, Eat Lancet diets do not include wastes while GlobAgri diets do (more specifically wastes at the distribution and consumption level). Therefore we had to harmonise the Eat Lancet flexitarian diet to the GlobAgri product aggregates and rules regarding wastes. The correspondence between the GlobAgri and the Eat Lancet product aggregates is detailed in the Appendix (Table A.5-2). On the other hand, the harmonised Eat Lancet diet used in our scenario S3 includes half of the wastes calculated in "2010" by comparing the initial diets in both GlobAgri and the Eat Lancet commission study.

Figure 5-9: The average European food diet in "2010" and in 2050 under our three pesticide-free agriculture scenarios



Sources: Based on FAOStat, FAO (2018), Tibi *et al.* (2020) and Willett *et al.* (2019).

5.3.1.2. Hypotheses of change of cropping systems and their quantitative translation

We developed three strategies for crop protection in 2050:

- Crop protection based on strengthening plant immunity;
- Crop protection based on managing the holobiont;
- Crop protection based on landscape diversification.

Then, cropping systems were re-built based on these alternative crop protection strategies. This resulted in three hypotheses of change of cropping systems in 2050. Our pesticide-free scenarios involve the three hypotheses of change of cropping systems, but one hypothesis is predominant in each scenario. The first hypothesis is predominant in scenario S1, the second in scenario S2 and the third in scenario S3.

In the GlobAgri-AE2050 model there are three input variables/parameters that are directly concerned with the evolution of cropping systems to 2050: crop yields, cropping intensity ratios and cultivable areas.

In the reference scenario, crop yields and cropping intensity ratios evolve according to observed current trends. As cropping systems are mostly conventional intensification systems in Europe, projected European crop yields and cropping intensity ratios in 2050 under the reference scenario figure the future productive performance that is expected from these systems.

On the contrary, our three hypotheses for cropping systems in 2050 imply a rupture relative to the conventional intensification systems since they all assume a removal of chemical pesticide use. How and to what extent, our three hypotheses for cropping systems could change European crop yields, cropping intensity ratios and maximum cultivable areas evolution to 2050 relative to the reference scenario? Are we able to differentiate European crop yields, cropping intensity ratios and maximum cultivable areas pathways to 2050 according to our alternative hypotheses?

As far as cropping intensity and maximum cultivable area are concerned, existing literature and data provide information that can be used to calibrate their expected values in 2050 under the three cropping system hypotheses. However, regarding crop yields we face a serious challenge. Indeed, existing information is not directly exploitable since it refers to cropping systems, which are fundamentally different from ours (organic systems or systems designed to reduce chemical pesticide use but not to remove chemical pesticides). In addition, the existing literature may provide information on the performance of specific agroecological practices but rarely on the performance of the whole cropping systems that would integrate these agroecological practices. Furthermore, among this literature, existing studies provide information on the environmental performance of specific agroecological practices but information on their performance in terms of crop yields is not so frequent. Finally, when this information exists, most often the yield gap resulting from using a specific agroecological practice vs. not using it is calculated whatever the whole cropping system (e.g., meta-analyses on crop diversification). In the following, we summarise existing information and data and explain how we use it to calibrate yield, cropping intensity and cultivable area evolution in Europe under our three hypotheses for cropping systems in 2050.

Cropping intensities

In FAO (2018) cropping intensity is expected to increase in world average whatever the scenario: +6% between 2012 and 2050 in the BAU scenario, +18% in the TSS scenario (towards sustainable systems). According to FAO (2018), a greater increase is attainable in the TSS scenario "*thanks to the adoption of sustainable intensification technologies, which ensure sufficient nutrient availability in the soil as less synthetic fertilizer is used*" (FAO, 2018, p. 85).

Following the FAO (2018) expectation, we assumed that cropping intensity could increase with our three hypotheses for cropping systems. Furthermore, we assumed that increasing diversification should make the cropland used more intensively, implying a positive relationship between diversification and cropping intensity. But we do not have any information on the potential size effect of such diversification practices in terms of cropping intensity.

In FAO (2018), for the Europe and Central Asia region, cropping intensity is expected to increase between 2012 and 2050 by +8% in the BAU scenario and +22% in the TSS scenario. We explained previously why the +8% increase seemed too optimistic and was not used in our reference scenario. However, this +8% increase could fit with our hypotheses for cropping systems. In addition the most diversified cropping system (based on landscape diversification used in scenario S3) could benefit from a greater increase. As the +22% increase in the FAO TSS scenario of the FAO seemed to us too optimistic, we decided to give a +12% increase (i.e., 8% plus half 8%) to the most diversified cropping system (scenario S3). Resulting cropping intensity ratios in 2050 for the European sub-regions, according to scenarios, are reported in Table 5-15.

Table 5-15: Cropping intensity (CI) ratios in "2010" and in 2050 under our three pesticide-free agriculture scenarios

	CI "2010"	CI 2050 S1 and S2	CI 2050 S3
France	0.83	0.90	0.93
Germany	0.97	1.05	1.09
UK	0.88	0.95	0.99
Poland	0.98	1.07	1.10
South Europe	0.77	0.84	0.86
East Europe	0.90	0.97	1.01
Central Europe	0.83	0.90	0.93
Rest of Europe	0.81	0.88	0.91

Source: Based on FAOStat and FAO (2018).

Maximum cultivable area

In all our scenarios, it is assumed that the European cropland area cannot expand. This means that the maximum cultivable area in European sub-regions is set equal to their initial "2010" cropland area.

This maximum cultivable area is assumed to be constant until 2050 in all hypotheses for cropping systems, but the last one based on landscape diversification. Indeed, in this last hypothesis, landscapes are composed of a stable matrix of natural and semi-natural habitats, and a mosaic of crops that can be changed in its composition and configuration. Establishing this stable matrix of natural and semi-natural habitats (SNH) could reduce the land area available to grow crops. In the GlobAgri model, this would result in a reduction of the maximum cultivable area of European sub-regions.

For calibrating this reduction, we use the Garibaldi *et al.* (2021)'s recommendations. According to this study, the review of the scientific evidence suggests a minimum of 20% native habitat area within working landscapes with more than 80% of land sowed or planted for farming, ranching, and/or forestry. In addition, Garibaldi *et al.* specify that the 20% minimum target can be applied at all spatial scales, from single fields to whole landscapes.

Translating this recommendation into an equivalent reduction of the maximum cultivable area in European sub-regions for GlobAgri-AE2050 is not an easy task because the existing literature is rather confusing: land-cover types that are considered as SNH differ across studies, the base area for applying the SNH target as well. Generally, studies that are dealing with the impact assessment of EU policies directed to agriculture adopt a strict definition of SNH and focus on utilised agricultural area (UAA) or on cropland area (e.g., Barreiro-Hurle *et al.*, 2021; Mayer *et al.*, 2021). Studies, which are aimed at assessing the potential of SNH for crop protection or the current area under SNH in order to evaluate the extent to which the provision of ecosystemic services may be assured, retain a larger definition of SNH and a larger base area (e. g., Paraccini *et al.*, 2008; Holland *et al.*, 2016).

Barreiro-Hurle *et al.* (2021) provide an impact assessment of the EU Farm to Fork and Biodiversity Strategies. When evaluating the area equivalent for reaching the 10% target of agricultural area under high-diversity landscape features, they considered that area under high-diversity landscape corresponds to area under fallow land and area under linear landscape elements. Thus they first evaluated the current fallow land in the EU (4.1% of total UAA at EU level). Then they added the current area covered by linear landscape elements (0.6% of total UAA). They finally deduced the additional area needed to meet the target (5.3% of total UAA). Considering that the total UAA in the EU28 is about 173 million hectares, this would result in 9 million hectares of farmland becoming unavailable for agricultural output production. Similarly, Mayers *et al.* (2021) consider, among agroecological practices involved in their analysis, 7% of EU cropland under hedges. This would result in nearly 8 million hectares of cropland if we do not consider hedges already present (or 7 million hectares if we consider that hedges already present may be approximated by the linear landscape elements as evaluated by Barreiro-Hurle *et al.* and are all located on cropland).

Studies, which are interested in SNH for their impact on ecosystemic services provision provide significantly different results, even when they focus on farmland. The main reason is that they adopt a larger definition of SNH. According to Holland *et al.* (2016), the land-cover categories that contribute positively to crop protection are linear woody, forest, grassy linear habitat, herbaceous ungrazed habitat, high-nature value grassland. This is much larger than the fallow land and the land under hedges or landscape elements as considered by Barreiro-Hurle *et al.* and Meyer *et al.* In the same vein, when assessing the high-nature value (HNV) of farmland in Europe, Paraccini *et al.* (2008) adopted a large set of concerned land-cover categories. When they calculated the shares of HNV farmland in total agricultural area (greater than UAA when using the Corine Land Cover categories) for EU Member States, they found that in average 30% of EU total agricultural land is already HNV, this share ranging from 5% in Denmark to 78% in Slovenia. Compared to the Garibaldi *et al.*'s 20% target, Paracini *et al.*'s results suggest that only Germany (14.6% HNV share), Denmark (5%), Lithuania (15.1%), Luxemburg (9%) and the Netherlands (14.1%) would be for forced to divert some additional land (around 2 million hectares) from agricultural output production.

As we are interested in the SNH that contribute positively to crop protection for our scenario S3, we adopted a large definition of SNH, in line with Paraccini *et al.* (2008) and Holland *et al.* (2016). Using GAEZ land-cover categories and data, we calculated the share of SNH in each pixel (5 arcminutes corresponding for Europe to 27 to 75 km2) holding positive cultivable area in the 8 European sub-regions. We considered as SNH, the GAEZ categories: Grassland, Shrubcovered land, Tree covered land, Mangroves and Herbaceous regularly flooded land. Table 5-16 reports for each sub-region the share of pixels where the 20% SNH target is already reached, and the additional area that should be put under SNH in order the reach the target. Coherently, our results are closer to those of Paraccini *et al.* (2008). We find that for Europe as a whole, the 20% SNH target would require a -3.5 million hectares reduction of the maximum cultivable area, the greatest cuts arising in South Europe (nearly -1Mha), East Europe and Rest of Europe (about -0.6 Mha each) and France and UK (about -0.4 Mha each).

Table 5-16: Additional area required to reach the 20% SNH target in the European sub-regions

	Shares of pixels with SNH >20% total area (%)	Area required to reach the 20% target (1000 ha)
France	0.796	428
Germany	0.935	116
United_Kingdom	0.613	462
Poland	0.970	24
South_Europe	0.385	970
East_Europe	0.681	661
Central_Europe	0.629	145
Rest_Europe	0.624	666
Total Europe		3 472 (3% cropland; 2% UAA)

Source: Own calculation based on GAEZ.v4 raster data.

Crop yields

Among the very large existing literature dealing with the relationship between pesticides and crop yields, we selected several studies that we considered as representative, most comprehensive and rather recent. Table A.5-3 in Appendix provides a short synthesis of available information in these selected studies.

Table A.5-3 suggests that there are different streams of studies dealing with pesticides and crop yields, each stream placing this relationship in a different context. The first stream brings together the studies assessing the actual yield loss due to pests in current cropping systems (i.e., using chemical pesticides). For Europe as a whole, the estimated loss is around -20% whatever the crop. The second stream of literature involves the studies, which assess the impact on crop yields of banning the use of chemical pesticides keeping current cropping systems unchanged. Coherently, such studies find that crop yields would drop: in world average from -50% for wheat to -77% for rice and -75% for potatoes. The third stream groups the studies interested with the impacts on crop yields of a -50% reduction of chemical pesticide use. Based on a literature review, these studies assume that this -50% cut in chemical pesticide use would result in an average -10% decrease of crop yields in Europe (one study estimating a range of decrease from -2% for maize to -20% for fruits and vegetable). The fourth stream of literature brings together the studies dealing with the impact of a drastic decrease of chemical pesticides on crop yields when cropping systems are adjusted consistently for compensating the loss of this crop protection input. Estimates of crop yield decrease in France range from -10% to -40% for wheat, -10% for maize, from -10% to -20% for rapeseed, -4% for pulses, -19% for potatoes, from -9% to 0 for sugar beet, and from -20 to -40% for fruits and vegetables. Finally, the fifth stream of literature contains the studies comparing organic to conventional yields. These are well-known meta-analyses which conclude that in average organic yields are 19% to 25% lower than conventional yields. This loss may be reduced by half when considering only the best organic management practices.

On the other hand, INRAE achieved an exhaustive review of the literature on the relationship between vegetal diversification and crop protection. The synthesis report of this review states that there is a positive link between crop diversification practices (crop mix, intercropping, cover crop, diversified rotation) and crop yields and a neutral link between landscape elements (hedges, agroforestry) and crop yields. The potential size effect of crop diversification practices on yields would be significant and range from +2% to +47%, including a significant effect of rotations (+10 to +20% yield gain) and of crop mix (+20 to +40%) (Tibi *et al.*, 2022).

Based on this literature review, we used the Bommarco *et al.* (2013)'s approach to calibrate the projected 2050 crop yields under our three scenarios of pesticide-free agriculture. The Bommarco *et al.*'s approach is illustrated in Figure 5-10. In all panels, the principle is that the production (and yields) level directly depends on regulating and supporting services (pest regulation, pollination, soil nutrients and water). Furthermore, the highest level production can attain is set by the most limiting regulation or supporting service (in Figure 5-10, pest regulation). Finally as regard pest regulation and soil nutrients services, a proportion of the service may be provided by anthropogenic inputs (chemical pesticides and mineral fertilisers, the red share of the pest regulation and soil nutrients bars).

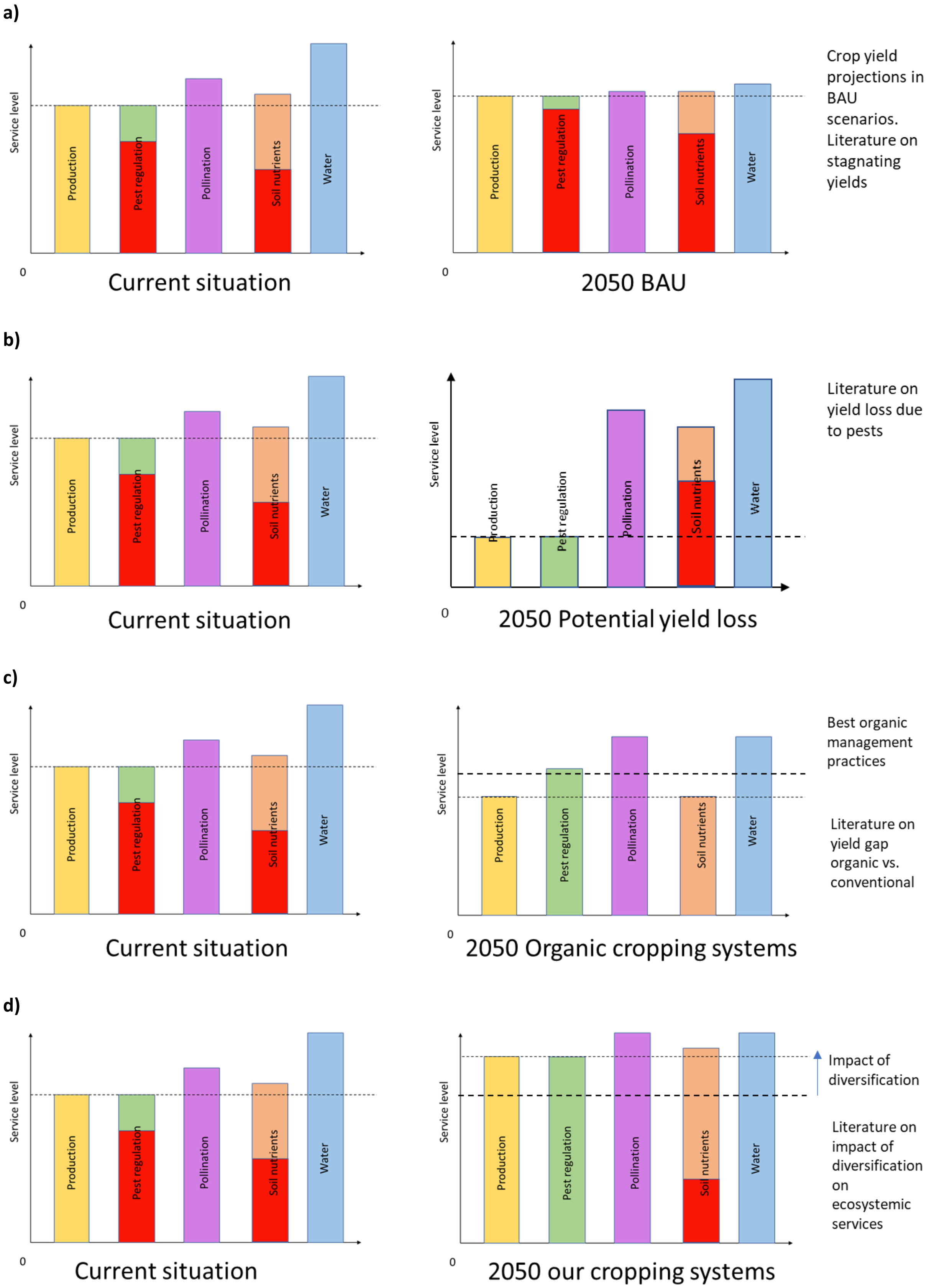
Panel 5-10.a figures out the projection of production level (or crop yields) to 2050 keeping cropping systems unchanged and following current trends (corresponding to our reference scenario). In this case, pest regulation and soil nutrients services can be boosted increasing the share of anthropogenic inputs, resulting in a slightly increased production level. However, these rising anthropogenic inputs affect negatively other services and it is more and more difficult to increase production and crop yields. This situation corresponds to assumptions that are used for projecting yields in BAU scenarios. Panel 5-10.b illustrates the situation where the production level and crop yields are projected to 2050 in current cropping systems where chemical pesticide use is abandoned. As cropping systems are not adjusted to boost pesticide regulation through alternative crop protection strategies, the pest regulation service drops as the production and crop yields do. This situation may be related to the literature dealing with potential crop loss due to pests. In panel 5-10.c the production level and crop yields are projected to 2050 assuming a transition towards organic cropping systems. In such a case, cropping systems are adjusted in order to compensate for the ban of anthropogenic inputs (cropping system adjustments boost biological regulation which makes the green share of the pest regulation and the rose share of soil nutrients bars to increase on the right-hand side of panel 5-10.c). At the same time the pollination service increases. But, as suggested in panel 5-10.c, soil nutrients become the most limiting service in this case (potentially boosted by the best organic management practices as mentioned previously). This situation may be related to the literature dealing with the organic to conventional yield gaps. Finally, panel 5-10.d illustrates the situation where the production level and crop yields are projected to 2050 while cropping systems are adjusted to compensate for the abandonment of chemical pesticides, like in our pesticide-free agriculture scenarios. The only difference relative to the previous case is that the soil nutrients service is not likely to become limiting since mineral fertilisers may continue to be used. This situation may be related to the literature on the positive link between crop diversification and crop yields.

Based on the above discussion, and because future crop yields in pesticide-free cropping systems are very uncertain, we propose two sets of assumptions for crop yields in 2050 under our three scenarios:

- Chemical pesticide-free cropping systems could lead to crop yield decrease relative to conventional systems. In this pessimistic case, the yield loss would not be greater than the yield loss estimated for organic systems. Following the existing literature, we assume that the loss would be half the loss estimate when comparing organic to conventional yields. To calibrate the yield loss we decided to use the meta-analysis by de Ponti *et al.* (2012) because it provides more detailed results in terms of considered crops and country/region. The calibrated losses are applied to the 2050 crop yields projected under the reference scenario. They are not differentiated according to scenarios. The resulting crop yield levels are the lower-bound (lb) yields in 2050. They are systematically lower than the reference yields.
- Because of the positive link between crop diversification and crop yields, chemical pesticide-free cropping systems could allow to limit, even over compensate, the above losses. In this optimistic case, the yield gain would not be greater than the yield gain due to crop diversification as estimated in the existing literature. Furthermore, considering that crop diversification varies across scenarios, we assume that yield gains are differentiated across scenarios. We retain an average +20% yield response to crop diversification. We assume that scenario S1, exhibiting the least crop diversification, would allow to reach half this yield response, while scenario S2 would allow to reach ¾ of the yield response and scenario S3, with the greatest vegetal diversification, would allow to reach the entire response. The calibrated yield gains are applied to the lower-bound yields in 2050. Obtained yields can be lower, equal or greater than the reference yields. In the latter case, we capped their level to the corresponding reference yield level. The resulting crop yields levels are the upper-bound (ub) yields in 2050.

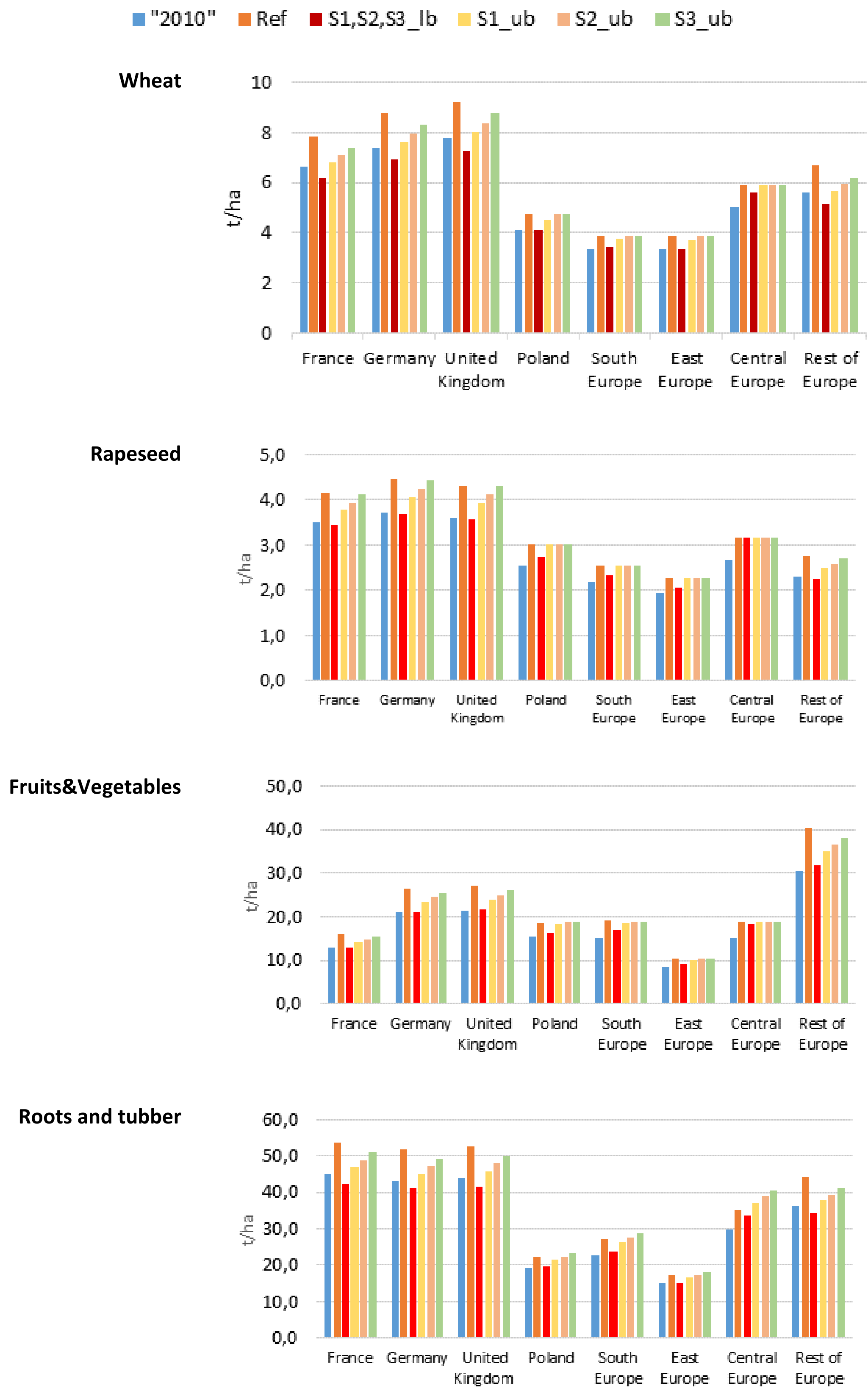
Figure 5-11 reports the calibrated yields under both hypotheses for several crops and the 8 European sub-regions under our three scenarios. Crop yield levels in 2050 under all scenarios for all crops and all European sub-regions are reported in Appendix (Table A.5-1).

Figure 5-10: Contribution of regulating and supporting services to provisioning services (crop production) and links to existing literature on pesticides and yields and on crop diversification and yields



Source: Adapted from Bommarco *et al.* (2013).

Figure 5-11: Crop yields in "2010" and in 2050 under the reference and our three pesticide-free agriculture scenarios (lb and ub) for various crops in the European sub-regions (t/ha)



Source: Own computation based on FAOStat ("2010"), Tibi *et al.* (2020) (Reference scenario), de Ponti *et al.* (2012) (S1,S2,S3_lb), Tibi *et al.* (2022) (S1_ub, S2_ub and S3_ub).

Whatever the crop and the European sub-regions, lower-bound yields are always lower than corresponding reference yields. The extent of the gap between both yields varies across crops and sub-regions as the organic to conventional yield gap do in de Ponti *et al.* (2012). For most crops, the lower-bound assumption makes yields to decrease relative to initial "2010" yields in France, Germany, UK and Rest of Europe, while lower-bound yields in Poland, South, East and Central Europe remain higher than initial "2010" yields.

Due to our conservative assumption to cap the upper-bound yield levels to the reference yield levels, upper-bound yields are always lower than or equal to reference yields. For most crops they are lower than reference yields whatever the scenario (even with scenario S3) in France, Germany, UK and Rest of Europe. For most crops they nearly reach back (Scen S1) or reach back (Scen S2 and S3) corresponding reference yields in Poland, South, East and Central Europe. For all crops and all European sub-regions, upper bound yields are greater than corresponding initial "2010" yields.

5.3.1.3. Hypotheses of change of trade policies and their quantitative translation

Previously presented food diets in Europe involve pesticide-free foods exclusively. These pesticide-free food diets could not arise in 2050 in Europe if food products produced abroad using pesticides could enter freely on European markets. As a consequence our European sub-regions should increase import barriers to agricultural and food products produced using pesticides coming from non-European sub-regions.

In our transition pathways, hypotheses of change of public policies and trade include two alternative hypotheses on trade policies in 2050 related to pesticides:

- Global harmonized regulation on pesticides through Codex and WTO. In 2050, pesticides regulations have been harmonized at the global level. All traded food products conform to these harmonized regulations and are pesticide-free food products;
- Bilateral trade agreements including mirror or reciprocity clauses related to human, animal and/or environment health. Europe has decided to require that imported agri-food products conform to the health and environmental rules that are in force in European agri-food sectors and markets. Consequently, foreign agri-food products entering European markets must be produced without chemical pesticides. Additional requirements related to the nutritional quality of foods (mainly, non-ultra-processed foods) and/or to the sustainability of agri-food systems (mainly, animal food products and related feeds non-detrimental to the environment) may also be considered.

In the GlobAgri-AE2050 model there are two input parameters, which are concerned by the evolution of trade policies to 2050: import coefficients (i.e., the share of imports in total domestic use) and export shares (i.e., the share of exports on world markets).

We propose to translate the two alternative hypotheses for trade policies as follows:

- Under the first hypothesis, we suppose that import coefficients and export shares of European sub-regions are unchanged. As all traded food products are considered as pesticide-free food products, there is no need of domestic market protection for European sub-regions. On the export side, European and foreign food products are undifferentiated and we assume that exporting positions of countries on world markets are unchanged;[9]

[9] Let's remind however that under our maintained assumption of no cropland expansion in Europe, these export share coefficients become endogenous (cf. Section 5.1). Therefore, they are endogenously reduced when the scenario would make the European sub-regions cropland areas to increase, so that one must reduce exports to impede cropland expansion.

- Under the second hypothesis, we suppose that import coefficients as well as export shares are reduced (see footnote 9). Concerned products and the extent of the reductions vary according to two factors: the content of the mirror or reciprocity clauses included in bilateral trade agreements and the ability of foreign countries to conform to European rules and their willingness to sign bilateral trade agreements with Europe.

The first hypothesis is involved in our scenario S1, while the second hypothesis is associated with scenarios S2 and S3. Nevertheless, the content of the mirror or reciprocity clauses included in bilateral agreements is different in both scenarios. In scenario S2, mirror or reciprocity clauses should concern agri-food products, which are produced without chemical pesticides, and agri-food products which are considered of bad nutritional quality (i.e., ultra-processed foods). In scenario S3 an additional concern is included in mirror and reciprocity clauses: the requirement that traded agri-food products originate from agri-food systems, which are considered as sustainable.

When trade restrictions apply to products which are produced with chemical pesticides, they do not concern GlobAgri-AE2050 animal product aggregates, nor aggregates, which are not used for food consumption (e.g., fibers, protein cakes and to a lesser extent other products). We also assume that such trade restrictions do not affect some vegetal products, which cannot be produced in Europe due to agro-climatic conditions, while they remain present in European food diets (e.g., palm product oil and other plant products).

According to Mertens *et al.* (2022), the top five ultra-processed foods consumed by European adults are: fine bakery wares, sausages, sauces, margarines and composite dishes. According to Monteiro *et al.* (2019), "*Ingredients that are characteristic of ultra-processed foods can be divided into food substances of no or rare culinary use and classes of additives whose function is to make the final product palatable or often hyper-palatable ('cosmetic additives'). Food substances of no or rare culinary use, and used only in the manufacture of ultra-processed foods, include varieties of sugars (fructose, high-fructose corn syrup, 'fruit juice concentrates', invert sugar, maltodextrin, dextrose, lactose), modified oils (hydrogenated or interesterified oils) and protein sources (hydrolysed proteins, soya protein isolate, gluten, casein, whey protein and 'mechanically separated meat')*". As our GlobAgri-AE2050 product nomenclature is not adapted to this classification of ultra-processed foods, we could not translate correctly above statements. Hence, we considered that the non-ultra-processed products requirement would imply to consider palm product oil and pork and poultry meat in addition to products already considered under the pesticide-free requirement.

Finally, as far as the sustainability of food systems requirement is concerned we assumed that related trade restrictions would concern, in addition to all previous GlobAgri-AE2050 aggregates, ruminant livestock products and eggs and all protein cakes, as feeds that are characteristic of intensive livestock production.

As already mentioned, the extent of applied restrictions would depend on the ability of foreign countries to conform to European rules and their willingness to sign bilateral trade agreements with Europe. As we have no information on this subject, we calibrated trade coefficients decreases based on shares of extra-EU imports.

5.3.2. Simulation results

In all scenarios (lb and ub yields), the land constraint is active for the same regions as in the reference scenario: all European sub-regions, India, Rest of Asia, Near and Middle East, North Africa, West Africa and Oceania.

Scenario S1 differs from the reference scenario only through crop yields and cropping intensity in Europe. With scenario S2, two main differences compared to the reference scenario are added for

Europe: food diet (lower energy content, lower animal product content and more diversified) and import restrictions for vegetal products used for food and for ultra-processed foods. Scenario S3 also differs from the reference scenario through crop yields and cropping intensity, food diet and import restriction in Europe, but implemented changes are more marked than in scenario S2: cropping intensity is higher, food diet is different (even lower energy and animal product content), while import restrictions concern all products. In addition the European maximum cultivable area is reduced in scenario S3.

5.3.2.1. Impacts of the three scenarios on cropland area

Scenarios S1, S2 and S3 with lower-bound yields

When the scenarios are associated with the lower-bound yields (less optimistic assumption), European crop yields are lower in 2050 than with the reference scenario. As shown in Table 5-17, the European cropland area is fixed across scenarios, except with scenario S3 where the cropland area decreases due to the 20% target for SNH. At the global level, the cropland area increases in all scenarios. The increase is slightly greater with scenario S1 compared to the reference scenario (+221 Mha vs. +196 Mha, respectively). This is the effect of the reduced crop yields in Europe. Indeed, as the European cropland area is fixed, the global domestic production decreases (in spite of the increasing cropping intensity), as do the European exports. As world needs for agricultural products are unchanged, this means that European exports are replaced by exports from other origins, where most often agriculture is less productive than in Europe. The overall result is a greater cropland area required at the world level.

With scenario S2, the world cropland area increase is slightly lower compared to the reference scenario (+187 Mha). Here the increasing impact of the reduced crop yields in Europe is offset by the decreasing impact resulting from both a less demanding diet in Europe (European exports reduce less than in scenario S1) and European restrictions on imports.

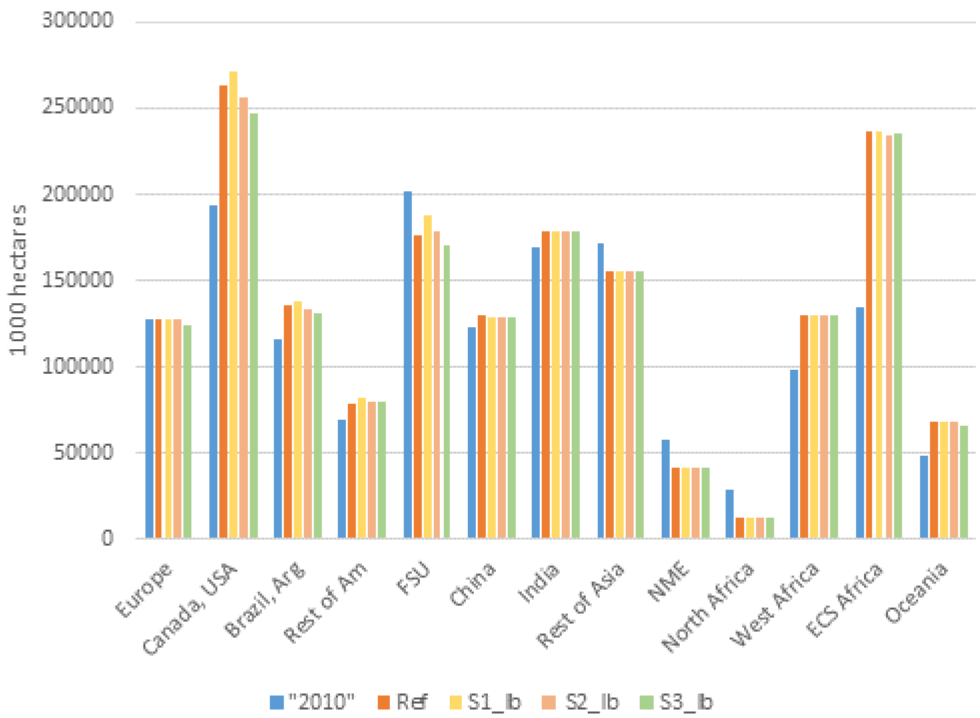
For the same reasons, but with even less demanding diet and extended import restrictions in Europe, scenario S3 leads to the lowest increase in the world cropland area (+161 Mha).

Table 5-17: Cropland area expansion between "2010" and 2050 under the reference scenario and scenarios S1, S2 and S3 (with lb yields) for Europe and the world as a whole (1 000 ha) (% change vs. "2010")

	Ref scenario	Scenario S1_lb	Scenario S2_lb	Scenario S3_lb
Europe	0	0	0	-3 472 (-3%)
Total world	+196 072 (+13%)	+221 176 (14%)	+187 022 (12%)	+161 332 (10%)

As suggested in Figure 5-12, the major world agricultural exporters are the regions the most sensitive to what happens in Europe. USA/Canada, Brazil/Argentina and Former Soviet Union (FSU) see their cropland area expand more or less depending on the scenario arising in Europe. This is consistent with the above-described export and import adjustments in Europe induced by the different scenarios.

Figure 5-12: Cropland (cultivated) area in "2010" and in 2050 under the reference and S1, S2 and S3 scenarios (lb yields) (1000 ha)



Scenarios S1, S2 and S3 with upper-bound yields

Comparing the scenarios S1, S2 and S3 with lower-bound and upper-bound yields reveals how sensitive the simulation results are to the crop yield assumptions. Shifting from lower-bound to upper-bound yields leads to a decrease in world cropland expansion in all three scenarios. Table 5-18 shows that the decrease is about -20 million hectares in the three scenarios, suggesting that changing from lower to upper bound yields does not change significantly simulation results in terms of cropland expansion.

Table 5-18: Cropland area expansion between "2010" and 2050 under scenarios S1, S2 and S3 (with lb and ub yields) for Europe and the world as a whole (Million hectares) (% change vs. "2010")

	Scenario S1		**Scenario S2**		**Scenario S3**	
	lb	ub	lb	ub	lb	ub
Europe	0		0		-3.5 (-3%)	-5.6 (-4%)
Total world	**+221 (14%)**	+199 (13%)	+187 (12%)	+162 (11%)	+161 (10%)	+143 (9%)

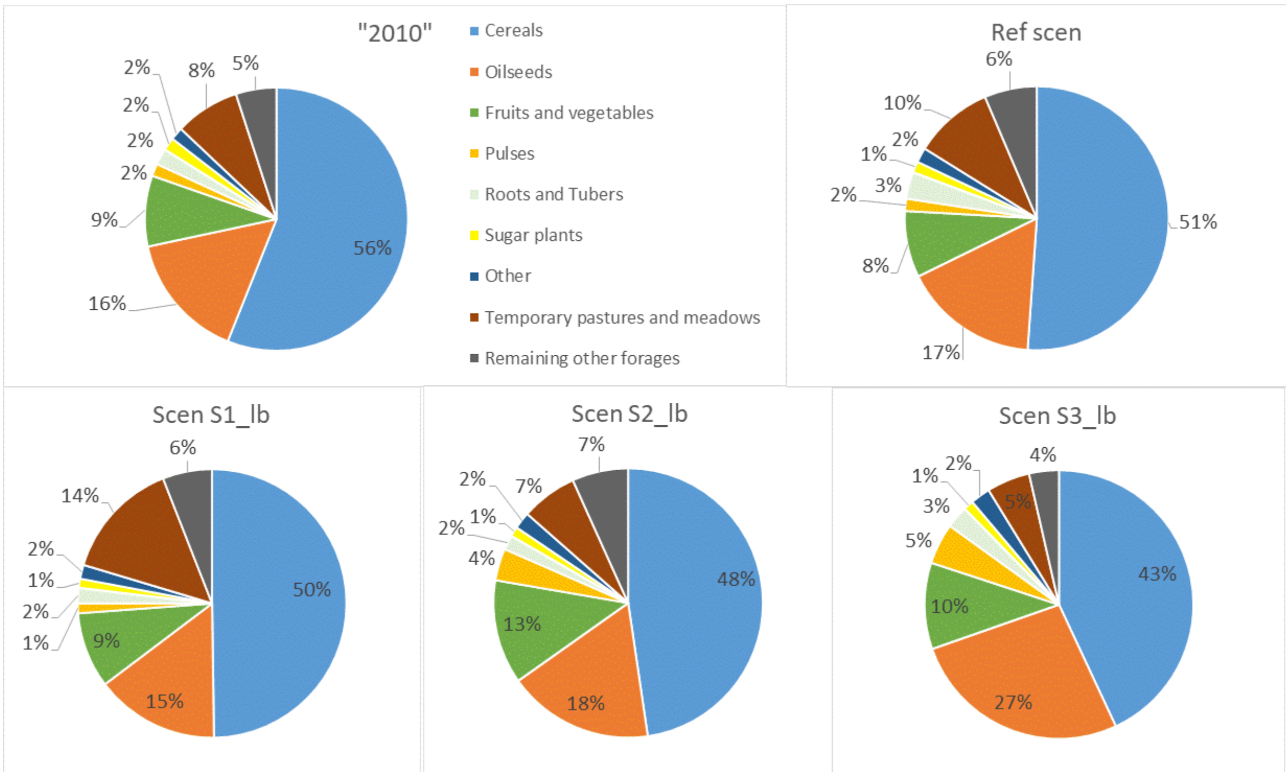
5.3.2.2. Impacts of the three scenarios on European harvested areas

Scenarios S1, S2 and S3 with lower-bound yields

While total cropland area does not vary in Europe (except in scenario S3), total harvested area increases in our scenarios compared to the reference scenario. This is due to the assumed rise in cropping intensity ratios. European total harvested area amounts to 108.3 Mha in the base year "2010" and in the reference scenario, 117.4 Mha with scenarios S1 and S2 (lb) and 118.7 Mha with scenario S3 (lb).

As suggested by Figure 5-13, the shares of the total harvested area devoted to each category of crops vary according to scenarios. The main driver here is the changing food diet from one scenario to the other. Hence, the European crop acreage is very similar among the reference scenario and scenario S1, which share the same food diet. Compared to the reference scenario, scenarios S2 and S3 induce increased shares for fruits and vegetables and pulses in line with the respective patterns of diets in both scenarios. The share devoted to cereals decreases with both scenarios. In this case, diets in scenarios S2 and S3 induce a reduction in animal product food consumption. This results in a decreased use of cereals for feed. The decrease is more marked in scenario S3 because the drop in animal product food consumption is significantly greater than in scenario S2. As far as oilseeds are concerned, several opposite effects are at play. In scenario S2, vegetable oil food consumption decreases, contributing to reduce the required oilseed area harvested relative to the reference scenario. But European imports of vegetable oils are restricted, forcing Europe to expand its oilseed harvested area. Meanwhile, Europe needs less oilcakes for feed use, which reduces the oilseed harvested area required. Finally, the import restriction prevails and the share of harvested area devoted to oilseeds increases with scenario S2 relative to the reference scenario. Effects at play are similar in scenario S3 but here the increasing effect of oilseeds food consumption (soya-based foods) as well as the increasing effect of import restrictions (extended to oilcakes) are more marked. These effects prevail over the decreasing effect of reduced feed use and the share of harvested area devoted to oilseeds in Europe rises as well with scenario S3.

Figure 5-13: Shares of European harvested area devoted to various crop types in "2010" and in 2050 under the reference scenario and scenarios S1, S2 and S3 (lb yields) (%)



Finally, one may notice that the share of harvested area devoted to temporary pastures and meadows decreases significantly with scenarios S2 and S3 relative to scenario S1 and to the reference scenario. The decrease results from the reduced feed use of quality forages following the decrease in animal product food consumption in both scenarios, the drop in ruminant product food consumption being drastic in scenario S3. In 2050, the share of harvested area devoted to temporary pastures and meadows in Europe drops to 7% with scenario S2 and 5% with scenario S3. Such low shares may be inconsistent given the potential crucial role of temporary pastures and meadows for the good functioning of pesticide-free cropping systems (Meiss *et al.*, 2010; Martin *et al.*, 2020; Favreliere *et al.*, 2020). This suggests that in both scenarios S2 and S3, keeping higher shares of temporary pastures and meadows would likely require, either to give back a larger share to ruminant livestock products in food diets or to develop alternative outlets for quality forages.

Scenarios S1, S2 and S3 with upper-bound yields

Unsurprisingly, shifting from lower-bound to upper bound yields has no significant effect on acreages devoted to the various crop types in Europe (Figure A.5-4 in Appendix).

5.3.2.3. Impacts of the three scenarios on pastureland area

Scenarios S1, S2 and S3 with lower-bound yields

In the reference scenario, permanent pasture area (or pastureland area) increases by +636 million hectares (+33%) at the world level. Our scenarios make this pastureland expansion to reduce compared to the reference scenario (Table 5-19). This overall reduction results from the significant decrease simulated for Europe (nearly -13 Mha in scenario S1, -20 Mha in scenario S2 and up to -36 Mha in scenario S3, i.e., -51% of the initial "2010" pastureland area in Europe). This sharp decrease in scenario S3 obviously results from the drop of animal products (especially ruminant meat and dairy) consumption in this scenario. This first effect is reinforced by the restrictions on imports, which force Europe to replace imports by domestic production. As the cropland area is fixed in Europe, domestic production may increase only through rising cropping intensity and export reduction. This second effect affects proportionally more livestock than vegetal products. Finally the third effect is the decreasing yield effect, which magnifies the above-described second effect. The European pastureland area decreases less in scenario S2 because the reduction of animal products consumption and the restrictions on imports are lower in this scenario relative to scenario S3. In scenario S1, only the decreasing yield effect is playing. This yield effect reinforces the impact of the constraint on the European cropland area, which limits the possibilities of expansion of domestic production (including livestock production). In the reference scenario, Europe managed to increase slightly its livestock domestic production and exports (pastureland area increase), in scenario S1, this increase is no longer possible.

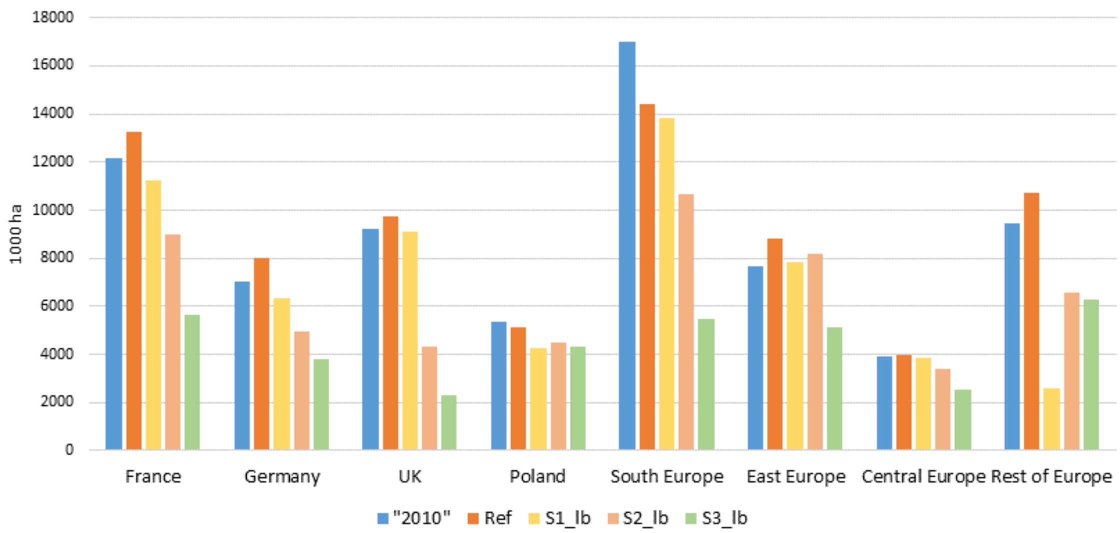
Table 5-19: Pastureland area expansion between "2010" and 2050 under the reference scenario and scenarios S1, S2 and S3 (with lb yields) for Europe, Non-European rest of the world and the world as a whole (1 000 ha) (% change vs. "2010")

	Ref scenario	Scenario S1_lb	Scenario S2_lb	Scenario S3_lb
Europe	+2 214 (+3%)	-12 748(-18%)	-20 285 (-28%)	-36 382 (-51%)
Non-Eur rest of world	+633 755 (+34%)	+675 889 (+36%)	+639 263 (+34%)	+588 491 (+32%)
Total world	+635 979 (+33%)	+663 140 (34%)	+ 618 978 (32%)	+552 108 (29%)

The impact of our scenarios on European exports of ruminant livestock products is the main driver of pastureland area adjustments in the non-European rest of the world. In scenario S1, the European consumption of dairy and ruminant meat is high. Thus the constraint on cropland area makes European exports of these products to decrease strongly. As a result exports and domestic production of these products increase significantly in the non-European rest of the world. With scenario S1 pastureland area expands by +676 Mha, this is more than with the reference scenario, which involves the same food diet but higher crop yields. The expansion of pastureland area in the non-European rest of the world is lower with scenario S2 (+639 Mha, roughly equal than with the reference scenario). With scenario S3, European imports of ruminant meat and dairy decrease and the drop in the domestic consumption of these products is so strong that corresponding exports remain at higher level than in other scenarios. This explains that the pastureland expansion in the non-European rest of the world is significantly lower in scenario S3 (+588 Mha) than in all other scenarios including the reference scenario.

In Europe, one observes the same ranking of pastureland area decrease across scenarios as the one described previously for Europe as a whole, in France, Germany, UK, South Europe and Central Europe (Figure 5-14). The drop with scenario S3 is particularly marked in UK and South Europe (-75% and -68% respectively relative to the "2010" initial situation). For other sub-regions the ranking is different with scenario S2 resulting in the lowest decrease across scenarios instead of scenario S1 (Poland, East Europe and Rest of Europe) and sometimes scenario S3 leading to a lower decrease than scenario S1 (Rest of Europe and to a far lesser extent Poland). In this last case, the main explanation is the high export shares of Rest of Europe for ruminant meat and dairy, which in scenario S1 where the domestic consumption is high, makes exports very sensitive to the constraint on cropland (amplified by the yield decrease in scenario S1 relative to the reference scenario). In the former case, it is likely that the import restriction effect dominates in scenario S2 for these European sub-regions, making their domestic ruminant livestock production to decrease less than in other scenarios.

Figure 5-14: Pastureland area in "2010" and in 2050 under the reference and S1, S2 and S3 scenarios (lb yields) in the 8 European sub-regions (1000 ha)



Scenarios S1, S2 and S3 with upper-bound yields

As shown in Table 5-20, the upper-bound yield hypothesis alleviates the pastureland area changes both in Europe and at the global level, whatever the scenario. Coherently the crop yield effect, which is the only effect at stake here, makes European regions less constrained in terms of cropland. This induces more exports and increased domestic production, including of animal products, with a consequent increase in the need for pastureland in Europe compared to the lower-bound scenarios. As a result, in all scenarios European pastureland area decreases less (even slightly increases in scenario S1) with the upper-bound than with the lower-bound yields. With increased ruminant production in Europe, which is generally more efficient than in other regions, less pastureland is consequently needed at a global level. Thus, the world pastureland area expansion is lower with the upper-bound than with the lower-bond yields, whatever the scenario.

Table 5-20: Pastureland area expansion between "2010" and 2050 under scenarios S1, S2 and S3 (with lb and ub yields) for Europe and the world as a whole (Million hectares) (% change vs. "2010")

	Scenario S1		Scenario S2		Scenario S3	
	lb	ub	lb	ub	lb	ub
Europe	**-12.7(-18%)**	+1.5 (+2%)	**-20.3 (-28%)**	-9.3 (-13%)	**-36.4 (-51%)**	-32.9 (-46%)
Total world	**+663 (34%)**	+652 (+34%)	**+619 (32%)**	+616 (+32%)	**+552 (29%)**	+542 (+28%)

5.3.2.4. Impacts of the three scenarios on European production and use

Scenarios S1, S2 and S3 with lower-bound yields

As a complement to previous results, Figure 5-15 provides the total domestic use in Europe (in 10^{12} kilocalories), distinguishing food, feed and other uses (left panel) and production and net import (in 10^{12} kilocalories) in Europe (right panel). The reading of Figure 5-15 is as follows: in "2010" Europe uses 1884 10^{12} kcal (719 for food, 820 for feed and 345 for other uses). These used calories come from domestic production (1687 10^{12} kcal) and net imports (199 10^{12} kcal) (Figure 5-15.a). Total net imports are composed of a positive amount (+204 10^{12} kcal) for plant products (Europe is a net importer) and a small negative amount (-5 10^{12} kcal) for animal products (Europe is a net exporter). Then Figure 5-15 shows how the European balance is distorted from the reference scenario to our pesticide-free agriculture scenarios (lb yields).

As far as the reference scenario is concerned, Figure 5-15.a shows that total domestic use increases compared to the "2010" base year. The increase comes mostly from the feed use. Additional needs are covered by increasing domestic production and reducing net imports. Imports being a fixed share of domestic use, the reference scenario makes European imports to increase, meaning that exports increase more than imports. Figure 5-15.b and 5-15.c suggests that in proportion exports of animal products increase more than exports of plant products.

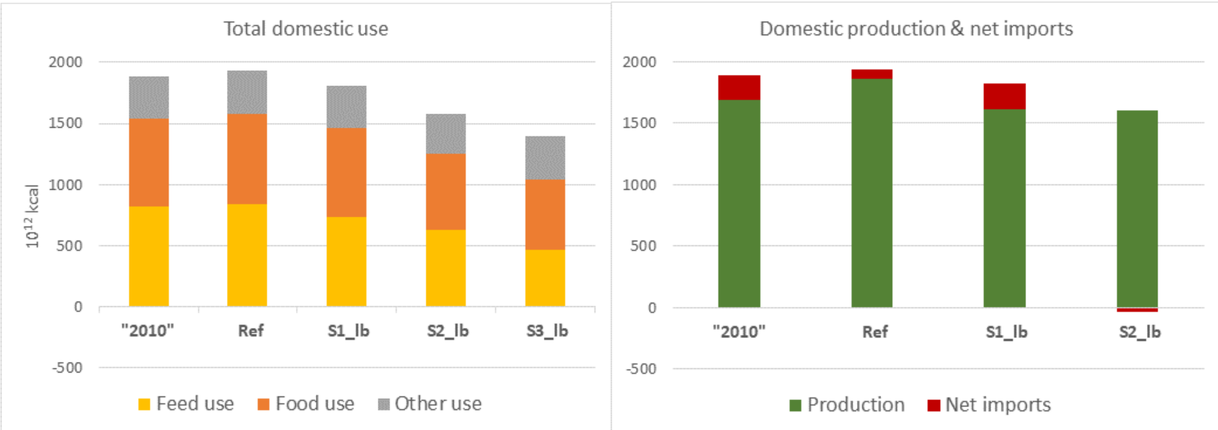
Shifting from the reference scenario to scenario S1, the decreased crop yields in the latter makes it more difficult to increase domestic production. Thus, Europe is forced to reduce its exports, the reduction for animal products being proportionally stronger than the one for plant products. This results in decreased domestic feed use and in total a decrease in European total use.

Figure 5-15 clearly shows the impacts of changing food diets in scenarios S2 and S3 on total domestic use. Both food use and feed use are decreased (relative to other scenarios), but in proportion feed use decreases more than food use (drop of animal products in both diets, much more marked in scenario S3). As European total use decreases, European imports decrease (net imports decrease). This downward adjustment is reinforced by the restrictions on imports that are implemented in scenarios S2 and S3. In scenario S2, Europe becomes self-sufficient, and domestic production equals total domestic use. In scenario S3, Europe becomes a net exporter implying a greater domestic production than in the previous scenario.

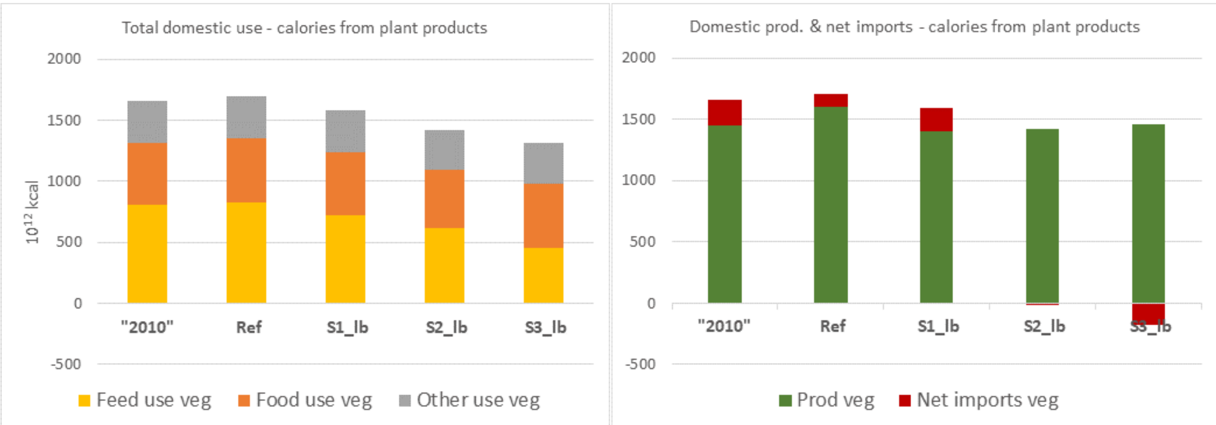
As shown in Figures 5-15.b and 5-15.c, the main difference between scenarios S2 and S3 regarding domestic use concerns animal products: the food use of calories from animal products decreases by half from scenario S2 to scenario S3 (Figure 5-15.c). The corresponding domestic production adjusts down in scenario S3, but the drop is lower than the one experienced by total domestic use. This allows Europe to increase much more its net exports of animal products in scenario S3 than in scenario S2 (Figure 5-15.c).

Figure 5-15: Balance between domestic use, production and trade in "2010" and in 2050 under the reference, S1, S2 and S3 scenarios for Europe as a whole (lb yields) (10^{12} kcal)
(the scale on vertical axis is different for c)

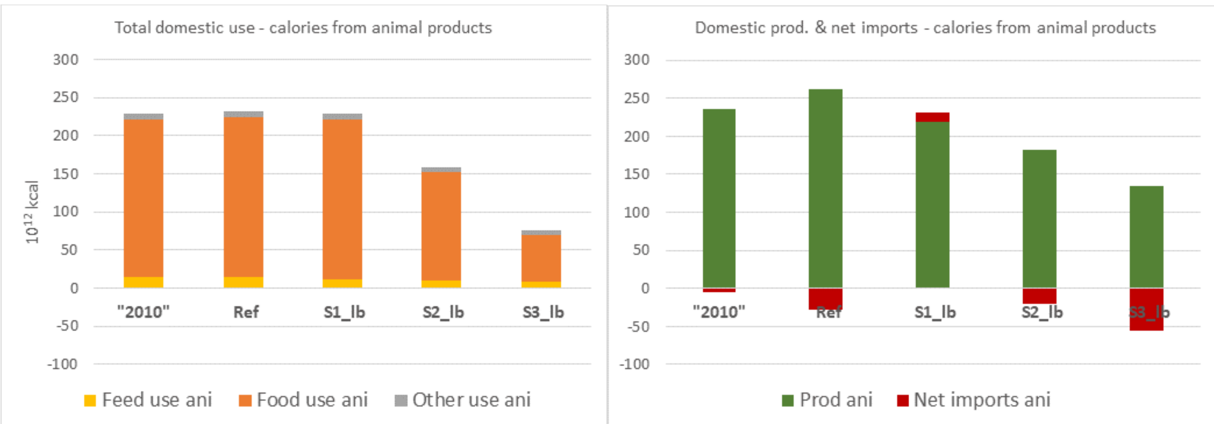
a) Total calories



b) Calories from plant products



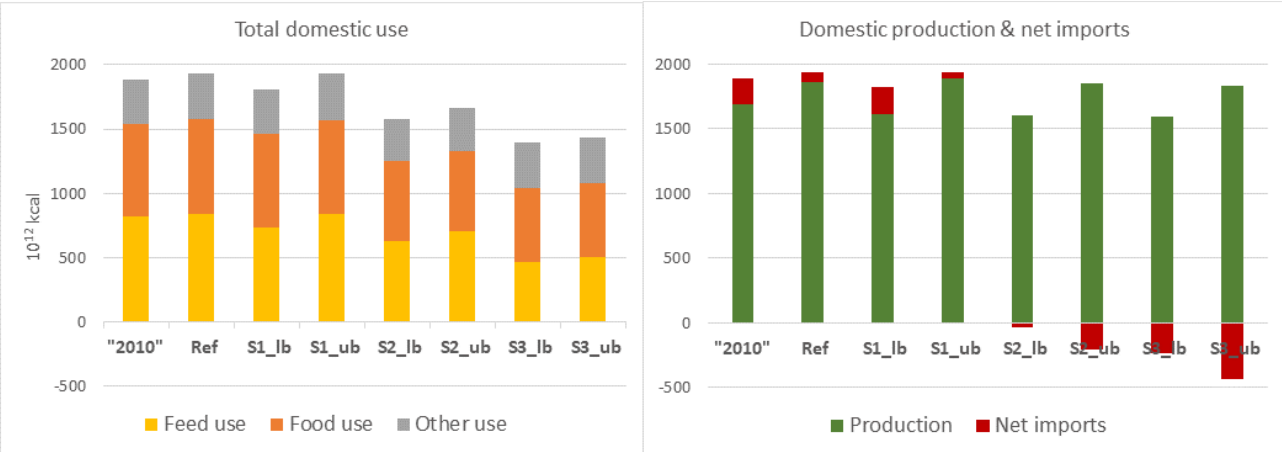
c) Calories from animal products



Scenarios S1, S2 and S3 with upper-bound yields

Whatever the scenario, shifting from the lower-bound to the upper bound yields, allows Europe to produce more and export more (Figure 5-16). As increasing domestic livestock production and exports requires more feed ingredients, the European total domestic use is greater with the upper-bound assumption because the feed use increases more.

Figure 5-16: Balance between domestic use, production and trade in "2010" and in 2050 under the reference, S1, S2 and S3 scenarios (lb and ub yields) for Europe as a whole (total calories, 10^{12} kcal)



5.3.2.5. Impacts of the three scenarios on trade

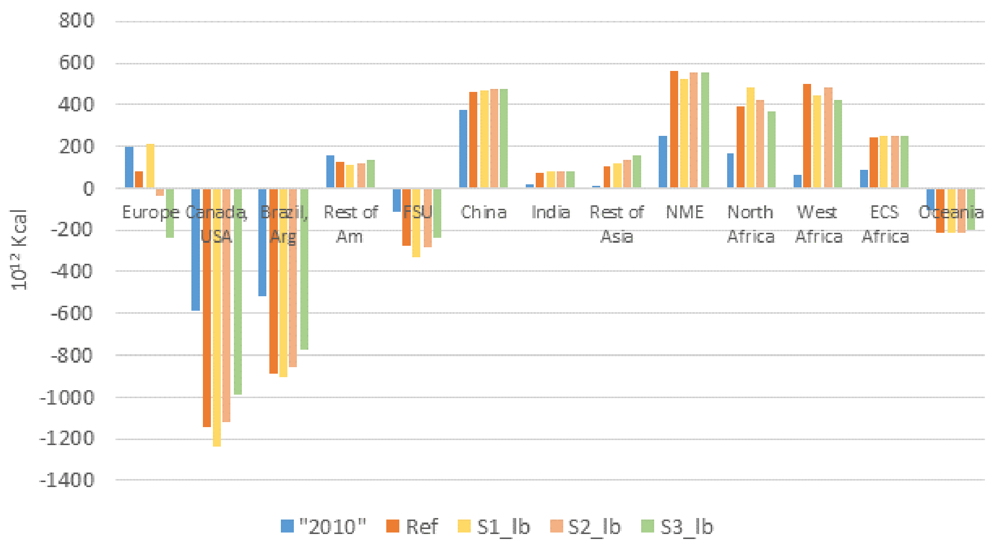
Scenarios S1, S2 and S3 with lower-bound yields

In line with results described in the previous paragraph, Figure 5-17.a suggests that with scenario S3, Europe increases its net imports relative to the reference scenario, while it becomes a net exporter with scenario S2 and especially scenario S3. At reverse, one can see that our pesticide-free agriculture scenarios do not modify the trade position of other world regions. For net exporting regions (Canada/USA, Brazil/Argentina, FSU and Oceania) net exports are greater with scenario S1 (responding to increased European net imports) and lower with scenarios S2 and S3 (responding to decreased European net imports). One may notice that net exports of Oceania are rather constant across scenarios because this region reaches its maximum cultivable area constraint. For net importing regions, net imports are little affected by what happens in Europe, except North and West Africa. Indeed these two regions experience very strong pressures on their cropland area, which translate into reduction to zero of their exports and increased imports. The extent to which they are able to increase their imports is sensitive to what happens in Europe.

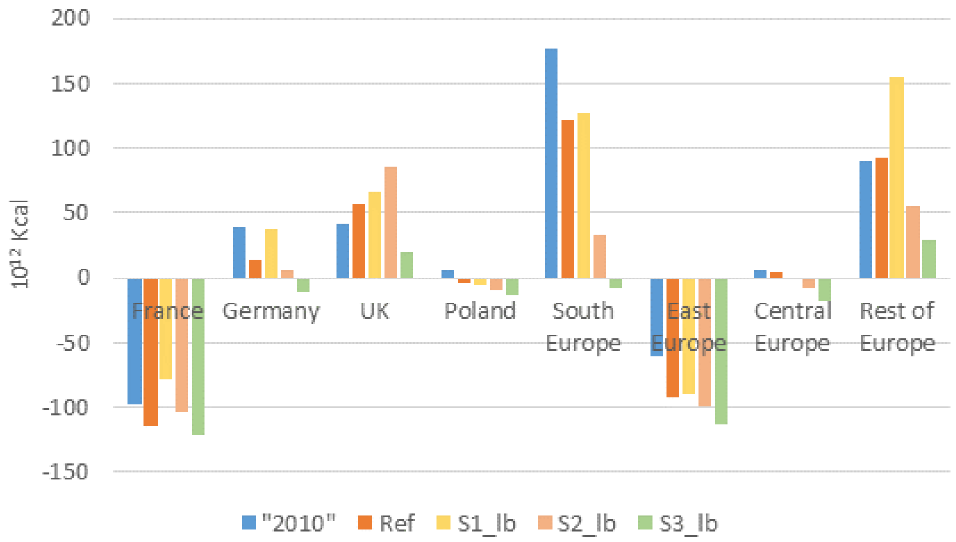
Figure 5-17.b shows that the net exporting position of France and East Europe deteriorates with scenario S1 relative to the reference scenario, but recovers with scenarios S2 and S3. Finally scenario S3 improves the net exporting position of both countries compared to the reference scenario. This is mostly the same for net importing sub-regions: the net importing position deteriorates with scenario S1 and recovers with scenarios S2 and especially S3. With scenario S3, Germany and South Europe become slightly net exporters. Adjustments are different in Poland and UK. Poland is almost self-sufficient with the reference scenario and its net exporting position is improving also with scenario S1. UK is a net importer and its net importing position deteriorates the most with scenario S2.

Figure 5-17: Net imports in "2010" and in 2050 under the reference and S1, S2 and S3 scenarios (lb yields) (in 10^{12} Kcal)

a) World regions



b) European sub-regions

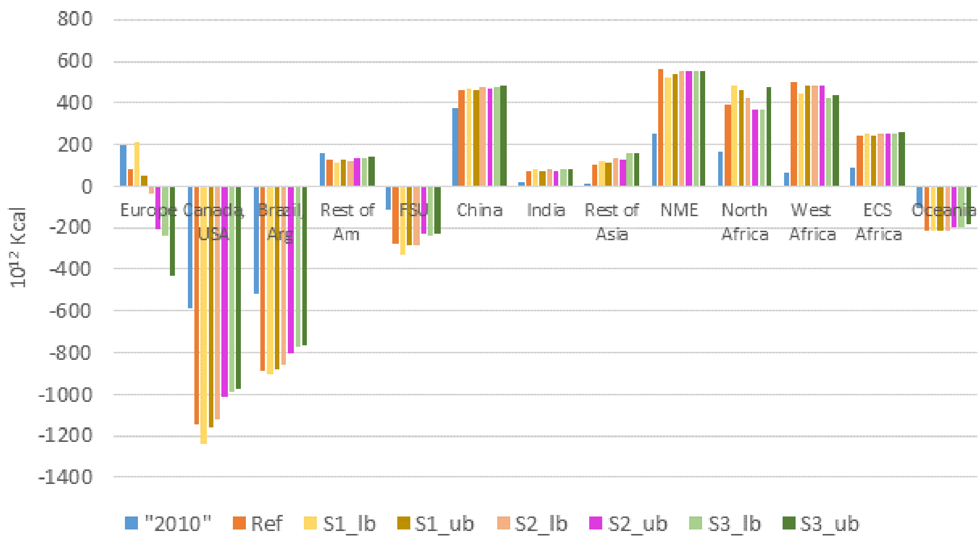


Scenarios S1, S2 and S3 with upper-bound yields

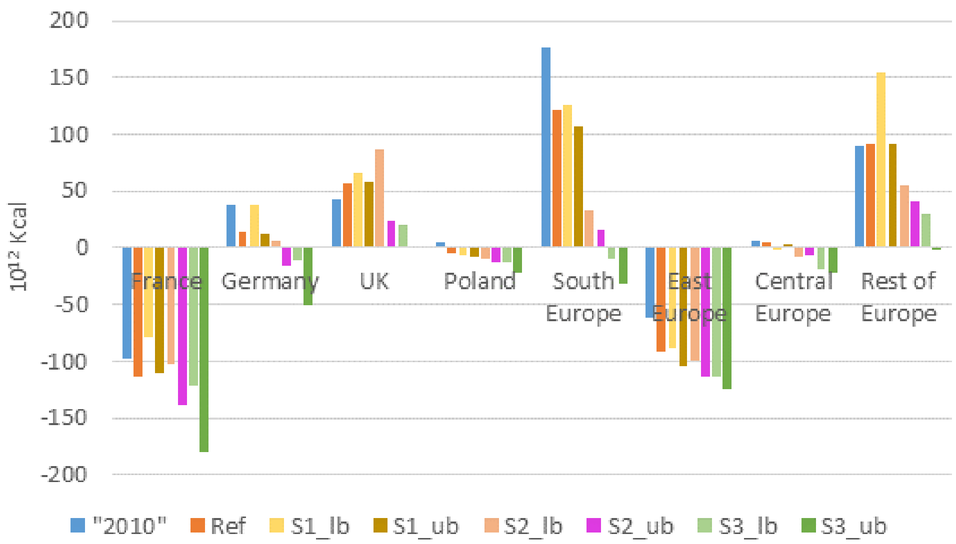
Shifting from lower-bound to upper-bound yields exacerbates all above-described adjustments in net exporting and net importing positions of world regions (Figure 5-18.a) and of European sub-regions (Figure 5-18.b).

Figure 5-18: Net imports in "2010" and in 2050 under the reference, S1, S2 and S3 scenarios (lb and ub yields) (in 10^{12} Kcal)

a) World regions



b) European sub-regions



5.3.2.6. Impacts of the three scenarios on agricultural greenhouse gas emissions

Scenarios S1, S2 and S3 with lower-bound yields

Compared to the reference scenario, our pesticide-free agriculture scenarios lead clearly the agricultural GHG emissions to decrease in Europe (-8% in scenario S1, -20% in scenario S2 and -37% in scenario S3 *vs.* +10% in the reference scenario). Whatever the scenario, the decrease comes for a larger share from livestock production emissions (Table 5-21). In scenario S1, the decrease in Europe is over-compensated by an increase in the non-European rest of the world, resulting in an increase in total agricultural emissions at the global level compared to the reference scenarios (+36% *vs.* +32% in the reference scenario). This means that with scenario S1, there is some emission leakage from Europe to other world regions. This is not the case with scenarios S2 and S3 where the decrease in European agricultural GHG emissions is only partially compensated by the rise in non-European rest of the world. Indeed in both scenarios S2 and S3, global agricultural emissions increase less than in the reference scenario (+31% and +26%, respectively, *vs.* +32% in the reference scenario). In both scenarios S2 and S3 the restrictions on imports contribute to limit the emission leakage.

Table 5-21: Changes in world and European agricultural GHG emissions between "2010" and 2050 under the reference scenario and scenarios S1, S2 and S3 (lb yields) (%)

"2010"-2050 change	Ref scenario			Scenario S1_lb			Scenario S2_lb			Scenario S3_lb		
	Tot	Veg.[1]	Ani.[2]	Tot	Veg.[1]	Ani.[2]	Tot	Veg.[1]	Ani.[2]	Tot	Veg.[1]	Ani.[2]
Europe	+10%	+11%	+9%	-8%	-3%	-10%	-20%	-7%	-24%	-37%	-9%	-48%
Non-Eur. row[3]	+34%	+29%	+37%	+36%	+29%	+39%	+35%	+28%	+39%	+32%	+27%	+34%
Total world	+32%	+27%	+35%	+36%	+27%	+35%	+31%	+26%	+33%	+26%	+24%	+27%

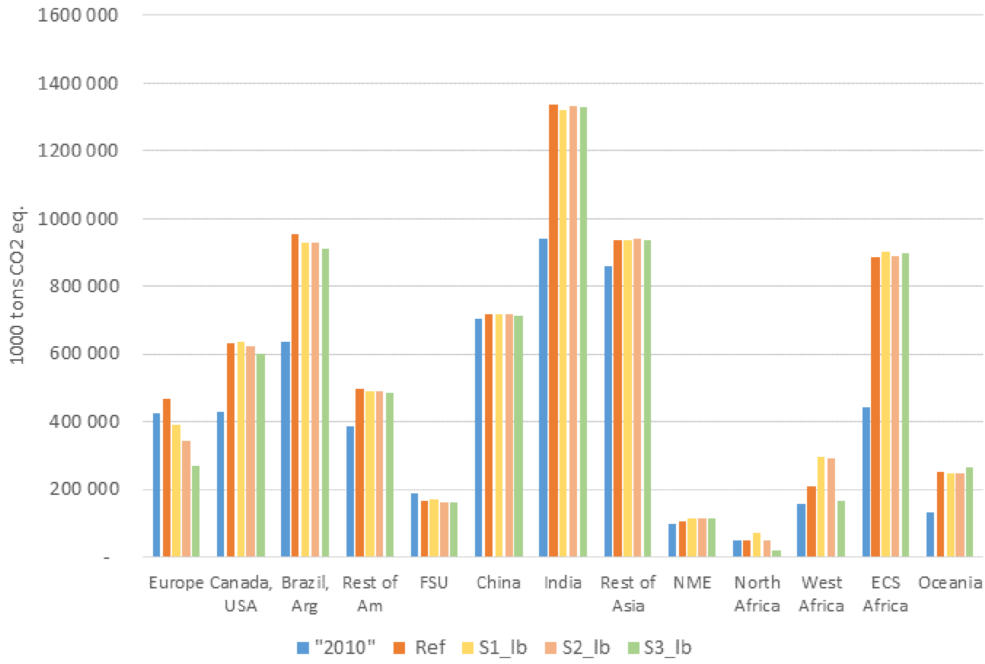
[1] Burning of residues, crop residues, rice, synthetic fertilizers, pasture and soil emissions from organic fertilizers (in CO_2 equivalent)
[2] Enteric fermentation and manure management (in CO_2 equivalent).
[3] row = rest of the world

Increases in agricultural GHG emissions arise in North and West Africa, i.e., the two world regions that are the most constrained by their maximum cultivable area. Such regions are very sensitive to the pressures that Europe puts on world markets. Emissions in other world regions are nearly unresponsive to what happens in Europe (Figure 5-19.a).

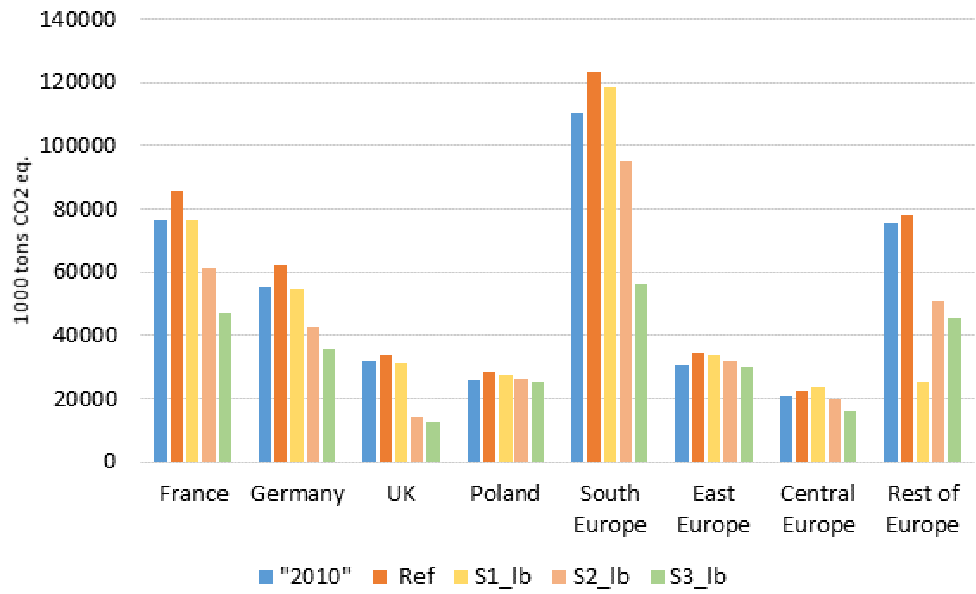
Within Europe, all scenarios make agricultural emissions to decrease relative to the reference scenario in all sub-regions, except Central Europe where emissions increase slightly with scenario S1 (Figure 5-19.b). Scenario S3 induces the largest drops for all sub-regions but Rest of Europe where the largest drop is obtained with scenario S1.

Figure 5-19: Total agricultural GHG emissions in "2010" and in 2050 under the reference and S1, S2 and S3 scenarios (lb yields) (1000 t CO_2 equivalent)

a) World regions



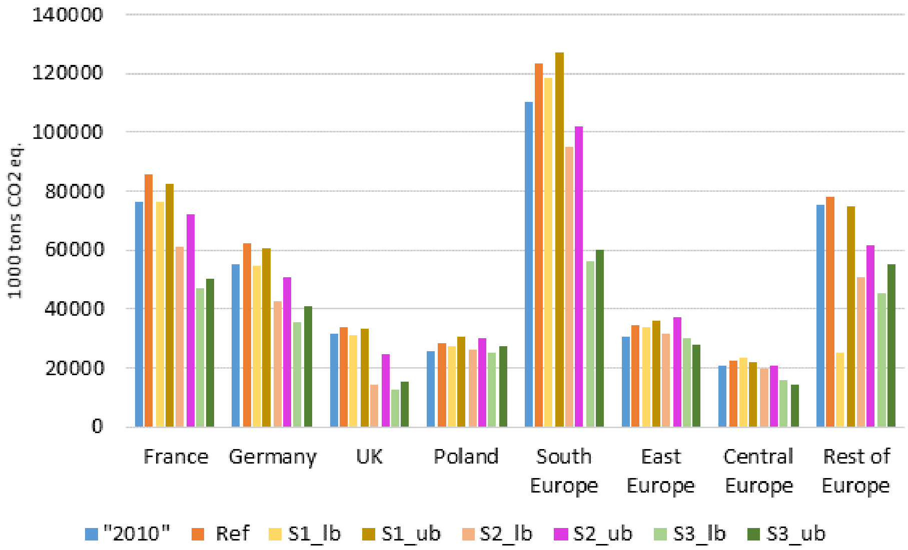
b) European regions



Scenarios S1, S2 and S3 with upper-bound yields

With upper-bound yields, European sub-regions are able to produce more resulting in greater agricultural GHG emissions in these regions (Figure 5-20).

Figure 5-20: Total agricultural GHG emissions in "2010" and in 2050 under the reference scenario and scenarios S1, S2 and S3 (lb and ub yields) in European sub-regions (1000 t CO_2 equivalent)



5.3.2.7. Impacts of the three scenarios on land-use change emissions

Scenarios S1, S2 and S3 with lower-bound yields

Compared to the reference scenario, all our pesticide-free agriculture scenarios lead to a decrease in land-use change emissions in Europe, which reinforces the capacity of Europe to store carbon throughout the projection period (Table 5-22). From -6 million tons of CO_2 equivalent in the reference scenario, the scenario S1 allows to store -9 million tons, the scenario S2 -17 million tons and the scenario S3 up to -43 million tons of CO_2 equivalent per year[10].

Table 5-22: Land-use change emissions from soil and biomass (cumulated and per year) under the reference and S1, S2, S3 scenarios (lb yields) (Mt CO_2 eq)

	Ref scenario	Scen S1_lb	Scen S2_lb	Scen S3_lb
World				
Total cumulated	125 164	133 348	124 523	112 054
Per year (amortized over 40 years)	3 129	3 334	3 113	2 801
Europe				
Total cumulated	-227	-351	-690	-1 731
Per year (amortized over 40 years)	-6	-9	-17	-43

[10] Calculated from the cumulated net storage and amortized on 40 years.

The increasing carbon storage in Europe is mainly explained by the decrease in pastureland area in the three scenarios (respectively -13, -20 and -40 million hectares in the S1, S2 and S3 scenarios). In our baseline assumption the land that was formerly dedicated to permanent pasture now becomes shrubland, which has a slightly greater capacity to store carbon than European grassland [11]. In scenario S3, the additional decrease in cropland (-3.5 million hectares) reinforces the decrease in European land-use change emissions, as cropland is replaced by SNH (which has the capacity to store carbon unless cropland).

At the world level, only the scenario S1 leads to an increase in land-use change emissions compared to the reference scenario. This is due to the compensation of the decrease in European exports of animal products by an increase in livestock production and pastureland expansion in other regions. This, in turn, leads to greater replacement of shrubland and even deforestation in some regions if the amount of shrubland available is insufficient to satisfy the increasing demand for pasture. The other two scenarios benefit from the more sustainable production and consumption patterns that take place in Europe compared to the reference scenario (lesser use of resources and restrictions on imports) with a consequent decrease in land-use emissions.

Alternative assumptions on the use of freed-up land

In our baseline assumption, freed pastureland reverts to shrubland. An alternative assumption is that this freed pastureland is used for afforestation. Table 5-23 reports land-use change emissions across scenarios under this alternative assumption.

Table 5-23: Land-use change emissions from soil and biomass (cumulated and per year) under the reference and S1, S2, S3 scenarios (lb yields) *if freed pastureland area is afforested* (Mt CO_2 eq), according to different carbon stock values for forest biomass

	Ref scenario	Scenario S1_lb	Scenario S2_lb	Scenario S3_lb
Europe (Minimum Values)				
Total cumulated	**-102**	**-286**	**-646**	**-1 571**
Per year (amortized over 40 years)	**-3**	**-7**	**-16**	**-39**
Europe (Average values)				
Total cumulated	-4	-1 735	-3 238	-6 557
Per year (amortized over 40 years)	0	-43	-81	-164
Europe (Maximum values)				
Total cumulated	218	-3 184	-5 829	-11 544
Per year (amortized over 40 years)	5	-80	-146	-289

The net storage of carbon in Europe is divided by half in the reference scenario (from -6 million tons per year net storage to -3 million tons per year if pastureland is afforested). In the three other scenarios the net storage of carbon in Europe is also slightly reduced, from -9 to -7, from -17 to -16 and from -43 to -39 million tons of CO_2 equivalent per year in scenarios S1, S2 and S3 respectively.

This quite counter-intuitive result is clearly due to the assumption we made on the biomass carbon stock values for forests in our baseline assumption. Indeed, forests are a very large and uncertain space of carbon storage with largely varying values for carbon stocks depending on types of forests and their canopy. In our baseline calculations we imposed minimal values for forest biomass carbon stocks. This is not an important issue as long as forest land is little affected by cropland and pastureland expansion. This was the case under our baseline assumption where freed pastureland is assumed to revert to

[11] Our values for carbon stock are taken from the 2010 Directive (CE).

shrubland. [12] But this is no longer the case under the alternative assumption where freed pastureland is afforested. In this case, results in terms of land-use change emissions vary widely according to the retained carbon stock values for forest biomass (Table 5-23).

In the reference scenario, European pastureland expands. According to our assumption, pastureland expands first on shrubland and then, if necessary on forest land. Thus, when pastureland expands, some forest land may be diverted to pasture and the induced land-use change emissions are positive and higher the larger the value of carbon stocks in forest biomass. Table 5-23 shows that in the reference scenario, Europe is nearly a zero emitter of carbon when we consider the average values for carbon stocks in forest biomass. It is storing carbon with minimum values and becomes a net emitter with maximum values for carbon stocks in forest biomass. In all other scenarios, European pastureland decreases to the benefit of forest land. In this case, induced land-use change emissions are negative and higher in absolute value the larger the value of carbon stocks in forest biomass. Hence, the net storage of carbon in Europe becomes larger, the largest the pastureland decrease (i.e., from scenario S1 to S3) and the higher the carbon stock values for forests biomass (from minimum to maximum). As a consequence, if released pastureland was afforested in Europe, scenario S1 could allow Europe to store between -7 and -80 million tons of CO_2 equivalent per year, scenario S2 between -16 and -146 million tons of CO_2 equivalent and scenario S3 between -39 and -289 million tons of CO_2 equivalent per year.

Scenarios S1, S2 and S3 with upper-bound yields

With upper-bound yields, scenarios S1 and S3 lead to less storage of carbon in Europe than with lower-bound yields (Table 5-24). This is due to a smaller decrease in pastureland area in scenario S2 and even an increase in pastureland area in scenario S1 observed with upper-bound yields relative to lower-bound yields, as production rises thanks to higher yields. On the contrary, scenario S3 leads to increased carbon storage in Europe, because the decrease in cropland is more marked with upper-bound than with lower-bound yields (-5.6 Mha *vs.* -3.5 Mha), and results in greater carbon storage since released cropland is used for SNH, including permanent pasture, which unlike cropland store carbon.

At the global level, all scenarios induce lower land-use change emissions with upper-bound yields compared to lower-bound yields, meaning that increasing European production partially replaces production in other parts of the world, which most often are less efficient than Europe in terms of land use.

Table 5-24: Land-use change emissions from soil and biomass (cumulated and per year) under the reference and S1, S2, S3 scenarios (ub yields) (Mt CO_2 eq)

	Scenario S1_ub	Scenario S2_ub	Scenario S3_ub
World			
Total cumulated	127 002	117 778	109 447
Per year (amortized over 40 years)	3 175	2 944	2 736
Europe			
Total cumulated	-195	-583	-1 965
Per year (amortized over 40 years)	-5	-15	-49

[12] See complete results for the reference scenario for different values of forest biomass in Table A.5-5.

5.4. European chemical pesticide-free agriculture in 2050: Two variants of scenarios

Introduction

We propose two variants of our chemical pesticide-free agriculture scenarios in order to put light on two key assumptions regarding the future of European agro-food systems. With the first variant we raise the question: what would happen if European consumers are not ready to accompany the transition toward pesticide-free agriculture in scenarios S2 and S3? With the second variant we wonder what would happen if the European cropland is allowed to expand in our three scenarios.

5.4.1. The transition toward chemical pesticide-free agriculture is also a matter for European consumers

In this variant, we consider that European consumers are not ready to change their food consumption patterns. Thus, in scenarios S2 and S3, European food diets in 2050 are the same as in both the reference scenario and scenario S1. This variant of scenarios S2 and S3 is named S2_lb(ub)_Refdiet and S3_lb(ub)_Refdiet, respectively.

The first result with this food diet variant of scenarios S2 and S3 is that both scenarios become infeasible when crop yields are assumed to be at their lower bound in 2050. Under this assumption, Europe, which cannot expand its cropland area, is not able to produce enough food for feeding its domestic population. In addition, restrictions on imports prevent required additional food produced abroad to reach the European market. Therefore, under hypotheses of scenarios S2_lb_Refdiet and S3_lb_Refdiet, Europe is unable to balance its resources and uses.

Upper-bound yields allow Europe to produce more food domestically and under this assumption, the food diet variant of scenarios S2 and S3 become feasible. Therefore, in the following, we compare scenarios S2_ub and S2_ub_Refdiet as well as scenarios S3_ub and S3_ub_Refdiet.

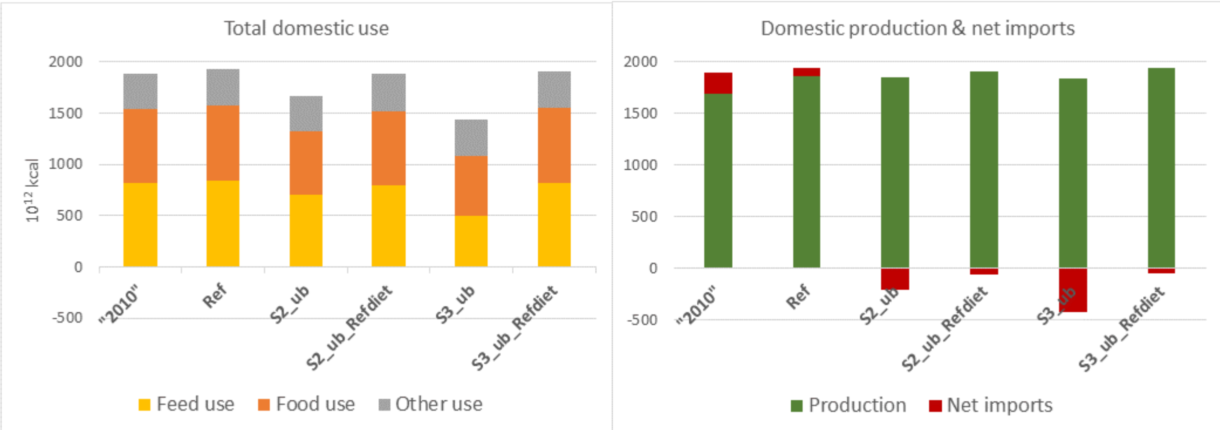
5.4.1.1. Impacts of the diet variant scenarios on European production and use

On the left panel of Figure 5-21, comparing scenarios S2_ub and S3_ub with their counterparts S2_ub_Refdiet and S3_ub_Refdiet reveals the extent to which keeping the trend diet in Europe contributes to increase domestic needs for both food and feed. In Figure 5-21.a, one can see that the positive gap induced by the trend diet is significantly more marked in scenario S3 than in scenario S2. Figures 5-21.b and 5-21.c indicate that for both scenarios, the gap induced by the trend diet is much stronger for animal than for plant products.

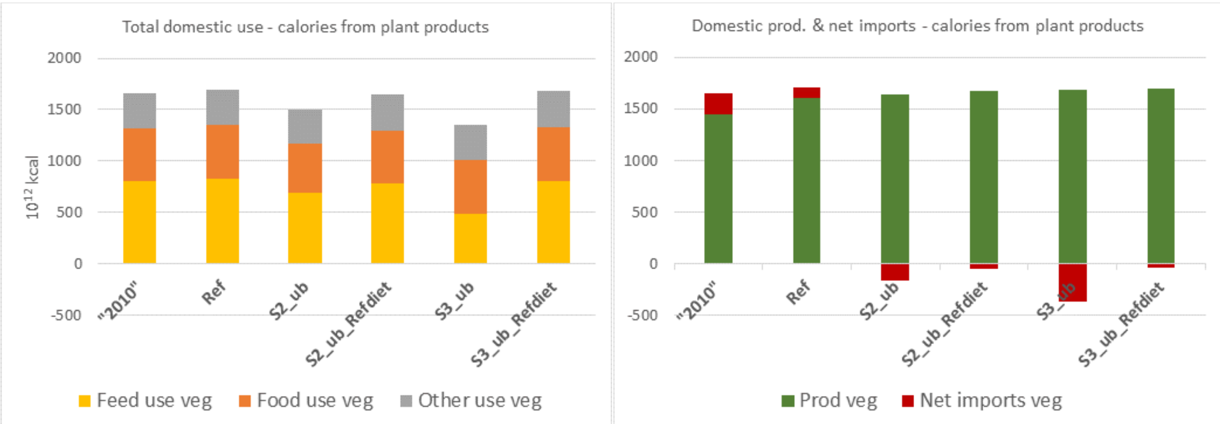
In both scenarios, Europe produces more for supplying this additional domestic needs. But as long as the European cropland cannot expand, some trade adjustments are also necessary. Increase in European imports from the non-European rest of the world is limited as a result of import restrictions, which are in force in scenarios S2 and S3. Therefore, the main trade lever for Europe is the reduction of exports. Figure 5-21.a shows that with both scenarios S2_ub_Refdiet and S3_ub_Refdiet, Europe becomes nearly self-sufficient, unlike with scenarios S2_ub and S3_ub where Europe was a net exporter of calories.

Figure 5-21: Balance between domestic use, production and trade in "2010" and in 2050 under the reference, S2 and S3 scenarios (ub yields) and their food diet variants S2_ub_Refdiet and S3_ub_Refdiet for Europe as a whole (10^{12} kcal) (the scale on vertical axis is different for c)

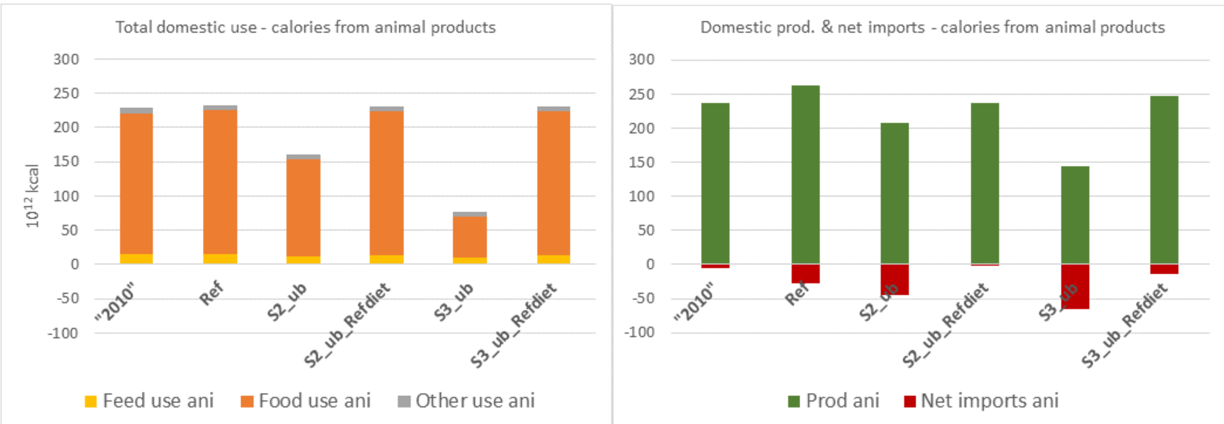
a) Total calories



b) Calories from plant products



c) Calories from animal products



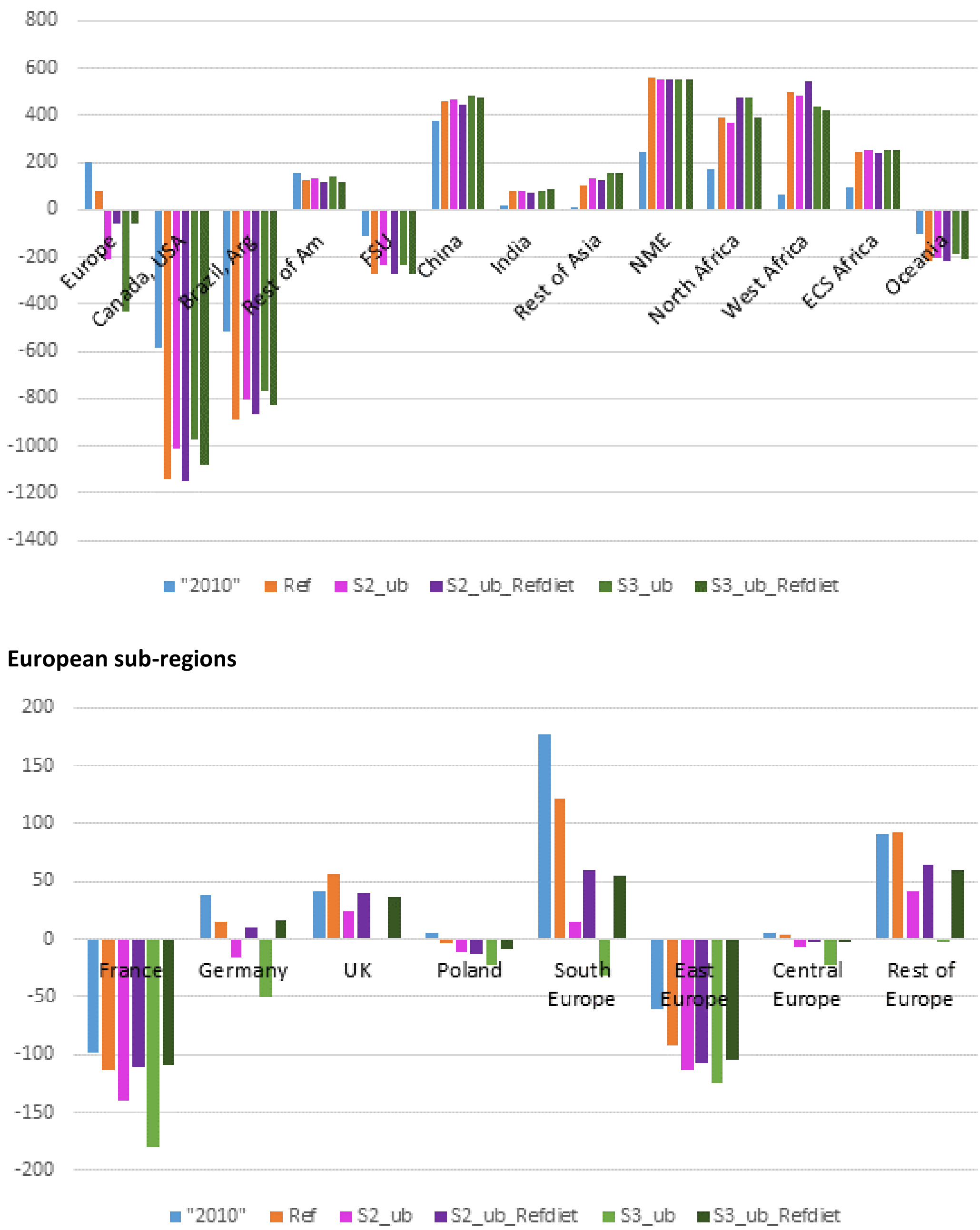
5.4.1.2. Impacts of the diet variant scenarios on European trade

Figure 5-22 confirms that a transition toward chemical-pesticide free agriculture in Europe unaccompanied by changing patterns in domestic food consumption would result in a drastic reduction of European net exports (Figure 5-22.a). Traditional net exporters, like USA/Canada, Brazil/Argentina, Former Soviet Union and Oceania would compensate for the loss of Europe's shares on world markets (each increasing their net exports with the food diet variant scenarios relative to the initial S2 and S3 scenarios).

Figure 5-22: Net imports in "2010" and in 2050 under the reference scenario, scenarios S2 and S3 (ub yields) and their food diet variant S2_ub_Refdiet and S3_ub_Refdiet (in 10^{12} Kcal)

a) World regions

b) European sub-regions



Within Europe, the increased domestic needs induced by the maintenance of the trend food diets contributes to reduce significantly the net exports of net exporting sub-regions (France and East Europe). Sub-regions, which were low net exporters with scenarios S2 and S3 become nearly self-sufficient with the corresponding food diet variant scenarios (Germany, Poland and Central Europe). At reverse, net importing sub-regions increase their net imports with the food diet variant of scenarios S2 and S3 (UK, South Europe, Rest of Europe).

5.4.1.3. Impacts of the diet variant scenarios on cropland and pastureland areas

The European diet is more demanding in the food diet variant scenarios than in the initial scenarios. As a consequence, the S2_ub_Refdiet and S3_ub_Refdiet scenarios are more cropland and pastureland using at the global level (Table 5-25). Unsurprisingly, the impacts of the food variant diet are significantly more marked with scenario S3 than with scenario S2. Similarly, the impacts of the food variant diet are more marked for pastureland than for cropland. Indeed, as shown by Figure 5-9, the reference diet differs widely from the diets originally used in scenarios S2 and S3 for the total energy content and for the animal products content. The gap is particularly marked with the food diet of scenario S3.

In Europe, according to our assumptions, the cropland cannot expand. It is constant between "2010" and 2050 under scenario S2 and its food diet variant. In scenario S3 and its food diet variant the European cropland area decreases due to the 20% SNH target. At the world level, the cropland area change between "2010" and 2050 under both food variant scenarios is close to the corresponding area change in the reference scenario.

As far as pastureland is concerned, the impacts of the food diet variant are much more significant with scenario S3 than with scenario S2. In Europe, the -33 Mha reduction in pastureland area with scenario S3 shifts to less than -2 Mha reduction with the food diet variant S3_ub_Refdiet. While with scenario S2, the -9 Mha reduction in European pastureland area is nearly unchanged to -8 Mha reduction with the food diet variant S2_ub_Refdiet. As Europe must adjust down its exports to supply its increased domestic food needs, other net exporting regions expand their production and related land use. This adjustment mechanism is particularly marked for animal products and explains the significant increase in pastureland area in the non-European rest of the world with both food diet variant scenarios relative to initial scenarios. In total, the food diet variant scenarios make the world pastureland area to increase significantly relative to their initial counterpart scenarios. One may notice that with both food diet variant scenarios, the world pastureland area expansion is even greater than with the reference scenario.

Table 5-25: Cropland and pastureland area expansion between "2010" and 2050 under the reference scenario, scenarios S2 and S3 (ub yields) and their food diet variant S2_ub_Refdiet and S3_ub_Refdiet, for Europe, non-European rest of the world and the world as a whole (Million ha) (% change vs. "2010")

	Reference	S2_ub	S2_ub_Refdiet	S3_ub	S3_ub_Refdiet
Cropland					
Europe	0	0	0	-5.6 (-4%)	-3.5 (-3%)
Total world	+196 (+13%)	+162 (+11%)	+194 (+13%)	+148 (+9%)	+189 (+12%)
Pastureland					
Europe	+2.2 (+3%)	-9 (-13%)	-8 (-11%)	-33 (-46%)	-1.6 (-2%)
Non-Eur rest of world	+634 (+34%)	+626 (+34%)	+675 (+36%)	+575 (+31%)	+654 (+35%)
Total world	+636 (+33%)	+616 (+32%)	+667 (+35%)	+542 (+28%)	+652 (+34%)

5.4.1.4. Impacts of the diet variant scenarios on GHG emissions

Unsurprisingly, the food diet variant scenarios induce higher agricultural GHG emissions than the corresponding initial scenarios (Table 5-26). While scenario S2_ub led to a -27 million tonnes (Mt) CO_2 equivalent reduction in European agricultural GHG emissions between "2010" and 2050, its food diet variant scenario S2_ub_Refdiet only allows a -1.4 Mt reduction. The gap is even larger for scenario S3, with a -135 Mt reduction resulting from the initial scenario S3_ub to a +27 Mt increase with its food diet variant counterpart. The impacts of the food diet variant scenarios are much more significant for GHG emissions from animal production relative to emissions from vegetal production, and with scenario S3 relative to scenario S2. These results are consistent with the previously described changes in European needs, domestic production and net exports caused by the shift from the initial diets in scenarios S2 and S3 to the reference diet in their food diet variant scenarios.

Comparing scenario S2 and its food diet variant scenario, Table 5-26 clearly shows that the slighter reduction in agricultural GHG emissions in Europe with the S2_ub_Refdiet scenario is accompanied by an increase in agricultural GHG emissions in the non-European rest of the world (from +1 670 Mt with scenario S2_ub to +1 797 Mt with scenario S2_ub_Refdiet). In other words, the domestic production increase together with the net export reduction in Europe, as a result of the diet shift, induce increased agricultural GHG emissions in both Europe (increased production) and the rest of the world (European net exports replaced by less efficient –in terms of GHG emissions- net exports from other origins). We observe similar but more marked adjustments when comparing scenario S3 and its food diet variant scenario. In this case, the diet shift makes both Europe and the rest of the world to increase significantly their agricultural GHG emissions.

Table 5-26. Change in agricultural GHG emissions between "2010" and 2050 under the reference scenario, scenarios S2 and S3 (ub yields) and their food diet variant S2_ub_Refdiet and S3_ub_Refdiet for Europe, non-European rest of the world and the world as a whole (Mt CO_2 eq) (% change vs. "2010")

	Reference	S2_ub	S2_ub_Refdiet	S3_ub	S3_ub_Refdiet
Total					
Europe	42 (+10%)	-27 (-6%)	-1.4 (0%)	-135 (-32%)	+27 (+6%)
Non-Eur rest of world	1 727 (+34%)	+1 670 (+33%)	+1 797 (+36%)	+1 536 (+31%)	+1 758 (+35%)
Total world	1 769 (+32%)	+1 643 (+30%)	+1 796 (+33%)	+1 400 (+26%)	+1 785 (+33%)
From vegetal production					
Europe	+13 (+11%)	+8 (+7%)	+12 (+10%)	-0.3 (-0%)	+14 (+12%)
Non-Eur rest of world	+460 (+29%)	+442 (+27%)	+466 (+29%)	+411 (+26%)	+453 (+28%)
Total world	+473 (+27%)	+450 (+26%)	+478 (+28%)	+411 (+24%)	+467 (+27%)
From animal production					
Europe	+29 (+9%)	-35 (-11%)	-13.5 (-4%)	-135 (-43%)	+13 (+4%)
Non-Eur rest of world	+1 267 (+37%)	+1 228 (+36%)	+1 331 (+39%)	+1 125 (+33%)	+1 305 (+38%)
Total world	+1 296 (+35%)	+1 194 (+32%)	+1 318 (+35%)	+990 (+27%)	+1 3018 (+35%)

As shown previously, the food diet variant scenarios induce slighter reduction of European pastureland area relative to the initial S2 and S3 scenarios (Table 5-25). The gap is significantly more limited when comparing scenario S2 and its food diet variant scenario S2_ub_Refdiet than when comparing scenario S3 and its food diet variant counterpart S3_ub_Refdiet. The land-use change emissions from soil and biomass in Europe follow the same pattern (Table 5-27). In both scenarios S2 and S3, Europe continues to store carbon throughout the projection period, even with the diet shift. However the carbon storage is significantly reduced with the food diet variant scenarios. Similarly, at the global level, land-use change emissions increase with the food diet variant scenarios.

Table 5-27: Land-use change emissions from soil and biomass (cumulated and per year) under the reference scenario, scenarios S2 and S3 (ub yields) and their food diet variant S2_ub_Refdiet and S3_ub_Refdiet (Mt CO_2 eq) in Europe and for the whole world

	Reference	S2_ub	S2_ub_Refdiet	S3_ub	S3_ub_Refdiet
World					
Total cumulated	+125 164	+117 778	+128 393	109 447	123 361
Per year (amortized over 40 years)	+3 129	+2 944	+3 210	2 736	3 084
Europe					
Total cumulated	-227	-583	-399	-1 965	-808
Per year (amortized over 40 years)	-6	-15	-10	-49	-20

5.4.2. To export or not to export? Or the differentiated impacts of the transition toward chemical pesticide-free agriculture in Europe according to the constraint on domestic cropland expansion

In this variant, we consider that European sub-regions may adjust freely their cropland area. Thus, in the cropland expansion variant scenarios, the cropland area in each European sub-region may expand until it reaches the maximum cultivable area of the sub-region (see 5.2.1.6). This cropland area variant cannot be applied to scenario S3 since in this scenario the 20% SNH target prevents the European sub-regional cropland areas to expand relative to the "2010" base year situation (Compared to the "2010" base year, the target imposes to devote 3.5 Mha of cropland to SNH and to sanctuary the total area devoted to pastureland, shrubland and forest land in Europe). The cropland expansion variants of scenarios S1 and S2 are named S1_lb(ub)_Clexp and S2_lb(ub)_Clexp, respectively.

In the following, we report and analyse the simulation results of scenarios S1 and S2 and their variants with lower-bound yields.

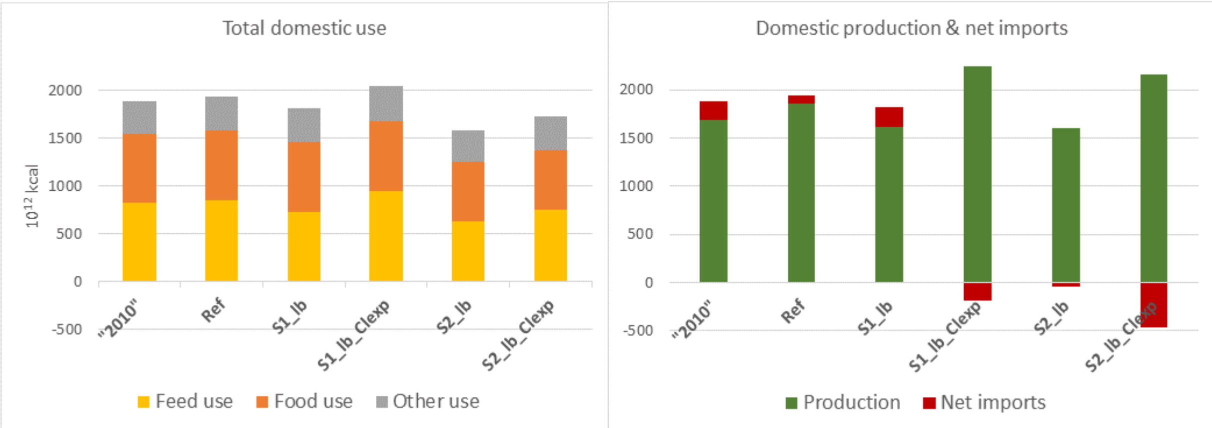
5.4.2.1. Impacts of the cropland expansion variant scenarios on European production and use

On the left panel of Figure 5-23, comparing scenarios S1_lb and S2_lb with their counterparts S1_lb_Clexp and S2_lb_Clexp reveals the extent to which allowing the European cropland area to expand contributes to increase domestic needs for feed (the domestic needs for food remain constant since the diets and the population assumption are unchanged). In Figure 5-23.a, one can see that the positive gap induced by the possibility of expanding the cropland area is more marked in scenario S2 than in scenario S1. Figures 5-23.b and 5-23.c indicate that for both scenarios, the gap induced by the cropland expansion variant is much stronger for plant than for animal products.

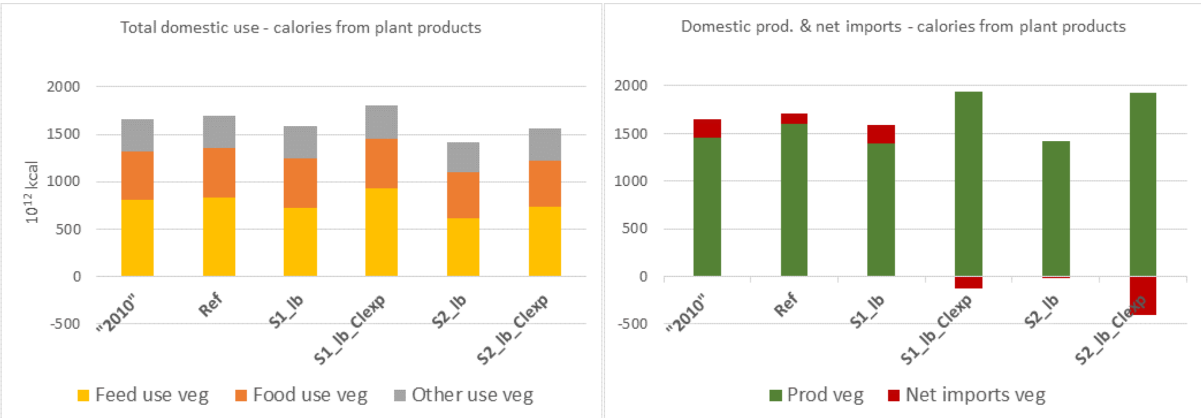
On the right panel of Figure 5-23, one observes that Europe produces more with the cropland expansion variant scenarios than with the initial scenarios, in order to supply the increasing domestic needs, but also to supply the increasing foreign needs. Indeed, compared with initial S2 and S3 scenarios, one crucial impact of their cropland expansion variant scenarios is to allow Europe to produce more to increase its net exports on foreign markets. Figures 5-23.b and 5-23.c show that the positive impact of the cropland expansion variant scenarios on European net exports is proportionally greater for animal products than for plant products. This is consistent with the important net exporting position of Europe for animal products. This also explains the significant positive impact of the cropland expansion variant scenarios on feed consumption.

Figure 5-23: Balance between domestic use, production and trade in "2010" and in 2050 under the reference scenario, S1 and S2 scenarios (lb yields) and their cropland expansion variant S1_lb_Clexp and S2_lb_Clexp for Europe as a whole (10^{12} kcal) (the scale on vertical axis is different for c)

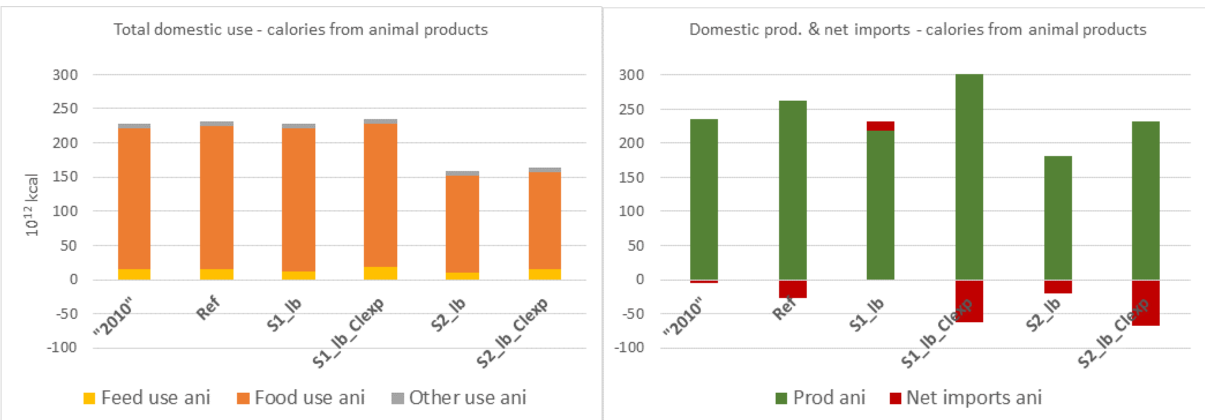
a) Total calories



b) Calories from plant products



c) Calories from animal products

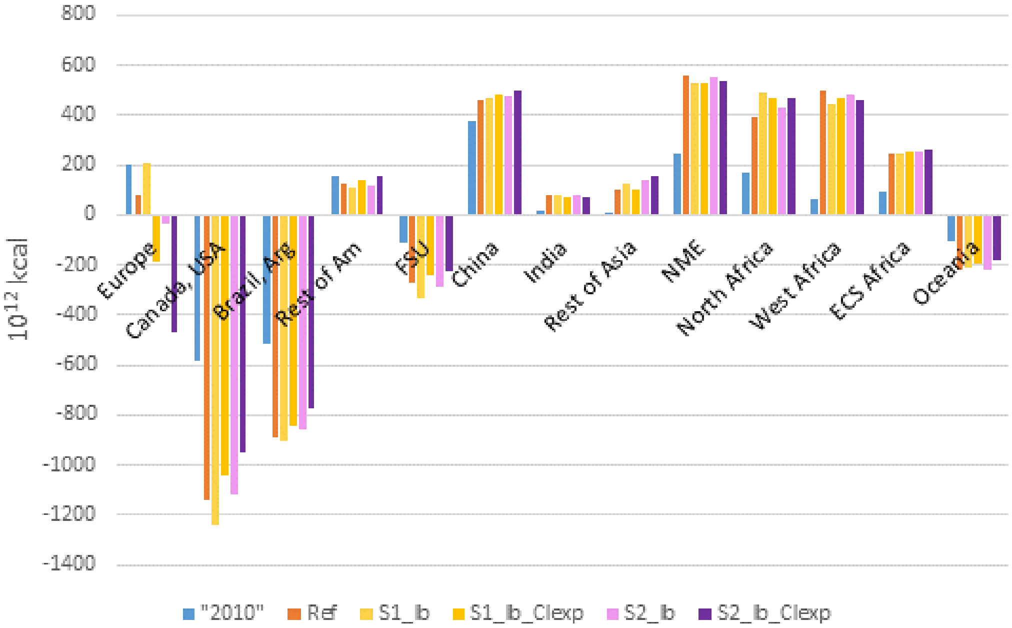


5.4.2.2. Impacts of the cropland expansion variant scenarios on European trade

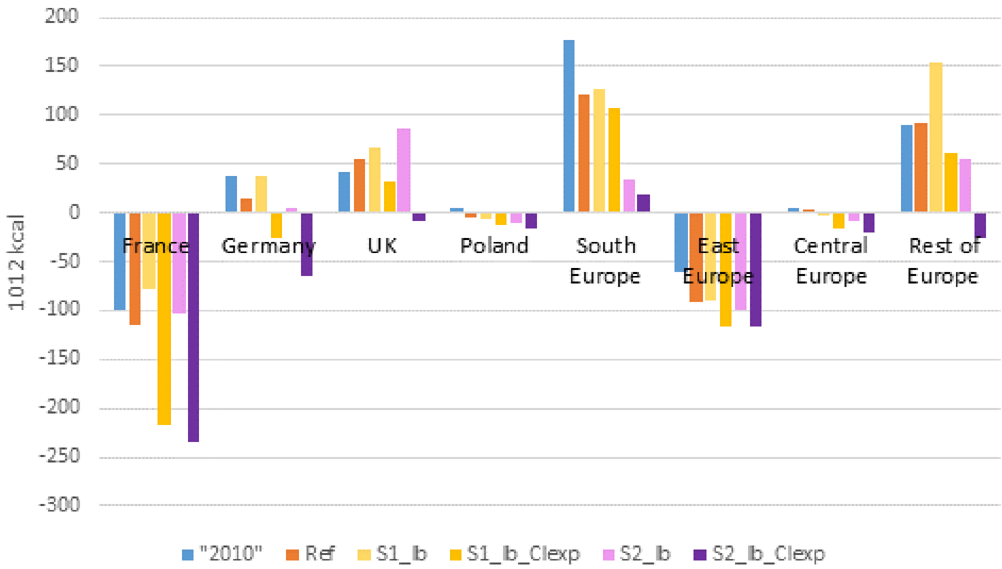
Figure 5-24 confirms that allowing the domestic cropland area to expand makes Europe able to produce more in order to meet the growing needs in foreign countries and broad regions. Indeed, compared to the initial scenarios, the variant scenarios S1_lb_Clexp and S2_lb_Clexp induce a sharp increase in European net exports (Figure 5-24.a). This increase is at the detriment of other traditional net exporting regions, the most important loss being suffered by USA-Canada.

Figure 5-24: Net imports in "2010" and in 2050 under the reference scenario, scenarios S1 and S2 (lb yields) and their cropland expansion variant S1_lb_Clexp and S2_lb_Clexp (in 10^{12} Kcal)

a) World regions



b) European sub-regions



Within Europe, the net exporting sub-regions (France and East Europe) increase significantly their net exports with the cropland expansion variant scenarios, the increase being particularly marked in France (Figure 5-24.b). Sub-regions, which were low net exporters with scenarios S1 and S2 (Poland and Central Europe), also increase their net exports with the cropland expansion variant scenarios. Germany, which was a net importer with scenarios S1 and S2, now becomes a net exporting region with scenarios S1_lb_Clexp and S2_lb_Clexp. On the other hand, net importing sub-regions (UK, South Europe, Rest of Europe) decrease their net imports with the cropland expansion variant of scenarios S1 and S2.

5.4.2.3. Impacts of the cropland expansion variant scenarios on cropland and pastureland areas

When Europe can expand its cropland area, it takes this opportunity to increase its domestic production and be able to export more as a response to the increasing needs in foreign countries and broad regions. This results in more than 30 Million additional hectares of cropland area in Europe (about +25% relative to the "2010" base year) with both variant scenarios S1_lb_Clexp and S2_lb_Clexp (Table 5-28). While this cropland was fixed with the initial scenarios S1_lb and S2_lb. As European sub-regions are generally more productive per hectare than most non-European regions, the whole world needs less cropland area in the cropland expansion variant scenarios than in the initial scenarios.

Table 5-28: Cropland and pastureland area expansion between "2010" and 2050 under the reference scenario, scenarios S1 and S2 (lb yields) and their cropland expansion variant S1_lb_Clexp and S2_lb_Clexp, for Europe, non-European rest of the world and the world as a whole (Million ha) (% change vs. "2010")

	Reference	S1_lb	S1_lb_Clexp	S2_lb	S2_lb_Clexp
Cropland					
Europe	0	0	+31 (+25%)	0	+33 (+26%)
Total world	+196 (+13%)	+221 (+14%)	+194 (+13%)	+187 (+12%)	+169 (+11%)
Pastureland					
Europe	+2.2 (+3%)	-13 (-18%)	+ 11 (+15%)	-20 (-28%)	-7 (-8%)
Non-Eur rest of world	+634 (+34%)	+676 (+36%)	+620 (+33%)	+639 (+34%)	+596 (+32%)
Total world	+636 (+33%)	+663 (+34%)	+631 (+33%)	+619 (+32%)	+589 (+31%)

Expanding cropland allows Europe to produce and export more. This is true for most products and this is particularly marked for animal products, which account for an important share of European exports. As a result, the European pastureland area also increase when shifting from initial scenarios to their cropland expansion variant: from -11 Mha with scenario S1_lb to +13 Mha with its variant S1_lb_Clexp; from -20 Mha with scenario S2_lb to -7 Mha with its variant S2_lb_Clexp. In scenario S2 the negative impact on domestic pastureland area resulting from the reduced European consumption of animal products induced by the healthy diet remains greater than the positive impact on pastureland area resulting from the increased European exports of animal products. As a result European pastureland area continue to decrease in the variant scenarios S2_lb_Clexp relative to the "2010" base year. However, it decreases much less than in the initial scenario S2_lb.

5.4.2.4. Impacts of the cropland expansion variant scenarios on GHG emissions

Unsurprisingly, the cropland expansion variant scenarios induce much greater agricultural GHG emissions in Europe than the corresponding initial scenarios (Table 5-29). While scenario S1_lb led to a -36 million tonnes (Mt) CO_2 equivalent reduction in European agricultural GHG emissions between "2010" and 2050, its cropland expansion variant scenario S1_lb_Clexp results in a +115 Mt increase. There is also a significant gap for scenario S2, with a -85 Mt reduction resulting from the initial scenario S2_lb to a +13 Mt increase with its cropland expansion variant counterpart. The impacts of the cropland expansion variant scenarios are of similar extent for GHG emissions from vegetal and from animal production. These results are consistent with the previously described changes in European needs, domestic production and net exports caused by the possibility given to the European sub-regions to expand their cropland areas.

Table 5-29: Change in agricultural GHG emissions between "2010" and 2050 under the reference scenario, scenarios S1 and S2 (lb yields) and their cropland expansion variant S1_lb_Clexp and S2_lb_Clexp, for Europe, non-European rest of the world and the world as a whole (Mt CO_2 eq) (% change vs. "2010")

	Reference	S1_lb	S1_lb_Clexp	S2_lb	S2_lb_Clexp
Total					
Europe	42 (+10%)	-36 (-8%)	+115 (+27%)	-85 (-20%)	+13 (+3%)
Non-Eur rest of world	1 727 (+34%)	+1 805 (+36%)	+1 592 (+32%)	+1 770 (+35%)	+1 603 (+32%)
Total world	1 769 (+32%)	+1 769 (+32%)	+1 707 (+31%)	+1 685 (+31%)	+1 617 (+30%)
From vegetal production					
Europe	+13 (+11%)	-4 (-3%)	+43 (+37%)	-9 (-7%)	+26 (+22%)
Non-Eur rest of world	+460 (+29%)	+468 (+29%)	+426 (+26%)	+449 (+28%)	+411 (+26%)
Total world	+473 (+27%)	+464 (+27%)	+469 (+27%)	+440 (+26%)	+437 (+25%)
From animal production					
Europe	+29 (+9%)	-32 (-10%)	+72 (+23%)	-76 (-24%)	-12 (-4%)
Non-Eur rest of world	+1 267 (+37%)	+1 337 (+39%)	+1 166 (+34%)	+1 321 (+39%)	+1 192 (+35%)
Total world	+1 296 (+35%)	+1 304 (+35%)	+1 238 (+33%)	+1 245 (+33%)	+1 180(+32%)

One may notice that while cropland expansion variant scenarios induce increased agricultural GHG emissions in Europe, they result in reduced agricultural GHG emissions in the non-European rest of the world and at the global level. This result indicates that as European sub-regions are generally more efficient than most non-European regions as regards agricultural GHG emissions, the increased emissions in Europe are more than offset by the decrease in non-European regions, and the world as a whole generates less agricultural GHG emissions for similar production levels with the variant *scenarios relative to the initial scenarios.*

According to our assumptions, allowing the cropland area to expand in European sub-regions imply that some domestic pastureland can be diverted to cropland, then that the pastureland may expand on shrubland and forest land if necessary. The first change from pastureland to cropland did not arise in the initial scenarios. In addition, the pastureland area expansion was limited due to the constraint on cropland. In the cropland expansion variant scenarios, all these obstacles are removed so that whatever the scenario, we observe large areas shifting from pastureland to cropland and large areas shifting from shrubland or forest land to pastureland in Europe. All these changes in land uses induce positive emissions from soil and biomass. Indeed Table 5-30 indicates that compared to initial scenarios, the cropland expansion variant scenarios S1_lb_Clexp and S2_lb_Clexp imply dramatic increases in emissions from soil and biomass. While Europe as a whole was storing carbon with initial scenarios S1_lb and S2_lb (respectively, -9 and -17 Mt CO_2 eq per year), it becomes a significant net emitter with the variant scenarios S1_lb_Clexp and S2_lb_Clexp (respectively, +100 and +92 Mt CO_2 eq per year).

These additional emissions in Europe are nevertheless more than offset by reduced emissions induced by land-use change in the non-European rest of the world. Finally, Table 5-30 shows that at the global level, despite the increased emissions in Europe, the land-use change induced emissions are lower with the variant scenarios than with the initial scenarios. This result suggests that there are some carbon leakages between Europe and the non-European rest of the world resulting from the constraint on the cropland expansion: in the initial scenarios, this constraint allows Europe to store carbon, but it induces land-use changes outside Europe, which generate positive emissions that more than offset the European carbon sink.

Table 5-30: Land-use change emissions from soil and biomass (cumulated and per year) under the reference scenario, scenarios S1 and S2 (lb yields) and their cropland expansion variant S1_lb_Clexp and S2_lb_Clexp (Mt CO_2 eq) in Europe and for the whole world

	Reference	S1_lb	S1_lb_Clexp	S2_lb	S2_lb_Clexp
World					
Total cumulated	+125 164	+133 348	+122 343	+124 523	115 367
Per year (amortized over 40 years)	+3 129	+3 334	+3 059	+3 113	2 884
Europe					
Total cumulated	-227	-351	+4006	-690	+3 664
Per year (amortized over 40 years)	-6	-9	+100	-17	+92

5.5. Main insights

Table 5-31 reports a set of indicators that allow to draw a picture of the agri-food system in Europe in the base year "2010", and in 2050 under our three scenarios with both lower-bound (Table 5-31.a) and upper-bound (Table 5-31.b) yields. Table 5-32 reports the same set of indicators for the two variants of our scenarios: the food diet variant (Table 5-32.a) and the cropland expansion variant (Table 5-32.b). Based on these tables, we propose a comparative assessment of our three scenarios, with the main lessons learned.

In the 2010 base year, a European consumes in average 3400 kcal per day (including wastes at the distribution and consumption levels), of which 25% come from animal-based foods. Each hectare of cropland produces in average 14.8 million kcal per year. Total domestic production amounts to 1700.10^{12} kcal per year. Total domestic production is used to supply both domestic needs (food, feed and other uses) and foreign needs (through exports). Regarding domestic needs, more calories are devoted to feed (820.10^{12} kcal) than to food (720.10^{12} kcal). While on the foreign market side, Europe is a net importer of calories: in average, it imports 200.10^{12} kcal more than it exports per year. European agricultural GHG emissions amount to 426 million tons CO_2 equivalent per year.

Assuming that current trends remain in place (Reference scenario), in 2050, a European consumes in average 3500 kcal per day in 2050, of which 26% come from animal-based foods. Each hectare of cropland produces in average 17.3 million kcal per year, thanks to slightly increasing average crop yields in Europe. Domestic production reaches 1862.10^{12} kcal per year. The domestic food use is nearly stagnating (+1% relative to 2010) mainly because the European population is stagnant. More calories are still devoted to feed (842.10^{12} kcal) than to food (731.10^{12} kcal). On the foreign market side, Europe benefits from the strong foreign demand and increases its exports. It results in a noticeable decrease in net imports, but Europe remains a net importer of calories: it imports in average 80.10^{12} kcal more than it exports per year. European agricultural GHG emissions amount to 468 million tons CO_2 equivalent per year, this is +10% more than in 2010. Land-use changes in the agricultural sector contribute to increase carbon storage in European soils and biomass by -6 million tons CO_2 equivalent per year. Thus, in 2050 the net emissions of the agricultural and land use sector have increased relative to 2010.

A transition towards chemical pesticide-free agriculture in Europe in 2050 could have contrasting impact on the volume of European agricultural production, depending on scenarios and on the retained assumption regarding crop yields (lower-bound or upper-bound). Under the lower-bound yield assumption, European domestic production in kcal is cut by -4% to -5% compared to 2010 with the three scenarios. Under the upper-bound yield assumption, the production volume of European agriculture could increase in kcal by +9% or +10% (scenarios S3 and S2, respectively) to 12% (scenario S1) from 2010 to 2050.

The total production volume of European agriculture hides different production patterns because European agriculture is embedded in completely different agri-food systems in the three scenarios. Production patterns largely mimic food diet patterns. This means that while production patterns in 2050 are not significantly different from those observed in 2010 with scenario S1, they are radically different with scenarios S2 and S3. In scenario S2, compared to 2010, Europe produces more secondary cereals, fruits and vegetables and pulses and less sugar plants and products in 2050. On the animal products side, European production decreases noticeably for all types of products, as does the production of feed ingredients, including quality forages, and the use of grass from permanent pasture. In scenario S3, Europe produces less cereals and more oilseeds (due to increasing consumption of soya-based foods, and import restrictions on all oilseed products, which are in force in this scenario) and pulses. European animal production decreases sharply in this scenario, as does the production of quality forage and the use of grass from permanent pasture.

A transition towards chemical pesticide-free agriculture in Europe in 2050 could be possible without transforming the European food diets, but to the detriment of European exports (scenario S1). Because of a constant cropland area and a trend diet, rich in energy and in animal products, a reduction in the production volume of the European agriculture (S1_lb) would result in a reduction in European exports in comparison with the reference scenario and scenarios S2 and S3. Thus, in such a case, the European agri-food system, albeit being based on global food chains, would lose export market shares and would not be able to benefit from the dynamic demand abroad. Obviously, the lower the reduction of the European agricultural production, the lower the decrease in exports (S1_ub).

Changing domestic diets towards healthy diets (S2) or towards healthy and more environmental-friendly diets (S3) would give Europe some room to balance domestic resources and uses while becoming a net exporter of calories. In scenario S2_lb, a European consumes in average 3000 kcal par day in 2050, of which 20% come from animal-based foods. This more frugal diet results in a -13% decrease in domestic food use relative to 2010. Furthermore, the reduction in animal-based food consumption implies a -24% decrease in domestic feed use. As a result, total domestic uses are -16% lower in 2050 compared to 2010. In kilocalories, feed use and food use are now nearly equivalent in 2050 at about 620.10^{12} kcal per year. The -15% decrease in total domestic uses is to be compared with the -5% decrease in domestic production to which are added the restrictions on imports, which further reduce domestic resources. However, the decrease in domestic uses remains greater than the decrease in domestic resources and Europe becomes a net exporter of kilocalories in 2050: almost 40.10^{12} kcal per year.

Adjustments are similar in scenario S3_lb, but reduced domestic uses and restrictions on imports are significantly more marked in this scenario. In scenario S3_lb, a European consumes in average 2860 kcal per day, of which only 10% come from animal-based foods. Thus, European food use decreases by -20% from 2010 to 2050, while feed use drops by -43%. As a result, total domestic uses are -26% lower in 2050 compared to 2010. The decrease in domestic uses being much larger than the decrease in domestic resources, Europe becomes a significant net exporter of kilocalories: nearly 240.10^{12} kcal per year.

At reverse, if we assume that European consumers are not ready to change their food consumption habits and keep the trend diet in scenarios S2 and S3, Europe has to manage with increasing total domestic uses from 2010 to 2050 on the utilisation side, and imports restrictions on the resource side. It results that with the lower-bound yields, and due to our assumption of constant cropland area, Europe is unable to balance its domestic resources and uses, even turning to zero its exports. The return to the balance is possible only with the upper-bound yields.

There is a balance to find between decreasing animal-based food consumption and maintaining temporary and permanent pastures. Scenarios S2 and S3 both imply a significant decrease in the European temporary and permanent pasture area, mainly as a result of the reduced consumption of animal products (especially of ruminant products) in these scenarios. From 8% of the total European harvested area in 2010, the share of area devoted to temporary pastures decreases to 7% in 2050 with scenario S2_lb and 5% with scenario S3_lb. In the same time, the European permanent pasture area reduces dramatically: -28% (-20 million hectares) over the 2010-2050 period with scenario S2_lb and more than -50% (-36 million hectares) with scenario S3_lb. In both scenarios, but more specifically in scenario S3, this drop in temporary and permanent pasture areas in Europe could reveal difficult to reconcile with well-functioning chemical pesticide-free cropping systems (notably as regards weed management) on the one hand and lead to undesirable biodiversity impacts on the other hand. To these regards, in all scenarios, we assume that the freed pastureland areas shift to shrublands. Shrublands are considered as SNH in the same way as permanent pastures. Thus, the 20% SNH target is not called into question in scenario S3. However, both land covers may support different ecosystem services and contribute differently to the quality of landscapes.

The three scenarios (but S1_ub) would contribute positively to decrease European agricultural GHG emissions and to increase carbon storage in soils and biomass. Under the lower-bound yield assumption, the three scenarios induce a decrease in agricultural greenhouse gas (GHG) emissions in 2050 compared to 2010: -8% (-36 million tons CO_2 equivalent) with scenario S1_lb, -20% (-85 Mt CO_2 eq) with scenario S2_lb and -37% (-158 Mt CO_2 eq) with scenario S3_lb. Whatever the scenario, the decrease comes to a greater extent from emission reduction of livestock production. With the upper-bound yield assumption the decrease in agricultural GHG emissions is lower in all three scenarios. With scenario S1_ub, Europe turns to increase its emissions relative to 2010 (+9%), while with scenarios S2_ub and S3_ub emissions decrease less: -6% and -32% respectively. Furthermore, compared to 2010, the three scenarios lead to a decrease in land-use change emissions in Europe, which reinforces the capacity of Europe to store carbon throughout the projection period. Scenario S1_lb allows to store -9 million tons CO_2 equivalent per year, scenario S2_lb -17 million tons and scenario S3_lb up to -43 million tons.

Scenario S3, and scenario S2 under certain conditions, could likely allow the European agriculture and land use sector to become carbon neutral in 2050. All three scenarios would help to make agriculture and the land use sector a lower net emitter of CO_2 equivalent. Indeed, net emissions from the combined AFOLU (Agriculture, Forest and Other Land Use) would decrease by -45 Mt CO_2 eq per year with scenario S1_lb, -102 Mt CO_2 eq with scenario S2_lb and -201 Mt CO_2 eq with scenario S3_lb. The net emission reduction would reach -116 Mt CO_2 eq, -231 Mt CO_2 eq and -447 Mt CO_2 eq, respectively under the assumption that freed pastureland area is not reverted to shrubland but used for afforestation (with the maximum carbon stock values for the forest biomass). Hence starting from the base year 2010, where European agriculture emits 426 Mt CO_2 eq per year while the LULUCF (Land Use, Land-Use Change and Forestry) sector stores -309 Mt of CO_2 equivalent[13], the AFOLU sector was a net emitter of carbon with 117 Mt of CO_2 eq in 2010. A net reduction of the same amount of emissions would be needed to make the sector carbon neutral. Considering the fact that the LULUCF sector has significantly reduced its carbon storage during the last ten years[14] (while emissions from the agricultural sector stagnated), carbon neutrality in the AFOLU sector could only be attained with a reduction greater than 209 Mt in net emissions. Compared to 2010 and considering only the additional carbon storage in soils and biomass induced by our scenarios, S1_lb and S2_lb would not make European AFOLU sector carbon neutral in 2050, while scenario S3_lb almost gets there. Scenarios S2_lb and S3 (lb or ub) could likely allow to reach this target under both assumptions that freed pastureland area is used for afforestation and carbon stocks for the forest biomass are close to their maximum values. However, even in the most favorable cases, our scenarios fall short of the official EU objective of climate neutrality in the AFOLU sector to be attained in 2035.[15]

The three scenarios would likely contribute to improve terrestrial biodiversity in Europe. In average, our three scenarios should contribute to improve terrestrial biodiversity in Europe. The first positive impact results from the removal of chemical pesticides in all three scenarios. The second positive impact comes from the increased diversification involved in the three scenarios, with a likely more important impact with the scenario S3 relative to scenarios S1 and S2. Other impacts result from land-use changes induced by the three scenarios. In average, they should be positive: no cropland expansion in the three scenarios, and increased area dedicated to SNH in scenario S3. The biodiversity impact of transforming permanent pastures into shrublands and/or forest could also be positive in average, but some uncertainties remain and we must be cautious here. This improved status of the biodiversity could reinforce the natural regulations occurring in all three scenarios, making the pesticide-free objective even more feasible.

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[13] Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022. Table ES. 5. European Environment Agency, 2022.

[14] According to European GHG inventories (EEA, 2022) the LULUCF sector stored only -217 Mt of CO_2 eq in 2020.

[15] Regulation COM/2021/554

Table 5-31: Overview of assumptions and simulated impacts of scenarios

a) Scenarios with lower-bound yields

	Europe Average	"2010"	Reference	S1_lb	S2_lb	S3_lb
Assumptions	Energy content aver. diet (kcal/cap/day)	3400	3500	3500	3000	2860
	Share of ani kcal in aver. diet (%)	25%	26%	26%	20%	10%
	Crop yields[1] (Million kcal/ha)	14.8	17.3	15	15	15
	Max cultivable area (Mha)	127	127	127	127	123.5
	Imports	No restric.	No restric.	No restric.	Restric. non pest-free food&Ultra-proc. food	Restric. non pest-free food&feed
Results	Total Agri land (Mha) (% vs 2010)	199	201 (+1%)	186 (-6%)	179 (-10%)	159 (-20%)
	- Cropland	127	127	127	127	123.5(-3%)
	- Permanent pasture	72	74 (+3%)	59 (-18%)	52 (-28%)	36 (-51%)
	Production (10^{12} Kcal) (% vs 2010)	1687	1862 (+10%)	1617 (-4%)	1602 (-5%)	1597 (-5%)
	- Plant	1451	1599 (+10%)	1397 (-4%)	1420 (-2%)	1463 (+1%)
	- Animal	236	262 (+11%)	219 (-7%)	182 (-23%)	134 (-43%)
	Total use (10^{12} Kcal) (% vs 2010)	1884	1931 (+3%)	1810 (-4%)	1578 (-16%)	1391 (-26%)
	- Food	720	731 (+2%)	731 (+2%)	625 (-13%)	578 (-20%)
	- Feed	820	842 (+3%)	730 (-11%)	625 (-24%)	465 (-43%)
	Net Imports					
	- 10^{12} Kcal	200	78	209	-39	-237
	- % of total use	11%	4%	12%	-2%	-17%
	Agri. GHG emissions (Mt CO_2 eq) (% vs 2010)	426	468 (+10%)	390 (-8%)	341 (-20%)	268 (-37%)
	LUC GHG emissions (Mt CO_2 eq/an)	-[2]	-6	-9	-17	-43

[1] Average yield in kcal/ha is computed using yields per hectare in 2050 of all crops, excluding forage crops, and initial harvested areas (« 2010 ») in order to exclude the composition effect that is the global yield effect due exclusively to the changes in the composition of the production basket. Average ex-post yields (that is yields including the composition effect) in 2050 in kcal/ha is +15% higher than in 2010 in Ref 2050, -2% lower in scenario S1_lb, -8% lower in scenario S2_lb and -9% lower in scenario S3_lb.

[2] Inventories for Europe in 2010 indicate – 309 Mt CO_2 equivalent for the LULUCF sector.

Table 5-31 (continued): Overview of assumptions and simulated impacts of scenarios

b) Scenarios with upper-bound yields

	Europe Average	"2010"	Reference	S1_ub	S2_ub	S3_ub
Assumptions	Energy content aver. diet (kcal/cap/day) Share of ani kcal in aver. diet (%)	3400 25%	3500 26%	3500 26%	3000 20%	2860 10%
	Crop yields[1] (Million kcal/ha)	14.8	17.3	16.3	16.7	17
	Max cultivable area (Mha)	127	127	127	127	123.5
	Imports	No restric.	No restric.	No restric.	Restric. non pest-free food&Ultra-proc. food	Restric non pest-free food&feed
Results	Total Agri land (Mha) (% vs 2010) - Cropland - Permanent Pasture	199 127 72	201 (+1%) 127 74 (+3%)	201 (+1%) 127 74 (+2%)	190 (-5%) 127 63 (-13%)	161 (-19%) 121 (-4%) 39 (-46%)
	Production (10^{12} Kcal) (% vs 2010) - Plant - Animal	1687 1451 236	1862 (+10%) 1599 (+10%) 262 (+11%)	1891 (+12%) 1634 (+12%) 257 (+9%)	1851 (+9%) 1644 (+13%) 207 (-12%)	1834 (+9%) 1689 (+16%) 145 (-39%)
	Total use (10^{12} Kcal) (% vs 2010) - Food - Feed	1884 720 820	1931 (+3%) 731 (+2%) 842 (+3%)	1930 (+3%) 731 (+2%) 840 (+2%)	1663 (-12%) 625 (-13%) 701 (-15%)	1432 (-24%) 578 (-20%) 500 (-39%)
	Net Imports - 10^{12} Kcal - % of total use	 200 11%	 78 4%	 48 +2%	 -208 -12%	 -431 -30%
	Agri. GHG emissions (Mt CO_2 eq) (% vs 2010)	426	468 (+10%)	466 (+9%)	399 (-6%)	291 (-32%)
	LUC GHG emissions (Mt CO_2 eq/an)	-[2]	-6	-5	-15	-49

[1] Average yield in kcal/ha is computed using yields per hectare in 2050 of all crops, excluding forage crops, and initial harvested areas (« 2010 ») in order to exclude the composition effect that is the global yield effect due exclusively to the changes in the composition of the production basket. Average ex-post yields (that is yields including the composition effect) in 2050 in kcal/ha is +15% higher than in 2010 in Ref 2050, -2% lower in scenario S1_lb, -8% lower in scenario S2_lb and -9% lower in scenario S3_lb.

[2] Inventories for Europe in 2010 indicate – 309 Mt CO_2 equivalent for the LULUCF sector.

Table 5-32: Overview of assumptions and simulated impacts of the variants of the scenarios

a) Food diet variant

	Europe Average	"2010"	Reference	S2_ub	S2_ub_Refdiet	S3_ub	S3_ub_Refdiet
Assumptions	Energy content aver. diet (kcal/cap/day) Share of ani kcal in aver. diet (%)	3400 25%	3500 26%	3000 20%	3500 26%	2860 10%	3500 26%
	Crop yields[1] (Million kcal/ha)	14.8	17.3	16.7	16.7	17	17
	Max cultivable area (Mha)	127	127	127	127	123.5	123.5
	Imports	No restric.	No restric.	Restric. non pest-free food&Ultra-proc. food	Restric. non pest-free food&Ultra-proc. food	Restric non pest-free food&feed	Restric non pest-free food&feed
Results	Total Agri land (Mha) (% vs 2010) - Cropland - Permanent Pasture	199 127 72	201 (+1%) 127 74 (+3%)	190 (-5%) 127 63 (-13%)	191 (-4%) 127 64 (-11%)	161 (-19%) 121 (-4%) 39 (-46%)	194 (-3%) 123.5 (-3%) 70 (-2%)
	Production (10^{12} Kcal) (% vs 2010) - Plant - Animal	1687 1451 236	1862 (+10%) 1599 (+10%) 262 (+11%)	+9% +13% -12%	+13% +15% 0%	+9% +16% -39%	+15% +17% +5%
	Total use (10^{12} Kcal) (% vs 2010) - Food - Feed	1884 720 820	1931 (+3%) 731 (+2%) 842 (+3%)	-12% -13% -15%	0% +2% -4%	-24% -20% -39%	+1% +2% 0%
	Net Imports - 10^{12} Kcal - % of total use	 200 11%	 78 4%	 -208 -12%	 -58 -3%	 -431 -30%	 -55 -2%
	Agri. GHG emissions (Mt CO_2 eq) (% vs 2010)	426	468 (+10%)	399 (-6%)	425 (0%)	291 (-32%)	453 (+6%)
	LUC GHG emissions (Mt CO_2 eq/an)	-[2]	-6	-15	-10	-49	-20

[1] Average yield in kcal/ha is computed using yields per hectare in 2050 of all crops, excluding forage crops, and initial harvested areas (« 2010 ») in order to exclude the composition effect that is the global yield effect due exclusively to the changes in the composition of the production basket. Average ex-post yields (that is yields including the composition effect) in 2050 in kcal/ha is +15% higher than in 2010 in Ref 2050, -2% lower in scenario S1_lb, -8% lower in scenario S2_lb and -9% lower in scenario S3_lb.

[2] Inventories for Europe in 2010 indicate – 309 Mt CO_2 equivalent for the LULUCF sector.

Table 5-32 (continued): Overview of assumptions and simulated impacts of the variants of the scenarios

b) Cropland expansion variant

	Europe Average	"2010"	Reference	S1_lb	S1_lb_Clexp	S2_lb	S2_lb_Clexp
Assumptions	Energy content aver. diet (kcal/cap/day)	3400	3500	3500	3500	3000	3000
	Share of ani kcal in aver. diet (%)	25%	26%	26%	26%	20%	20%
	Crop yields[1] (Million kcal/ha)	14.8	17.3	15	15	15	15
	Max cultivable area (Mha)	127	127	127	194	127	194
	Imports	No restric.	No restric.	No restric.	No restric.	Restric. non pest-free food&Ultra-proc. food	Restric. non pest-free food&Ultra-proc. food
Results	Total Agri land (Mha) (% vs 2010)	199	201 (+1%)	186 (-6%)	240 (+21%)	179 (-10%)	226 (+14%)
	- Cropland	127	127	127	158 (+25%)	127	160 (+26%)
	- Permanent Pasture	72	74 (+3%)	59 (-18%)	82 (+15%)	52 (-28%)	66 (-8%)
	Production (10^{12} Kcal) (% vs 2010)	1687	1862 (+10%)	-4%	+33%	-5%	+28%
	- Plant	1451	1599 (+10%)	-4%	+34%	-2%	+33%
	- Animal	236	262 (+11%)	-7%	+28%	-23%	-1%
	Total use (10^{12} Kcal) (% vs 2010)	1884	1931 (+3%)	-4%	+8%	-16%	-9%
	- Food	720	731 (+2%)	+2%	+2%	-13%	-13%
	- Feed	820	842 (+3%)	-11%	+15%	-24%	-8%
	Net Imports						
	- 10^{12} Kcal	200	78	209	-185	-39	-469
	- % of total use	11%	4%	12%	-9%	-2%	-27%
	Agri. GHG emissions (Mt CO_2 eq) (% vs 2010)	426	468 (+10%)	390 (-8%)	541 (+27%)	341 (-20%)	440 (+3%)
	LUC GHG emissions (Mt CO_2 eq/an)	-[2]	-6	-9	+100	-17	+92

[1] Average yield in kcal/ha is computed using yields per hectare in 2050 of all crops, excluding forage crops, and initial harvested areas (« 2010 ») in order to exclude the composition effect that is the global yield effect due exclusively to the changes in the composition of the production basket. Average ex-post yields (that is yields including the composition effect) in 2050 in kcal/ha is +15% higher than in 2010 in Ref 2050, -2% lower in scenario S1_lb, -8% lower in scenario S2_lb and -9% lower in scenario S3_lb.

[2] Inventories for Europe in 2010 indicate – 309 Mt CO_2 equivalent for the LULUCF sector.

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Appendix of the Chapter 5

List of Figures and Tables

Figure A.5-1: Food diets in regions outside Europe in "2010" and in 2050 according to FAO BAU projections (FAO_BAU) (in kcal/cap/day)

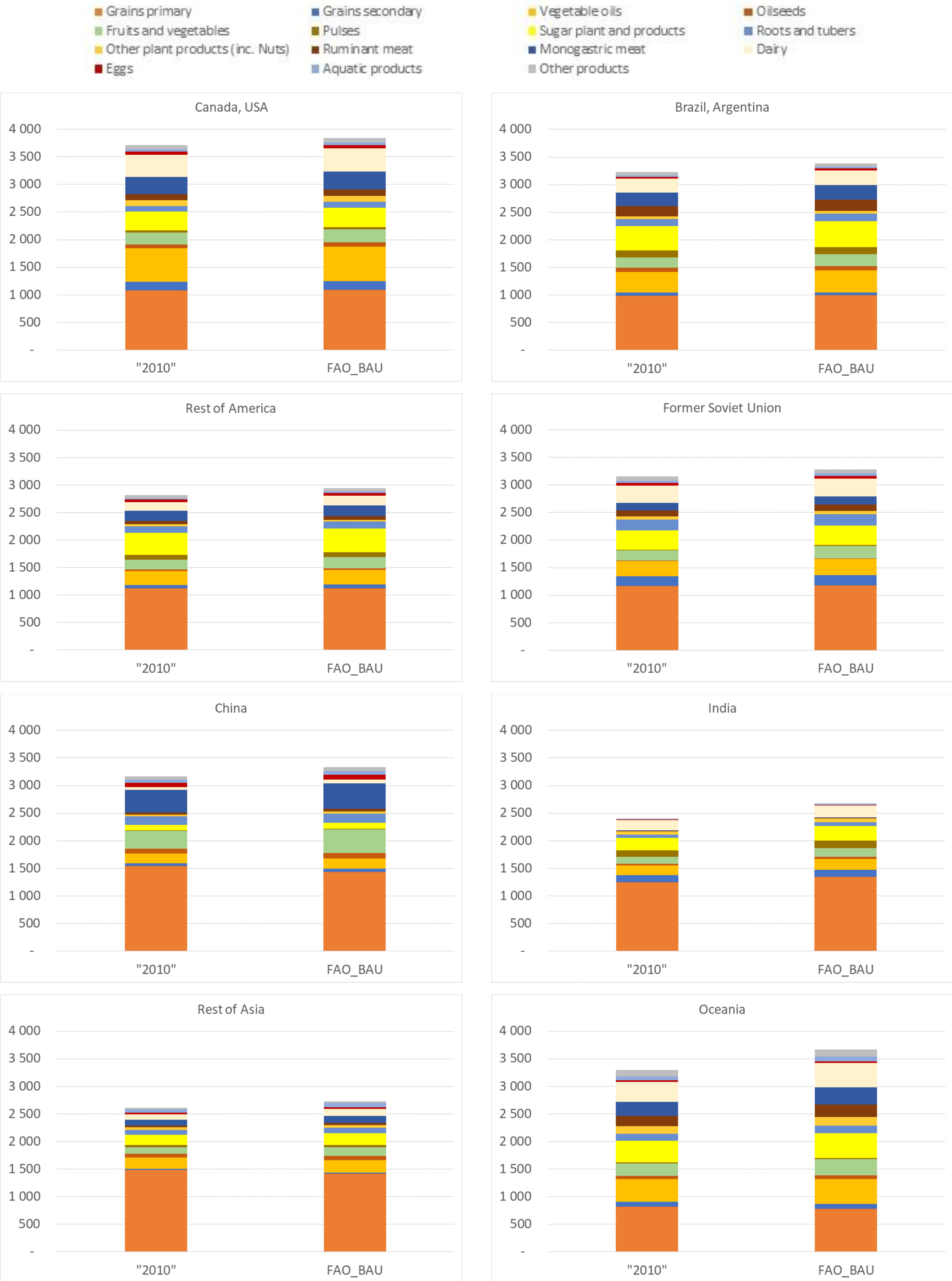

Figure A.5-1 (continued): Food diets in regions outside Europe in "2010" and in 2050 according to FAO BAU projections (FAO_BAU) (in kcal/cap/day)

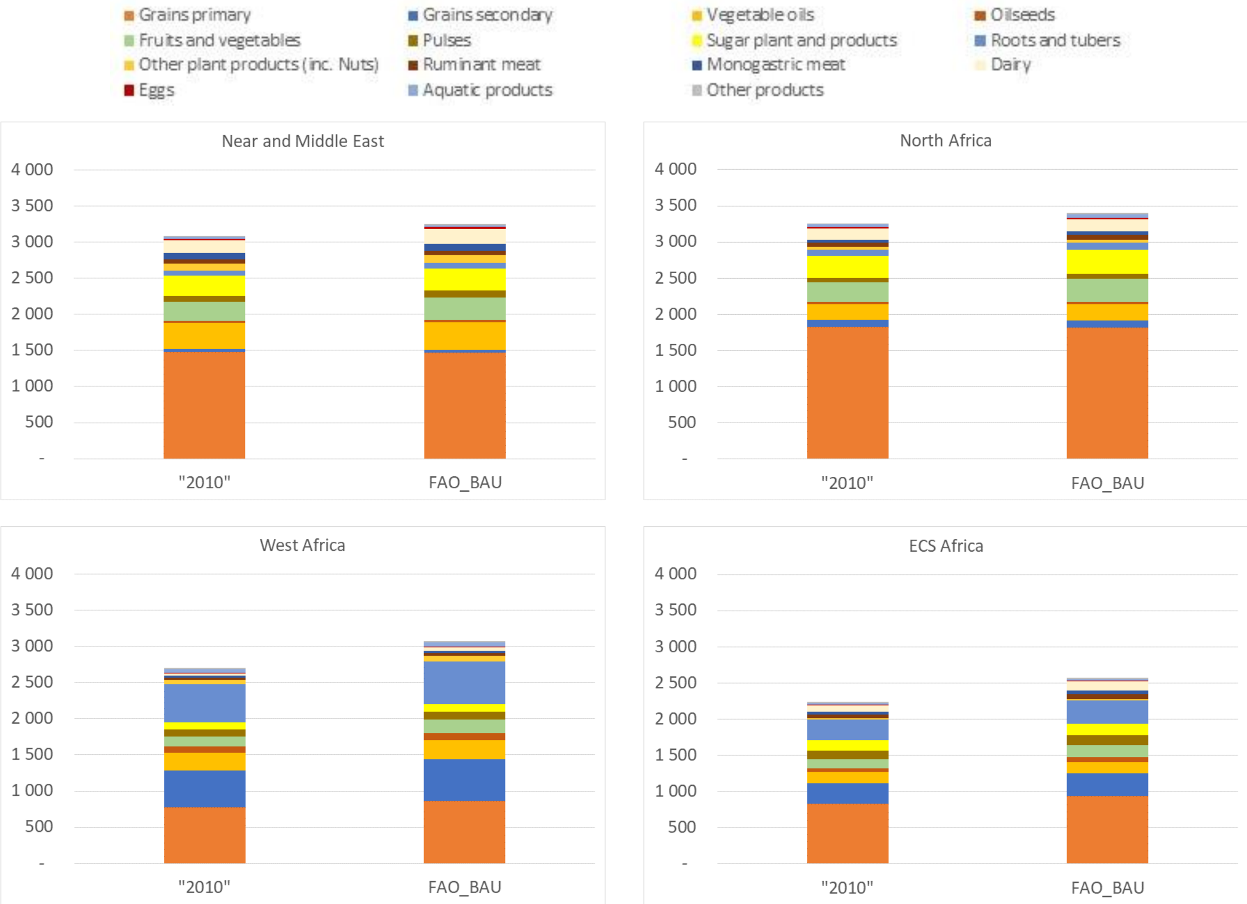

Figure A.5-2: Food diets in European sub-regions in "2010" and in 2050 under the various scenarios (in kcal/cap/day)

Figure A.5-3: Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

Name of variable	Explanation
FAO histo	Historical data for crop yields from FAOStat
"2010"	Average yield 2009/2010/2011, the base year for projections
2050 – slope 7505	Linearly projected crop yield in 2050 using the slope between 1975 and 2005
2050 – slope 9515	Linearly projected crop yield in 2050 using the slope between 1995 and 2015
A & B (2012) EU27	Projected crop yield until 2050 using Alexandratos & Bruinsma (2012) projections for EU27
AE2050 Low	The lower variant of 2050 crop yields in Tibi *et al.* (2020): using FAO (2018) for technical change, and Makowski *et al.* (2020) for climate change impact (without CO_2)
AE2050 High	The higher variant of 2050 crop yields in Tibi *et al.* (2020): using historical slopes (mostly 9515), constancy or Alexandratos & Bruinsma (2012) projections [expert choices] for technical change, and Makowski *et al.* (2020) for climate change impact (with CO_2)

France

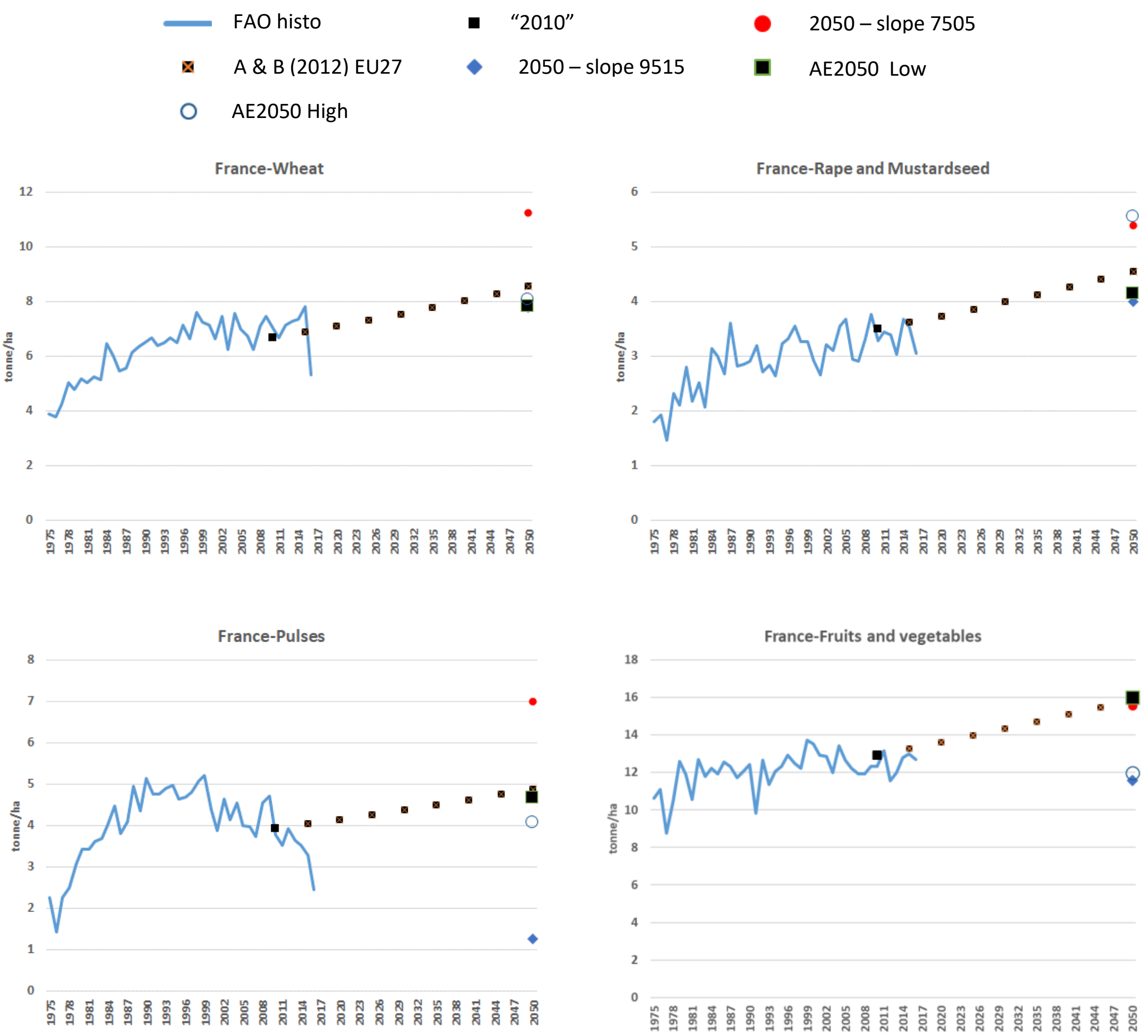

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

Germany

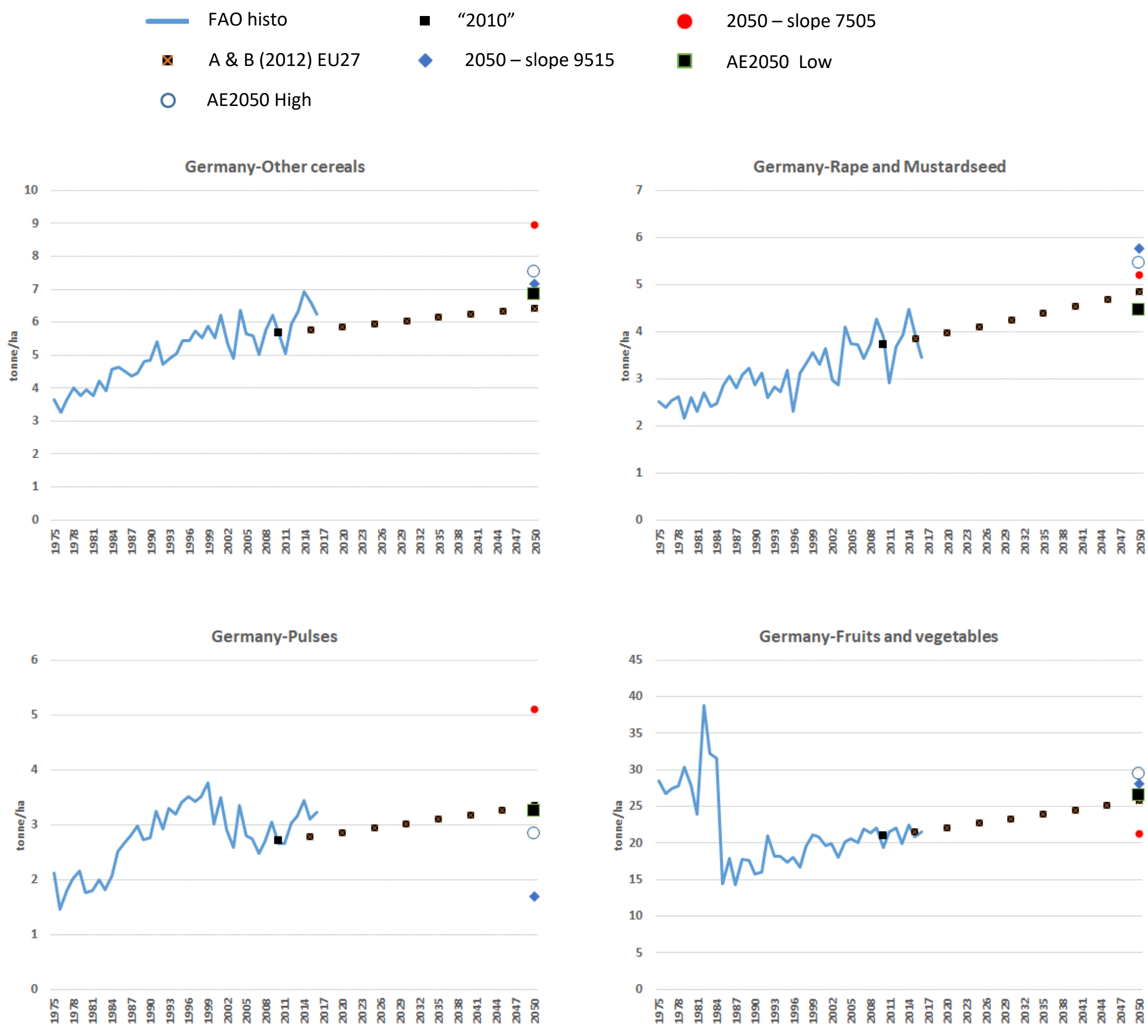

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

Poland

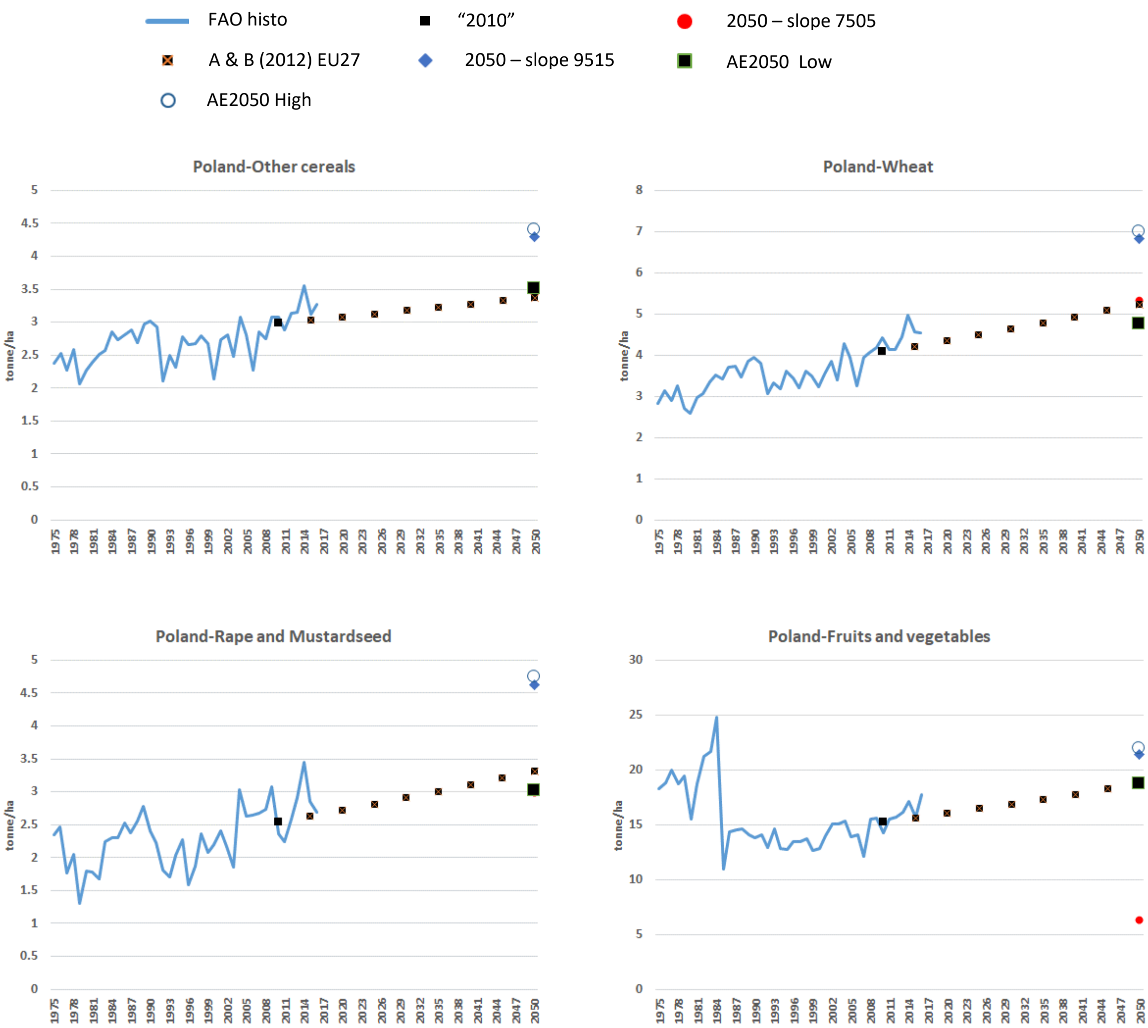

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

United Kingdom

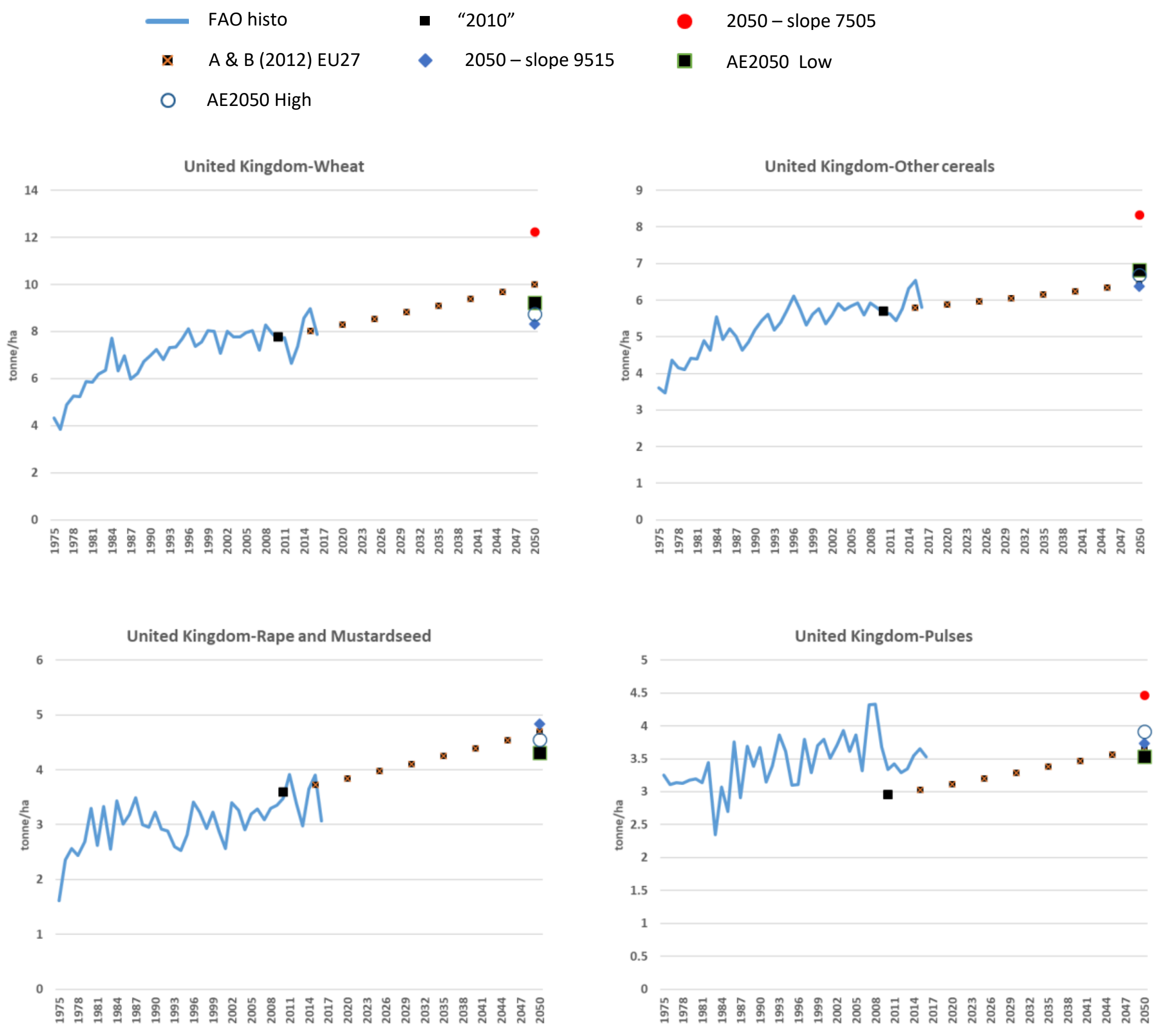

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

South Europe

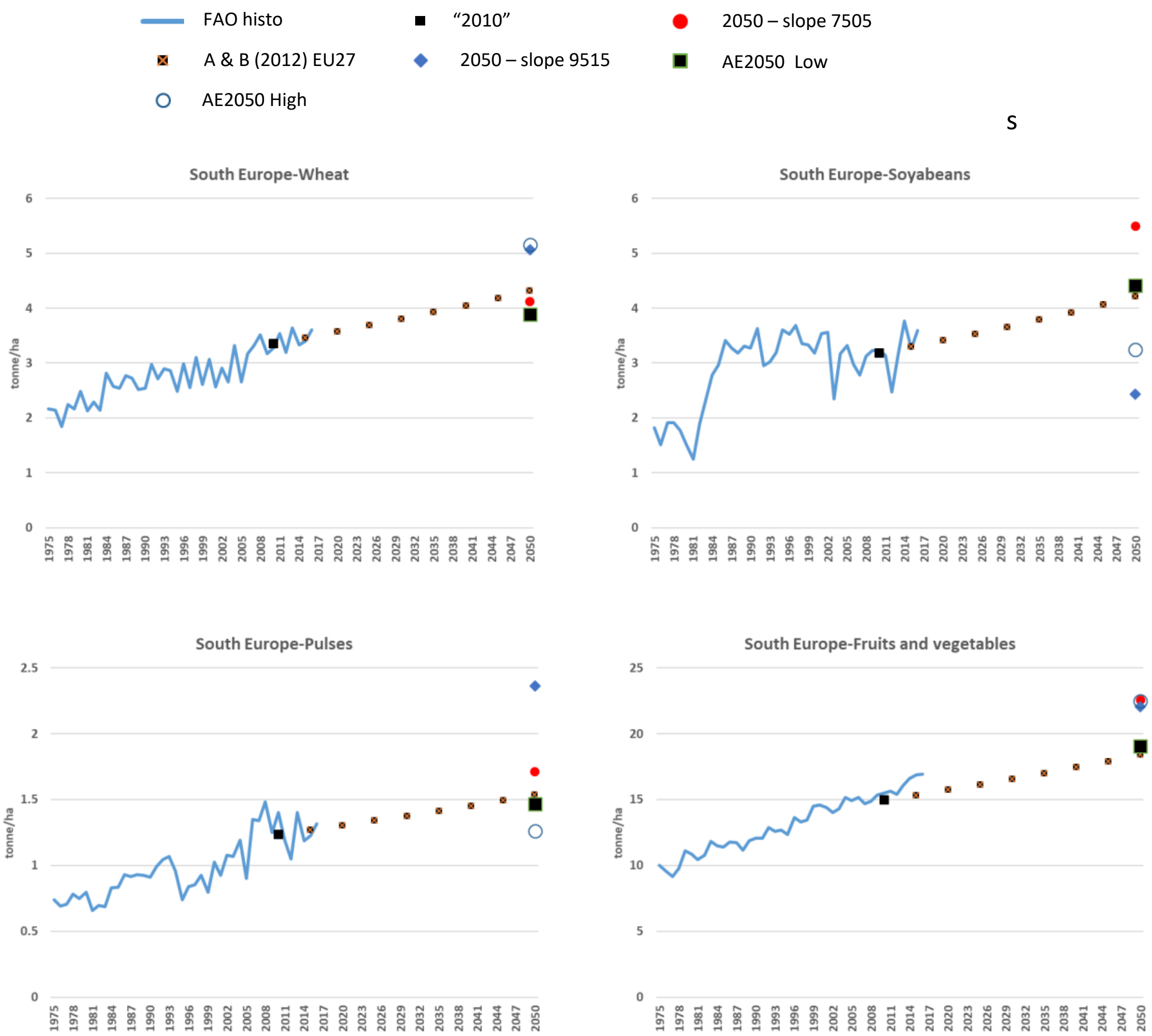

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

East Europe

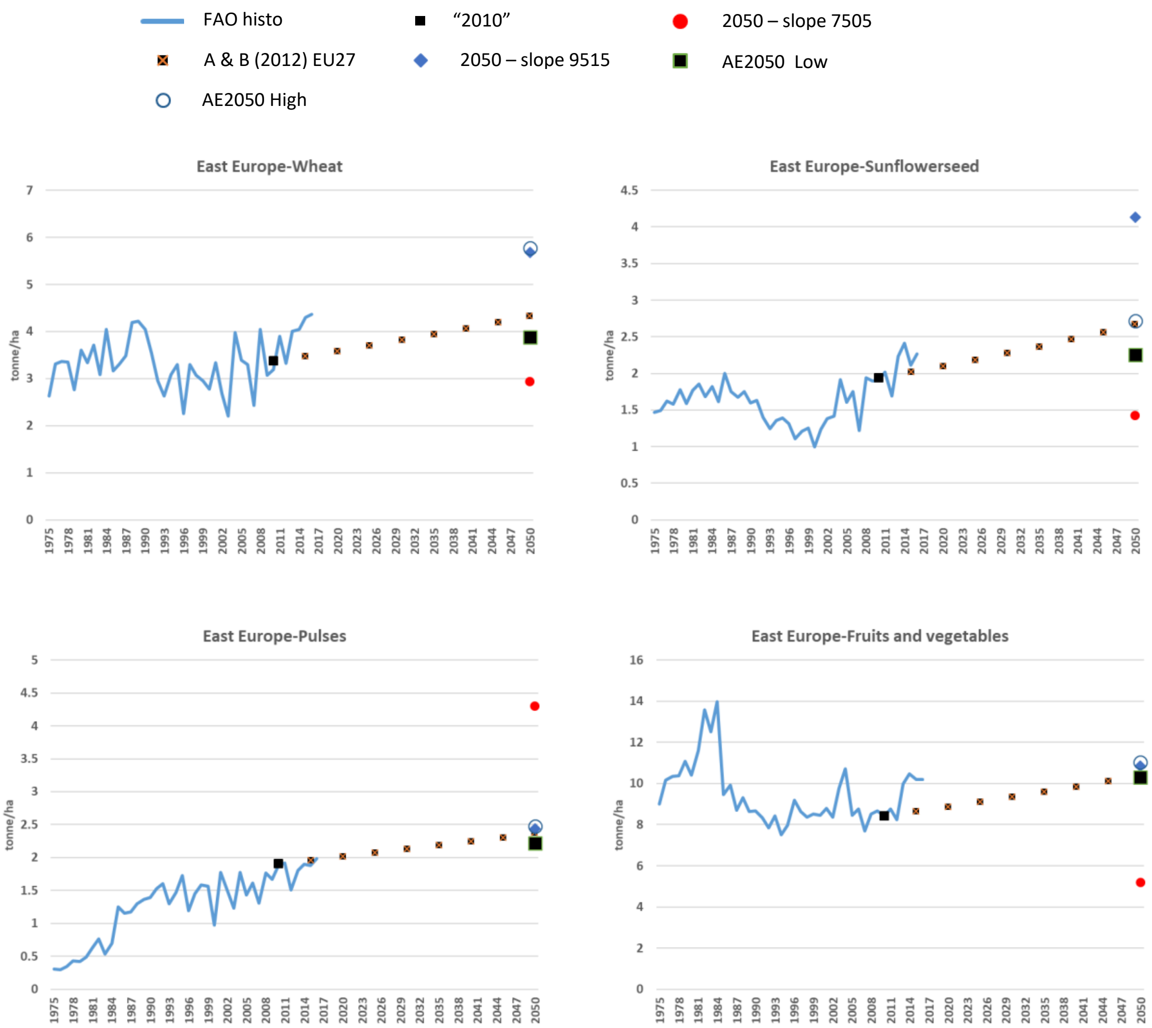

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

Central Europe

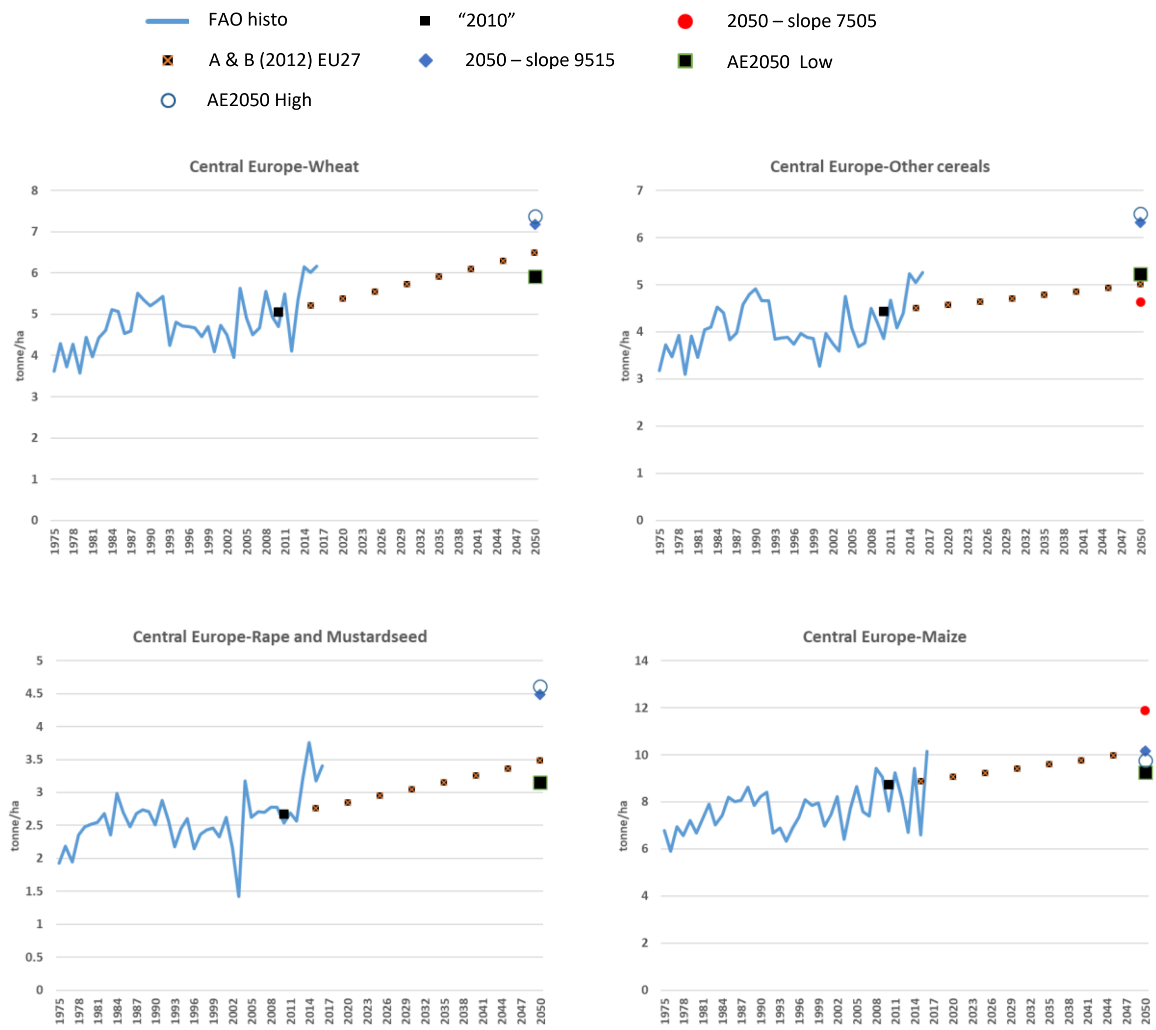

Figure A.5-3 (continued): Crop yield change for various crops in the European sub-regions: 1975-2017 observed change, "2010" base year to 2050 projected change under different assumptions (t/ha)

Rest of Europe

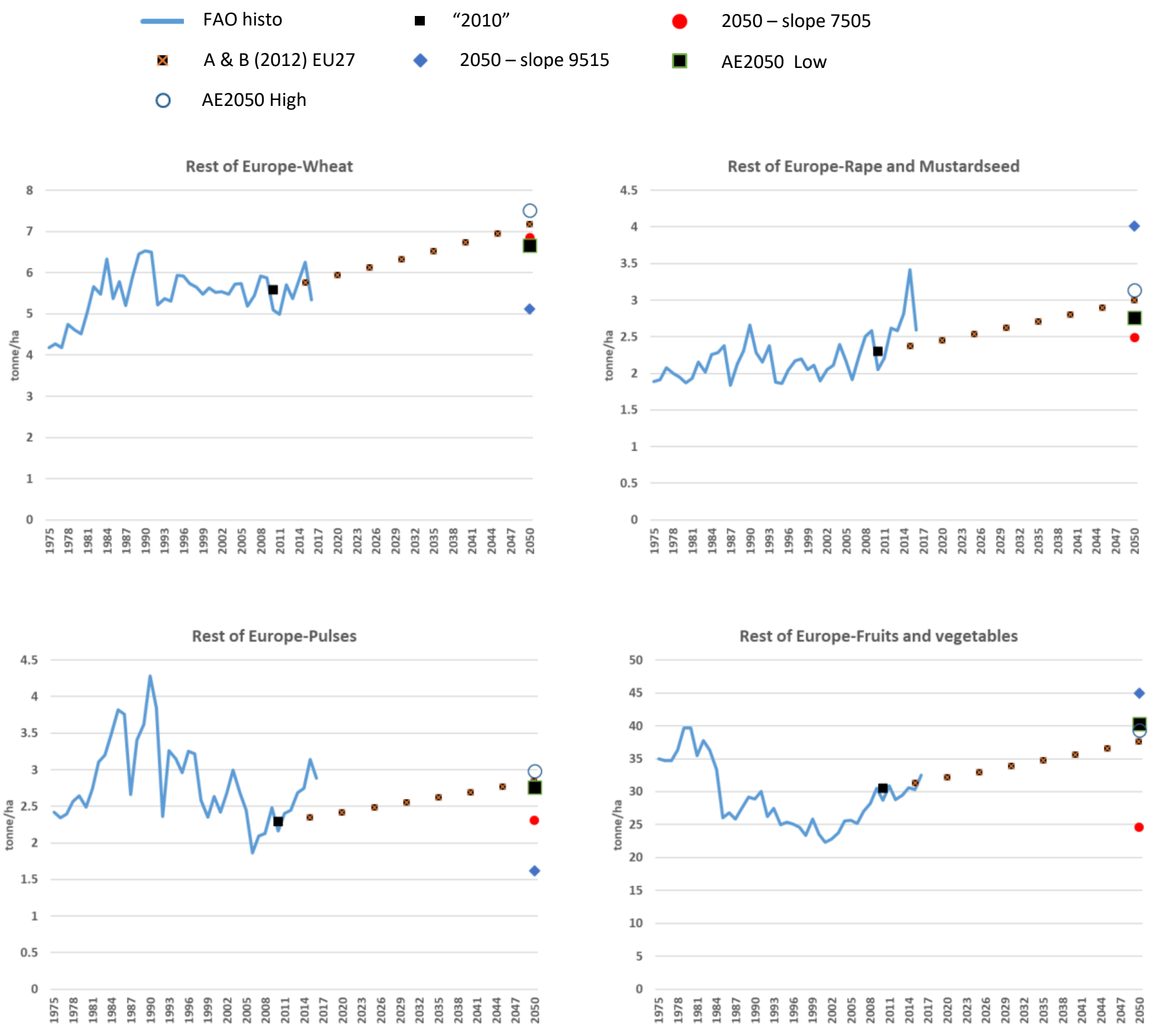

Figure A.5-4: Shares of European harvested area devoted to various crop types in "2010" and in 2050 under the reference scenario and scenarios 1, 2 and 3 (ub yields) (%)

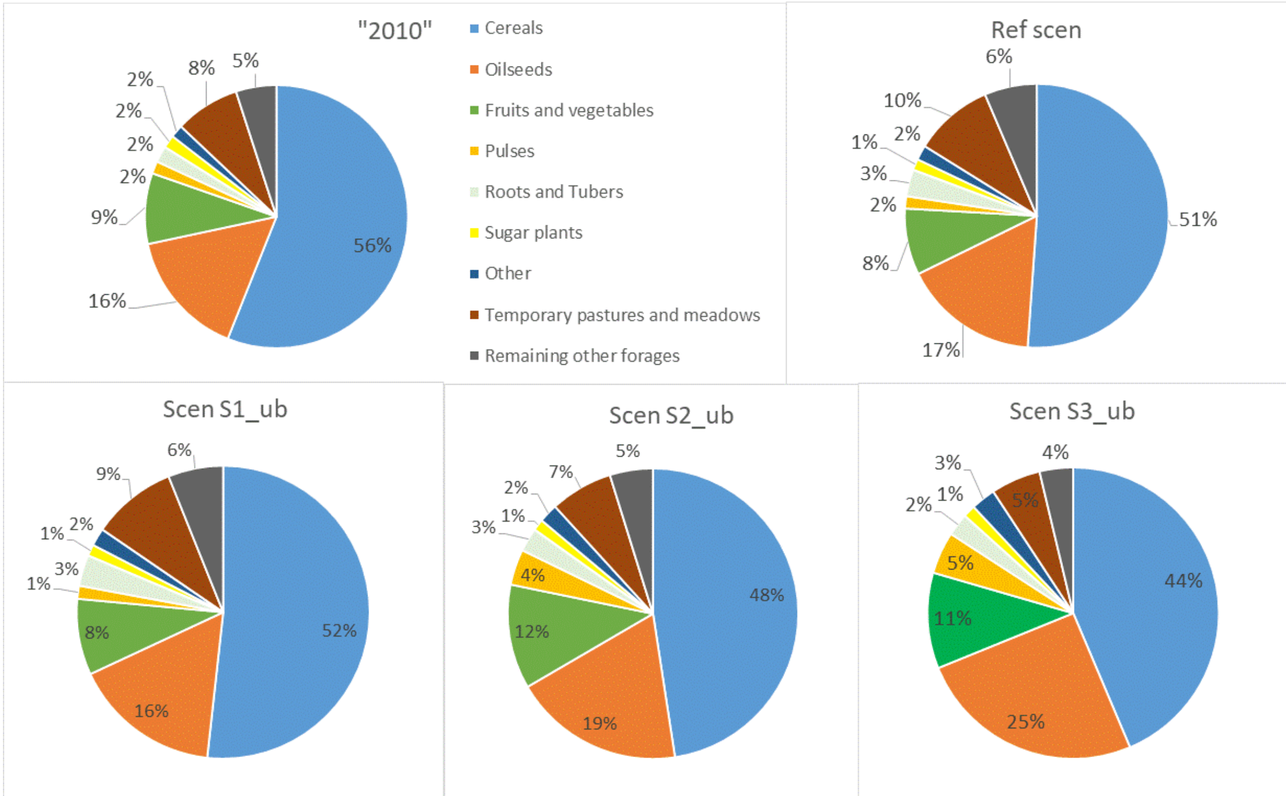

Table A.5-1: Crops yields in "2010" and in 2050 under all scenarios for all crops and all European sub-regions

France

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	6.7	7.8	6.2	6.8	7.1	7.4
Maize	9.3	10.1	8.7	9.6	10.0	10.1
Other cereals	5.9	7.0	5.8	6.4	6.7	7.0
Rice	5.7	6.9	6.1	6.7	6.9	6.9
Soyabeans	2.7	3.5	3.1	3.4	3.5	3.5
Sunflowerseed	2.4	2.9	2.3	2.5	2.7	2.8
Rape and Mustardseed	3.5	4.1	3.4	3.8	4.0	4.1
Other Oilcrops	1.5	1.7	1.5	1.6	1.7	1.7
Other plant products	1.7	2.0	1.8	2.0	2.0	2.0
Fruits and vegetables	12.9	16.0	12.8	14.1	14.8	15.4
Pulses	3.9	4.7	4.0	4.4	4.6	4.7
Roots and Tuber	45.1	53.5	42.5	46.8	48.9	51.0
Sugar plants and products	91.4	108.3	101.3	108.3	108.3	108.3
Fibers etc.	1.2	1.5	1.2	1.4	1.4	1.5
Other forages	8.5	9.3	7.9	8.7	9.1	9.3
Grass-like forage	6.6	7.3	6.3	6.9	7.2	7.3

Germany

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	7.4	8.8	6.9	7.6	8.0	8.3
Maize	9.7	10.5	9.1	10.0	10.4	10.5
Other cereals	5.7	6.8	5.6	6.2	6.5	6.8
Rice	1.5	1.9	1.6	1.8	1.9	1.9
Soyabeans	2.1	2.5	2.0	2.2	2.3	2.4
Sunflowerseed	3.7	4.5	3.7	4.1	4.3	4.4
Rape and Mustardseed	0.9	1.0	0.9	0.9	1.0	1.0
Other Oilcrops	2.6	3.1	2.7	3.0	3.1	3.1
Other plant products	21.0	26.4	21.2	23.3	24.4	25.5
Fruits and vegetables	2.7	3.2	2.8	3.1	3.2	3.2
Pulses	43.3	51.7	41.0	45.1	47.2	49.3
Roots and Tuber	68.7	82.6	77.3	82.6	82.6	82.6
Sugar plants and products	2.4	2.9	2.5	2.7	2.8	2.9
Fibers etc.	5.1	5.9	5.0	5.5	5.8	5.9
Other forages	6.5	7.6	6.5	7.2	7.5	7.6
Grass-like forage	0.0	0.0	0.0	0.0	0.0	0.0

Table A.5-1 (continued): Crops yields in "2010" and in 2050 under all scenarios for all crops and all European sub-regions

United Kingdom

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	7.8	9.2	7.3	8.0	8.4	8.7
Maize	5.7	6.8	5.6	6.2	6.5	6.8
Other cereals	3.6	4.3	3.6	3.9	4.1	4.3
Rice	1.8	2.2	1.8	2.0	2.1	2.2
Soyabeans	21.5	27.0	21.7	23.8	24.9	26.0
Sunflowerseed	3.0	3.5	3.0	3.3	3.5	3.5
Rape and Mustardseed	43.8	52.4	41.6	45.8	47.9	50.0
Other Oilcrops	68.1	81.5	76.2	81.5	81.5	81.5
Other plant products	1.4	1.7	1.4	1.6	1.6	1.7
Fruits and vegetables	7.3	7.8	6.7	7.3	7.6	7.8
Pulses	8.1	8.7	7.5	8.3	8.7	8.7
Roots and Tuber	0.0	0.0	0.0	0.0	0.0	0.0
Sugar plants and products	0.0	0.0	0.0	0.0	0.0	0.0
Fibers etc.	0.0	0.0	0.0	0.0	0.0	0.0
Other forages	0.0	0.0	0.0	0.0	0.0	0.0
Grass-like forage	0.0	0.0	0.0	0.0	0.0	0.0

Poland

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	4.1	4.8	4.1	4.5	4.7	4.8
Maize	6.4	6.8	6.4	6.8	6.8	6.8
Other cereals	3.0	3.5	3.2	3.5	3.5	3.5
Rice	1.5	1.9	1.8	1.9	1.9	1.9
Soyabeans	1.7	2.0	1.8	2.0	2.0	2.0
Sunflowerseed	2.5	3.0	2.7	3.0	3.0	3.0
Rape and Mustardseed	1.1	1.4	1.2	1.4	1.4	1.4
Other Oilcrops	0.5	0.6	0.6	0.6	0.6	0.6
Other plant products	15.2	18.7	16.5	18.1	18.7	18.7
Fruits and vegetables	2.2	2.5	2.4	2.5	2.5	2.5
Pulses	19.1	22.4	19.5	21.5	22.4	22.4
Roots and Tuber	53.3	62.7	64.2	62.7	62.7	62.7
Sugar plants and products	2.1	2.5	2.3	2.5	2.5	2.5
Fibers etc.	5.0	5.7	5.3	5.7	5.7	5.7
Other forages	1.6	1.8	1.7	1.8	1.8	1.8
Grass-like forage	0.0	0.0	0.0	0.0	0.0	0.0

Table A.5-1 (continued): Crops yields in "2010" and in 2050 under all scenarios for all crops and all European sub-regions

South Europe

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	3.4	3.9	3.4	3.7	3.9	3.9
Maize	8.6	9.8	9.4	9.8	9.8	9.8
Other cereals	2.7	3.1	2.8	3.1	3.1	3.1
Rice	6.7	7.5	7.3	7.5	7.5	7.5
Soyabeans	3.2	4.4	4.3	4.4	4.4	4.4
Sunflowerseed	1.4	1.6	1.5	1.6	1.6	1.6
Rape and Mustardseed	2.2	2.5	2.3	2.5	2.5	2.5
Other Oilcrops	2.7	3.1	2.9	3.1	3.1	3.1
Other plant products	0.8	1.1	1.1	1.1	1.1	1.1
Fruits and vegetables	15.0	19.0	17.0	18.7	19.0	19.0
Pulses	1.2	1.5	1.4	1.5	1.5	1.5
Roots and Tuber	22.5	27.2	23.9	26.3	27.2	27.2
Sugar plants and products	65.1	77.5	80.4	77.5	77.5	77.5
Fibers etc.	2.7	3.0	2.9	3.0	3.0	3.0
Other forages	6.0	6.9	6.5	6.9	6.9	6.9
Grass-like forage	4.1	4.8	4.6	4.8	4.8	4.8

East Europe

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	3.4	3.9	3.4	3.7	3.9	3.9
Maize	5.1	5.4	5.1	5.4	5.4	5.4
Other cereals	2.8	3.3	3.0	3.3	3.3	3.3
Rice	5.1	5.6	5.5	5.6	5.6	5.6
Soyabeans	2.5	3.1	3.0	3.1	3.1	3.1
Sunflowerseed	1.9	2.3	2.0	2.2	2.3	2.3
Rape and Mustardseed	1.9	2.3	2.1	2.3	2.3	2.3
Other Oilcrops	0.9	1.1	1.0	1.1	1.1	1.1
Other plant products	1.4	1.6	1.5	1.6	1.6	1.6
Fruits and vegetables	8.4	10.3	9.1	10.0	10.3	10.3
Pulses	1.9	2.2	2.1	2.2	2.2	2.2
Roots and Tuber	14.9	17.4	15.1	16.6	17.4	17.4
Sugar plants and products	47.5	55.1	56.5	55.1	55.1	55.1
Fibers etc.	1.6	2.0	1.8	2.0	2.0	2.0
Other forages	2.7	3.1	2.8	3.1	3.1	3.1
Grass-like forage	1.3	1.4	1.3	1.4	1.4	1.4

Table A.5-1 (continued): Crops yields in "2010" and in 2050 under all scenarios for all crops and all European sub-regions

Central Europe

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	5.1	5.9	5.6	5.9	5.9	5.9
Maize	8.7	9.3	9.6	9.3	9.3	9.3
Other cereals	4.4	5.2	5.2	5.2	5.2	5.2
Rice	2.4	3.0	3.2	3.0	3.0	3.0
Soyabeans	2.3	2.7	2.6	2.7	2.7	2.7
Sunflowerseed	2.7	3.2	3.2	3.2	3.2	3.2
Rape and Mustardseed	0.7	0.8	0.8	0.8	0.8	0.8
Other Oilcrops	2.8	3.3	3.5	3.3	3.3	3.3
Other plant products	15.2	18.8	18.2	18.8	18.8	18.8
Fruits and vegetables	2.3	2.7	2.8	2.7	2.7	2.7
Pulses	29.9	35.3	33.8	35.3	35.3	35.3
Roots and Tuber	66.9	79.0	89.1	79.0	79.0	79.0
Sugar plants and products	3.2	3.8	3.8	3.8	3.8	3.8
Fibers etc.	6.7	7.2	7.4	7.2	7.2	7.2
Other forages	4.3	4.6	4.8	4.6	4.6	4.6
Grass-like forage	0.0	0.0	0.0	0.0	0.0	0.0

Rest of Europe

Crop	"2010"	Ref	S1,2,3_lb	S1_ub	S2_ub	S3_ub
Wheat	5.6	6.7	5.2	5.7	5.9	6.2
Maize	11.2	11.9	10.0	11.0	11.5	11.9
Other cereals	4.0	4.8	3.9	4.3	4.5	4.7
Rice	2.3	2.8	2.2	2.5	2.6	2.7
Soyabeans	1.0	1.2	1.0	1.1	1.2	1.2
Sunflowerseed	1.1	1.3	1.1	1.2	1.3	1.3
Rape and Mustardseed	30.5	40.3	31.7	34.8	36.4	38.0
Other Oilcrops	2.3	2.8	2.3	2.5	2.7	2.8
Other plant products	36.4	44.1	34.3	37.7	39.4	41.1
Fruits and vegetables	67.4	81.1	74.3	81.1	81.1	81.1
Pulses	4.0	4.9	4.0	4.4	4.6	4.8
Roots and Tuber	6.4	7.1	5.9	6.5	6.8	7.1
Sugar plants and products	3.3	3.6	3.1	3.4	3.5	3.6
Fibers etc.	0.0	0.0	0.0	0.0	0.0	0.0
Other forages	0.0	0.0	0.0	0.0	0.0	0.0
Grass-like forage	0.0	0.0	0.0	0.0	0.0	0.0

Table A.5-2: Correspondences between Globagri and EATLancet products

GlobAgri aggregates	EATLancet
Aquatic animal products	Fish
Bovine meat	Beef
Dairy	Milk
Eggs	Eggs
Pork meat	Pork Meat
Poultry meat	Poultry Meat
Small ruminant meat	Lamb
Fibers etc.	Other products
Fruits and vegetables	Fruits + Vegetables
Other plant products	Nuts (Treenuts) + Other crops
Other products	Other calories
Pulses	Legumes
Roots and tuber	Roots
Maize	Maize
Other cereals	Other grains
Rice	Rice
Wheat	Wheat
Sugar plants and products	Sugar
Other oilcrops	Nuts (groundnuts) + Other crops
Oil other oilcrops	Oil_veg
Palm product oil	Oil_Palm
Rape and mustard oil	Oil_veg
Soyabeans	Soyabeans
Soyabean oil	Oil_veg
Sunflower seeds	Other crops
Sunflowerseed oil	Oil_veg

Table A.5-3: Impacts of reduced or no pesticide-use on crop yields in Europe: What does the existing literature tell us?

	Current pesticide-use – actual yield loss	No pesticide-use – unchanged cropping systems	50% reduced pesticide-use – marginally adjusted cropping systems	Nearly no pesticide-use – adjusted cropping systems	Organic
Cereals					
Europe			-10%[h]	-20%[a]	
Germany (1929)					
Wheat					
World average	-28%[a]; -21%[b]	-50%[a]			-27%[i]
Europe	-22%[b]		-6%[g]		
France				-10%[c]; [-20;-40%][d]; [-20;-30%][e]	-23%[i]
Switzerland				-21-26%[f]	
Maize					
World average	-31%[a]; -22%[b]	-68.5%[a]			-11%[i]
Europe	-22%[b]		-2%[g]		
France				-10%[c]	-19%[i]
Rice					
World average	-37%[a]; -30%[b]	-77%[a]			-6%[i]
Europe	-30%[b]				
France					-14%[i]
Protein-rich crops					
Europe			-10%[h]		
Soyabean					
World average	-26%[a]; -21%[b]	-60%[a]			-8%[i]
Europe	-20%[b]				
Rapeseed					
Europe			-8%[g]		
France				-19%[c]; [-10;-20%][d]	
Pulses					
France				-4%[c]	

Table A.5-3 (continued): Impacts of reduced or no pesticide-use on crop yields in Europe: What does the existing literature tell us?

	Current pesticide-use – actual yield loss	No pesticide-use – unchanged cropping systems	50% reduced pesticide-use – marginally adjusted cropping systems	Nearly no pesticide-use – adjusted cropping systems	Organic
Roots and tuber					
Europe			-10%[h]		-26%[i]
Potatoes					
World average	-40%[a]; -17%[b]	-75%[a]			-30%[i]
Europe	-17%[b]				-30%[i]
Germany (1929)				-30%[a]	
France				-19%[c]	-36%[i]
Sugar beet					
Europe			-12%[g]; -10%[h]		
Germany (1929)				-15%[a]	
France				-9%[c]; 0%[d]	-4%[i]
Fruits and vegetable					
Europe			[-15;-20%][g]; -10%[h]		[-20;-40%][i]
France				-20-40%[c]	-31%[i]
All products					
World average					-20%[i] -25%; -13% (best organic management practices)[j] -19%[k]

(a) Oerke *et al.* (2006); (b) Savary *et al.* (2019); (c) Bultault *et al.* (2009); (d) Cellier *et al.* (2018); (e) Hossard *et al.* (2014); (f) Möhring and Finger (2022); (g) Bremmer *et al.* (2021); (h) Barreiro-Hurle *et al.* (2021); (i) De Ponti *et al.* (2012); (j) Seufert *et al.* (2012); (k) Ponisio *et al.* (2015)

Table A.5-4: Regional land-use change emissions under the reference scenario (carbon stock in forest biomass (CVeg) = minimum values)

	Emissions from soil	Emission from biomass	Total emissions		Agricultural area	Pasture	Cropland	of which annual crops	of which oilpalm	of which sugarcane	Shrubland	Forests
Regions	Mt C	Mt C	Mt C	Mt CO_2	Mha	Mha	Mha	Mha	Mha	Mha	Mha	Mha
FR	0	1	1	5	1.091	1.091	-0.000	-0.000	0.000	0.000	-0.973	-0.118
GER	0	6	6	22	0.975	0.975	0.000	0.000	0.000	0.000	-0.058	-0.917
UK	0	0	0	1	0.504	0.504	-0.000	-0.000	0.000	0.000	-0.504	0.000
POL	0	0	0	-1	-0.259	-0.259	0.000	0.000	0.000	0.000	0.259	0.000
SEUR	0	-73	-73	-269	-2.577	-2.577	0.000	0.000	0.000	0.000	2.577	0.000
EEUR	0	3	3	11	1.115	1.115	0.000	0.000	0.000	0.000	-0.112	-1.003
CEUR	0	0	0	0	0.100	0.100	0.000	0.000	0.000	0.000	-0.100	0.000
REU	0	1	1	3	1.266	1.266	0.000	0.000	0.000	0.000	-1.266	0.000
CANUS	1 490	3 672	5 162	18 929	160.829	90.423	70.406	70.365	0.000	0.041	-160.829	0.000
BRAR	434	4 715	5 149	18 879	101.659	82.562	19.096	17.035	0.180	1.882	-101.659	0.000
ROAM	199	3 635	3 835	14 062	80.904	71.102	9.802	8.132	0.773	0.897	-80.904	0.000
FSU	-568	-257	-825	-3 026	-74.331	-48.945	-25.385	-25.385	0.000	0.000	74.331	0.000
CHN	135	1 350	1 484	5 443	66.132	59.476	6.657	6.696	0.068	-0.107	-46.712	-19.421
IND	156	965	1 121	4 112	29.002	19.610	9.393	9.300	0.000	0.093	-21.109	-7.894
ROAS	-534	758	224	822	37.145	53.422	-16.277	-21.699	5.321	0.101	-37.145	0.000
NME	-260	-644	-904	-3 316	-16.127	-0.102	-16.024	-15.916	0.000	-0.108	16.127	0.000
NAF	-104	-439	-543	-1 993	-9.791	6.035	-15.825	-15.735	0.000	-0.090	9.791	0.000
WAF	585	1 818	2 403	8 810	43.429	11.869	31.560	29.964	1.703	-0.107	-43.429	0.000
ECSA	2 101	12 480	14 582	53 466	301.065	198.430	102.634	101.334	0.263	1.038	-301.065	0.000
OCE	282	2 238	2 520	9 239	110.773	90.447	20.326	20.017	0.113	0.195	-22.942	-87.831
ROW	-7	-3	-10	-36	-0.852	-0.563	-0.289	-0.289	0.000	0.000	0.852	0.000
Total	3 909	30 226	34 136	125 164	832.052	635.979	196.072	183.817	8.423	3.833	-714.868	-117.184

Table A.5-5: Land-use change emissions from soil and biomass (cumulated and per year) under the reference scenario and scenarios 1, 2 and 3 (lb yields – panel a, ub yields – panel b) (Mt CO2 eq), according to different carbon stock values for forest biomass

Panel a) lower-bound yields

MINIMUM values		Ref	S1	S2	S3
World	total cumulated Mt CO_2 eq	125 164	133 348	124 523	112 054
	amortized on 40 years Mt CO_2 eq/an	3 129	3 334	3 113	**2 801**
EUROPE	total cumulated Mt CO_2 eq	-227	-351	-690	-1 731
	amortized on 40 years Mt CO_2 eq/an	-6	-9	-17	-43
AVERAGE values		**Ref**	**S1**	**S2**	**S3**
World	total cumulated Mt CO_2 eq	143 002	151 626	142 483	129 338
	amortized on 40 years Mt CO_2 eq/an	3 575	3 791	3 562	**3 233**
EUROPE	total cumulated Mt CO_2 eq	-4	-345	-654	-1 731
	amortized on 40 years Mt CO_2 eq/an	0	-9	-16	-43
MAX values		**Ref**	**S1**	**S2**	**S3**
World	total cumulated Mt CO_2 eq	160 839	169 904	160 443	146 622
	amortized on 40 years Mt CO_2 eq/an	4 021	4 248	4 011	**3 666**
EUROPE	total cumulated Mt CO_2 eq	218	-338	-617	-1 731
	amortized on 40 years Mt CO_2 eq/an	5	-8	-15	-43

Panel b) upper-bound yields

MINIMUM values		S1	S2	S3
World	total cumulated Mt CO_2 eq	127 002	117 778	109 447
	amortized on 40 years Mt CO_2 eq/an	3 175	2 944	**2 736**
EUROPE	total cumulated Mt CO_2 eq	-195	-583	-1 965
	amortized on 40 years Mt CO_2 eq/an	-5	-15	-49
AVERAGE values		**S1**	**S2**	**S3**
World	total cumulated Mt CO_2 eq	145 514	136 290	123 212
	amortized on 40 years Mt CO_2 eq/an	3 638	3 407	**3 080**
EUROPE	total cumulated Mt CO_2 eq	4	-400	-1 965
	amortized on 40 years Mt CO_2 eq/an	0	-10	-49
MAX values		**S1**	**S2**	**S3**
World	total cumulated Mt CO_2 eq	164 025	154 802	136 976
	amortized on 40 years Mt CO_2 eq/an	4 101	3 870	**3 424**
EUROPE	total cumulated Mt CO_2 eq	203	-218	-1 965
	amortized on 40 years Mt CO_2 eq/an	5	-5	-49

European Chemical Pesticide-Free Agriculture in 2050

Chapter 6

Insights from the foresight study

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Table of contents

Introduction

In this Chapter, we present the main insights from the foresight study resulting from two years of work within the European expert committee and thematic expert groups. We first draw up an analysis of the Strengths, Weaknesses, Opportunities and Threats (SWOT) of the three scenarios, in order to highlight their main characteristics, advantages and drawbacks.

We then focus on the chemical pesticide-free cropping systems, providing a transversal analysis of these cropping systems in 2050, their resilience to climate change, and identifying research needs to achieve efficient crop protection without chemical pesticides by 2050. Afterwards, we present the learnings from the quantification of the impacts of the three scenarios (see Chapter 5) on land use, production, trade and greenhouse gas emissions.

Then, we discuss the three transition pathways towards European chemical pesticide-free agriculture by 2050 presented in Section 4.1, and propose robust elements that would constitute necessary milestones and actions for a transition pathway common to all three scenarios.

We close this Chapter by summarising the ten key messages from this foresight study.

6.1. Strengths, weaknesses, opportunities and threats of the scenarios of chemical pesticide-free agriculture

Members of the European expert committee of the foresight carried out a SWOT analysis of the three scenarios, to identify internal and external factors that define their main advantages (internally – strengths, and externally – opportunities) and the obstacles to overcome (internally – weaknesses, and externally – threats). Table 6-1 lists the SWOT for each scenario, which are summarised below.

The main strength of **Scenario 1** is that it sets a global pesticide-free food market, meaning that **the same goal is shared and implemented across Europe.** The main technologies, digital, knowledge, infrastructures for data needed for this scenario are partly already available or under development, and the global firms are already in place. The implementation of the scenario **does not involve ruptures** in consumers' diet and in food systems organisation. It does however require **major developments in technologies**, including digital technologies, agricultural equipment, infrastructures for data management, in line with current innovation policies implemented across Europe. Its major weaknesses are that it could **reduce the public control** over the food system, and that it will **require strong investments** by farmers to acquire these technologies, who may face difficulties to mobilise enough capital or increase the volume of specific investments. It also raises the issue of the **ownership of data and of capital** by private companies, and on the **dependence of this technological pathway on resources** (especially energy and raw materials). For these reasons, this scenario is likely to be **highly sensitive to crises**: energetic, economical, geopolitical, and climatic. Overall, scenario 1 may lead to **fewer farmers** in Europe managing larger farms, and therefore less interaction with local communities.

Scenario 2 relies on microbiome management. It is a strength as this is currently a **very dynamic topic** in terms of research and education. It is also a topic of **interest for the public**, because of the relationships between microbiomes and human health, healthy food and healthy diets, with the potential to develop new markets. Another strength of this scenario is the inclusion of **soil health**, which is key for sustainability. There is an opportunity to develop scenario 2 as it adopts a **holistic approach**, in line with recent and potential orientations for future public policies (the Farm To Fork strategy from the European Green Deal and the Sustainable food systems framework), and an approach promoted by several scientists and organisations. The main challenge of the scenario is that, although very dynamic, this **scientific area and related knowledge are still limited**, especially on the continuum of microbiomes from the Farm to Fork, from the field to the plates. As a consequence, it would require **time and resources** to acquire the necessary knowledge and propose innovative solutions by 2050. Also, in this scenario, **cooperative systems** could not be ready and not committed to play a central role in the transition towards the holobiont paradigm. Although scenario 2 is based mainly on modulating microbiomes through agricultural practices, choice of crops and organic amendments, it could be interpreted as relying much upon bio-inputs, namely biocontrol and biostimulants solutions such as micro-organisms, ending up creating **a new dependency on this new type of inputs**, instead of allowing a redesign of cropping systems and plant protection strategies.

Scenario 3 meets strong **expectations from the civil society on environmental health** protection. Another strength of this scenario is that it **strongly promotes agroecological** principles that are **developing significantly** in Europe, both in terms of scientific knowledge and practices if we consider for example the constant development of organic agriculture. In addition, the current external context, the increasing costs of energy and on inputs prices are favouring **low inputs systems based on biological regulations.** Scenario 3 aims to relocate food systems by decoupling them from global food markets. The scenario shows great potential in **contributing to tackling the challenges of climate change: achieving GHG emissions reduction targets and carbon neutrality**. It also shows potential for

preserving human and ecosystem health including biodiversity restoration. It is in line with recent EU policy development (Sustainable Use of pesticides Regulation proposal, EU Green Deal, Nature Restauration Law). One of the main challenges with scenario 3 is that it requires strong and multi-actor coordination between farmers and diverse stakeholders within a territory for designing and managing landscape **complexity, at different levels**. It also requires actors such as **farmers and policy-makers** to think and implement **long-term and large-scale actions.** Finally, the scenario requires farmers to reverse their specialisation, to implement de-specialisation and to **manage different tasks and activities** (linked to crop diversification, management of semi-natural habitats, etc.). For these reasons notably, this scenario requires **collective learning** and **support of farmers** and food value chain in their transition. There may be **regional differences** in countries' capacities to invest and support this transition. The scenario is also highly **dependent on consumers' willingness to change their diet.**

Table 6-1: Strengths, weaknesses, opportunities and threats of the scenarios of European chemical pesticide-free agriculture

SCENARIO	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
SCENARIO 1 Global market	- Corresponds to a global development around the same goal (a pesticide-free food market); - Requires technologies, digital tools, infrastructures for data that are, for some of them, already available or under development; - Is a continuity of the mainstream food value chain model with global firms; - Does not require big changes in consumer's diets.	- Would lead to a reduction in public control over the food system; - There is limited evidence of the capacity of digital technologies to support pesticide-free systems currently; - Would create a dependence on few ecosystems that could be under pressure; - Would require strong mobilisation of capital by farmers; - Would lead to private ownership of data; - Would reduce direct interactions of farmers with biological entities (animal, vegetal) and local communities.	- Is aligned with decision makers' current vision of scientific progress; - Is in coherence with the French strategic plan and priorities (digital, robots, data, genetics); - Is an opportunity for external investors; - Takes into account the health of the plant.	- Would be highly sensitive to crises: economical, geopolitical; - Would favour the dehumanisation of agriculture (robots), could accelerate the disappearance of farmers; - Would create dependence on scarce resources, on biodiversity; - What if investor will not be interested?
SCENARIO 2 Healthy microbiomes	- Corresponds to an increased education on microbial processes, microbiome management; - Relies on soil health which is key for sustainability.	- As currently there is a lack of knowledge on microbiomes from soil to fork, there could be not enough time to acquire knowledge and/or not enough resources for research on microbial and holobiont; - The cooperative system could not be ready to lead the transition in this scenario; - Could be perceived as a substitution approach to replace pesticides by bioinputs, and therefore could create a dependence to other inputs; - Could be difficult to understand for the general public (requires investments in education).	- There is a strong interest from the general public for microbiomes and human health, healthy food, healthy diets; - Represents an opportunity for product innovations; - Receives support from decision makers (seen as scientific progress); - Could open or develop new markets; - Is in line with EU Green Deal and its holistic approach.	- How crop protection could work for plants without mycorrhizas? - The use of machinery could negatively affect soils; - Concerns about microbes and sanitarianism could limit the acceptability of the scenario; - The processing food supply chain could be reluctant to change; - Could prove difficult to implement the holobiont paradigm; - Contamination of soils could threaten the implementation of the scenario.

Table 6-1 (continued): Strengths, weaknesses, opportunities and threats of the scenarios of European chemical pesticide-free agriculture

SCENARIO	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
SCENARIO 3 Embedded landscapes	- Relies on agroecology principles, that are increasingly popular, promoting a sustainable, participatory and systemic approach; - Answers civil society expectations on environmental health (European citizen petition « saving bees and farmers » gathered more than 1 million signatures); - Benefits from numerous scientific developments and knowledge	- Would require strong coordination between farmers and support from society - Many farmers are still dependent on chemical pesticides - Could be limited by stakeholders' resistance to change - Would go in the opposite direction as the current trends of specialisation and increased size of farms - Would require training to manage complexity and adaptability - Would require multi-tasking for farmers (linked to crop protection monitoring, crop diversification, or management of semi-natural habitats); - Would require long-term and large scale planning from farmers and from policy-makers	- Agroecology show potentials in reducing GHG emissions, preserving human health, animal welfare, developing resilience of food systems to climate change; - The limits of agrochemicals efficacy; increase of energy costs and geopolitical situation could accelerate the transition towards this scenario; - Is in line with recent European policies and regulatory proposals (Sustainable Use of Pesticide Regulation [SUR], Green Deal, Nature Restoration Law); - The adaptability of local food systems could facilitate the transition; - Is consistent with an increasing decoupling from global food market	- Consumer's resistance to change their diets; - Companies lobbying; - Preconceived ideas that yields would decrease; - Lack of real-world evidence of success in agroecology; - Regional differences in financial capabilities to invest in the transition; - Competition between regions; - Lack of policy incentives.

6.2. A transversal analysis of the cropping systems in the scenarios

The foresight study gives us some specific information about pesticide-free cropping systems that we summarise below, by presenting a comparative analysis of cropping systems in the three scenarios, by assessing the resilience of these cropping systems to climate change, and by presenting the research needs to achieve chemical pesticide-free efficient crop protection in 2050.

6.2.1. A comparison of the chemical pesticide-free cropping systems in the three scenarios in terms of various intensity gradients

The complementarity of crop protection hypotheses in each scenario must be considered according to the cropping system and the food value chain in which it is embedded. It will determine the characteristics of pest monitoring and varietal selection, considering the local context.

Cropping systems in 2050 can be characterised along diverse intensity gradients in terms of use of exogenous inputs (such as biocontrol products, plant defence stimulators, and fertilisers), the mobilisation of ecosystem services, as well as the level of temporal and spatial diversification (Figure 6-1). In all three scenarios, there will be a reduction in the use of mineral fertilisers and irrigation in order to reduce pest pressure.

Figure 6-1: Intensity gradients for the cropping systems in each scenario

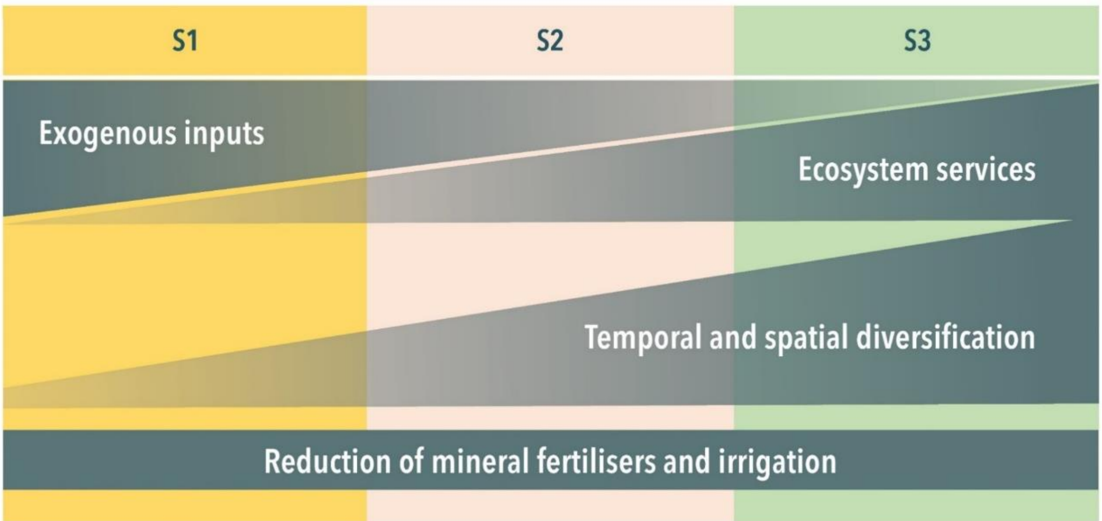


Figure 6-1 shows two opposite logics of intensification of cropping systems. On one end, in scenario 1 (S1), cropping systems have a higher level of exogenous inputs and a lower level of crop diversification and ecosystem services. On the other end, in scenario 3 (S3), cropping systems mobilise less exogenous inputs, and rely on a high level of diversification and ecosystem services.

How do the pesticide-free cropping systems in 2050 differ from organic cropping systems?

Principles of organic farming, which by definition exclude the use of synthetic pesticides, provides real-world insights and practices that have helped to shape the different pesticide-free scenarios, and specifically the practices of temporal and spatial diversification of crops.

However, organic farming includes, in addition to constraints on the use of pesticides, other criteria such as organic fertilisation only that are not included in this study. Our pesticide-free cropping systems can mobilise mineral fertilisers as long as it is coherent with the crop protection principles applied in the scenario.

6.2.2. The three cropping systems of the scenarios, and their resilience to climate change

As shown in Section 2.4, most studies point out that **the pest risk from insects, pathogens and weeds will increase in cropping systems under climate change**, especially in the currently coldest areas, and also in temperate and subtropical regions. The data show that all climates and ecosystems will be impacted. They will be affected not only by changes in average bioclimatic conditions (particularly temperature and CO_2 concentration), which are predictable and have been on a trend for several decades, but also by the increasingly frequent occurrence of extreme events and climatic hazards that are currently unpredictable and make local and regional forecasts of the various climatic factors highly uncertain. As a result, the nature and extent of the impact of climate change on pests and their interactions with host crops will vary according to the capacity of production systems and natural ecosystems to adapt. Further research is needed on the biophysical effects of climate change on pests and their interactions with crops.

Given the complexity of cropping systems, and more broadly of socio-ecosystems, it also seems essential to **focus efforts on strengthening the resilience of these systems in the context of climate change,** and more broadly of global change, with in particular organisational transformations at the territory level. Compromises will have to be made between the different facets of resilience, between strengthening the robustness of current systems and transforming them into territory systems and organisations better adapted to future climates and more resilient to variations, or between the different levels at which resilience can be applied, for example strengthening the robustness of a value chain by forcing the adaptation or transformation of its actors.

Climate change is already forcing changes in plant protection strategies, and this trend is set to increase. Climate-smart pest management requires holistic approaches at farm, landscape and territory levels, and heavily relies on the use of crop protection methods that enhance mitigation and strengthen resilience, of which preventive plant protection measures are key factors. Surveillance and monitoring activities of plant health and environmental factors at national, regional and international levels are essential and need to be strengthened to develop preventive measures and control plant health threats.

The elements presented on the one hand on the effects of climate change on pests and interactions between pests and host crops, as well as on the resilience of cropping systems (see 2.4.2), and on the other hand on crop protection strategies (see Sections 2.5 and 2.6) makes it possible to **identify, for each of the three scenarios of this foresight study, the main factors of robustness and adaptability of cropping systems,** and more broadly of production systems, to pest risks in a context of climate change (Table 6-2).

Table 6-2: Main factors of robustness and adaptability of cropping (and production) systems in the three scenarios (S1, S2, S3)

For each scenario, the first row presents factors directly related to the Cropping System (CS) and the second row presents factors corresponding to the other components (O) which are related to the cropping system in the scenario.

		Robustness	Adaptability
S1	CS	- Plant breeding to produce crops (including species associations and/or varietal mixtures) that are more tolerant/resistant to stresses and shocks	- Exogenous supply of biocontrol, plant defence stimulants, microbial communities to plants and soil
	O	- Integration of the whole value chain to enable risk sharing due to yield losses	- Generalisation of monitoring and forecasting systems to adapt permanently - Use of adapted agricultural equipment to intervene locally and rapidly
S2	CS	- Strengthened biological diversity of microbiomes and their functional diversity, to promote the recruitment of functional microorganisms by the cultivated plant in the face of biotic and abiotic disturbances - Suppression of soil pathogens by rhizosphere microorganisms - Plant breeding to enhance beneficial interactions between plants and microorganisms, and co-evolutionary processes	- Adaptation of cultural practices to modulate microbiome structures and functions locally and temporally - Local and temporal adaptation by exogenous or endogenous supply of microbial inputs
	O	- Regional organisation of agricultural sectors - Training of agricultural actors, including cooperatives	- Diagnosis and management of the soil microbiome - Regional organisation of agricultural sectors - Training of agricultural actors, including cooperatives - Adaptation of production processes and conservation of microbiomes
S3	CS	- Increase of functional diversity and redundancy in landscapes (spatial and temporal diversity, complexity, connectivity) to support biological regulation services, and stabilise production in response to stresses and shocks - Plant breeding adapted to diversification and to local soil and climate conditions - Changes in cropping practices and landscape to create discontinuities for pests and continuities for beneficial	- Exogenous supply of adapted varieties for the species, newly cultivated in the process of crop diversification - Temporal change of crop mosaics and cropping practices according to anticipated risks - Anticipation of stresses and shocks through monitoring systems (pests, plants, weather)
	O	- Intra- and inter-territorial coordination to exchange information, share experiences, diversify landscapes, etc. - Training of actors in the agricultural sector - Co-creation of knowledge and practices between local actors (including farmers)	- Intra- and inter-territorial coordination to exchange data and intervene locally and rapidly - Training of agricultural actors

6.2.3. Research needs to achieve chemical pesticide-free efficient crop protection by 2050

The three hypotheses of crop protection without chemical pesticides in 2050 – Designing complex and diversified landscapes adapted to local contexts and their evolution, Managing the holobiont by strengthening host-microbiota interactions, and Strengthening the immunity of cultivated plants – were drawn according to current knowledge, ongoing research programs and future perspectives. For each of these disruptive hypotheses (see Section 2.6), we evaluated the existing knowledge and techniques, and identified research gaps, by working with researchers involved in projects funded by the French Priority Research Program 'Growing and Protecting crops Differently'[1]. During a one-day workshop, experts assessed the chemical pesticide-free crop protection hypotheses against current knowledge and research needs. The summary of the workshop outcomes is presented in Table 6-3.

Research needs for the crop protection hypothesis 'Strengthening the immunity of cultivated plants'

The experts highlighted that, in this crop protection hypothesis, the existing knowledge on molecular mechanisms of action and on partial resistance to pests made it possible to develop solutions such as plant defence stimulants, service plants (such as companion crops, intercrops, living or dead mulches), or UV-C flashes.

Future research should complete this current knowledge in particular on the interactions between the various levers to stimulate plant immunity, also on the identification of the plant immunity markers, and on the mapping of resistance genes to main pests on a broader range of plant species.

Research needs for the crop protection hypothesis 'Managing the holobiont by strengthening host-microbiota interactions'

This crop protection hypothesis is supported by existing knowledge on mycorrhization and tools for assessment of the genetic diversity of microorganisms and their detection.

However, it requires developing knowledge to better understand, at first, the link between a specific microbial community structure and its functional traits, but also to identify the microbial communities of relevance for the different crops and their dynamics. This crop protection hypothesis also calls for the creation of a tool for monitoring the microbiome, and the identification of the ways to modulate the soil microorganisms.

Research needs for the crop protection hypothesis 'Designing complex and diversified landscapes adapted to local contexts and their changes'

To support this hypothesis, a vast corpus of knowledge already exists on the principles and mechanisms related to diversification, landscape design, at field and territory levels. Furthermore, several research projects are ongoing to understand how to implement these mechanisms.

Detection tools (such as sensors) and modelling tools (including artificial intelligence) for anticipating the quantitative impacts of pests on crops are needed, as well as working out solutions for perennial plants.

The experts considered that, in addition to research needs for chemical pesticide-free crop protection by 2050, further research regarding changes in cropping systems and in the farm structures, collective action, public policies, regulatory frameworks, and adaptation of the food value chain would be required. This complementary work will be conducted as part of a European project in 2024-2025.

[1] https://www6.inrae.fr/cultiver-proteger-autrement_eng/

Table 6-3: Summary of current scientific knowledge and techniques available, and knowledge gaps for each of the hypotheses of crop protection without chemical pesticides, identified by the group of experts from the priority research program 'Growing and Protecting crops Differently'

Hypothesis of crop protection	Strengthening the immunity of cultivated plants	Managing the holobiont by strengthening host-microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their changes
Scientific knowledge already available	- A great deal is known about the **molecular mechanisms of action** of plant defence substances; - We also have good knowledge about the **mechanisms of partial resistance** to pests and diseases.	- The link between the structure of a microbial community and the function performed by that community is known in relation to **mycorrhization and the nitrogen cycle** (functional groups capable of carrying out nitrification and denitrification); - We have tools to measure **microbiological diversity** (barcoding techniques, metagenomics); - We can **detect microorganisms** in various compartments (water, soil, air).	- We have very good knowledge about the **principles and mechanisms involved in diversification**, landscape design, at plot, landscape and regional levels; - We have models for **genome wide association** study (GWAS); - **Eco-physiological models** are available to study the interaction mechanisms between plants and the environment.
Technical solutions already available, or under test	- The introduction of **service plants**, particularly in horticulture, or against nematodes in forage sorghum; - External supply of plant defence substances (PDS); - Use of **UV-C flashes** (start-up company has trials on strawberry and wine); - Some interactions between levers stimulating plant immunity, for example between SDPs and QTLs (quantitative trait loci).	- **Tools to detect microorganisms, isolate and cultivate** are available; - Available techniques for local amplification and reimplantation of micro-organisms; - **Commercial mixtures of living micro-organisms**, for example mixture of fungi (Rhyzopus) and Streptomycetes, Bacillus, etc.; these are sold as biostimulants, but can also exert a phytoprotective effect (registration issues); - Techniques to produce **synthetic microbial communities** are being tested (SynCom). Some companies are working on formulating these SynCom.	- Tools to shorten production time for perennial plants, especially for wine production (grafting); - Workshops to co-design **ideotypes** or **mixtures**; - Decision Support tools on the design of **plant mixes**; - Tools that can be used in **breeding to favour diversification** (molecular marker); - Coordination of upstream sector at landscape level to commercialise products from crop diversification (ex. coupled innovation for mixed cropping); - Lot of studies on crop diversification (rotation, mixed crops) but few on landscape design (see below).

Table 6-3 (continued): Summary of current scientific knowledge and techniques available, and knowledge gaps for each of the hypotheses of crop protection without chemical pesticides, identified by the group of experts from the priority research program 'Growing and Protecting crops Differently'

Hypothesis of crop protection	Strengthening the immunity of cultivated plants	Managing the holobiont by strengthening host-microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their changes
Knowledge gaps	- Increase our knowledge of the **interactions between various levers stimulating plant immunity**, in particular the additive or antagonistic effects; - Establish a **mapping of resistance** genes to main pests; - Identify **markers of plant immunity**; - Workout the **acceptability of solutions such as Plant Defence Stimulants** (PDS) for users and the society (co-construction through living labs?).	- Understand the **link between the structure of a microbial community and the function performed by that community**; - Build up tools to **monitor soil microorganisms over time and space**; - Understand the **impact of inoculations** on the environment and on the following crop in the crop succession; - Understand the **microbial communities that are of importance for different crops**; - Identify the **good combinations of microorganisms** to inoculate, without antagonistic effects; - Study relationship between microbial communities and crops at national level; - Map **soil microbiomes and their dynamic**.	- **Quantify the effects of crops diversification and landscape design** to convince farmers; - Understand **mechanisms of interactions plants-plants / traits and associated genes**; - Develop ways of **managing the production of different types of crops on the same plot**, in terms of cultivation practices and also from a socio-technical point of view, with an integrated vision at plot and landscape level; - Identify **solutions for orchards**; - Better understand the **changes in the farm governance model**, its financing modes, decision-making rules, etc.; - Understanding how to get the different players in a given landscape to work together - Understand **how to organise the transition among actors**, local policy makers, consumers' changes, etc.
Examples of ongoing research programs	CapZeroPhyto https://www6.inrae.fr/cultiver-proteger-autrement_eng/Projects/CAPZEROPHYTO INVITE https://www.h2020-invite.eu/ Bioschamp - Biostimulant alternative casing for a sustainable and profitable mushroom industry: https://bioschamp.eu/	DEEP IMPACT (experiments of relationship between microbial communities and crops on wheat and rapeseed) https://www6.inrae.fr/cultiver-proteger-autrement_eng/Projects/DEEP-IMPACT Metaprogram HOLOFLUX - Holobionts and microbial flux within agrifood systems https://www6.inrae.fr/holoflux_eng/ CIRCLES - unlocking the potential of microbiomes for sustainable food production https://circlesproject.eu/about-circles/	BE-CREATIVE (on landscape diversification), MOBIDIV (network of experiments), SPECIFICS, VITAE https://www6.inrae.fr/cultiver-proteger-autrement_eng/Programme . Horizon Europe projects: DiverIMPACTS, Diverfarming, TRUE, LegValue, ReMIX, DIVERSify grouped within the Crop Diversification Cluster: https://www.cropdiversification.eu/

6.3. Insights from the simulations of the scenario impacts on European agricultural production and trade, land-use change and greenhouse gas emissions

Based on the simulations of the scenario impacts presented in Chapter 5, we propose below a comparative assessment of the three scenarios, with their main takeaways**.**

Scenarios have contrasting impacts on European agricultural production. Compared with 2010, European domestic production in calories varies from -5% to +12% in 2050, depending on scenarios and retained hypotheses on crop yields (lower-bound - lb - or upper-bound - ub - yields).

Furthermore, production patterns differ from one scenario to another because European agriculture is embedded in completely different food systems in the three scenarios. Production patterns largely mimic food diet patterns. This means that while production patterns in 2050 are not significantly different from those observed in 2010 with scenario S1, they are radically different in scenarios S2 and S3. In particular, as food diets in S2 and S3 have lower share of animal products, European livestock production decreases noticeably, as does the production of feed ingredients, including quality forages, and the use of grass from permanent pastures. European permanent pasture area decreases significantly in S2 (-28% in 2050 compared to 2010) and especially in S3 (-51%), with grasslands and rangelands shifting to shrublands or forests[2].

A transition towards chemical pesticide-free agriculture in Europe in 2050 could be possible without transforming the European food diets, but to the detriment of European exports (S1). Facing a constant cropland area and a trend diet, a reduction in the production volume of the European agriculture (lb yield assumption) would result in a sharp reduction in European exports in comparison with S2 and S3. If Europe would wish to keep its export position on world markets, higher yields or expansion of croplands would be necessary. The yield gap under agroecology transition is then a key stake. Due to the effects of ongoing climate change and changes in agricultural practices, new cropping systems including intercropping and relay-cropping could be implemented, leading the major increase in the Land Equivalent Ratio. Such changes are possible under the S1 scenario as they fit into the existing value chains.

The adoption of healthy diets (S2) or of healthy and more environment-friendly diets (S3) would give Europe some room to balance domestic resources and uses while becoming a net exporter of calories. In scenarios S2 and S3, Europeans consume less calories, with less animal-based food. This more frugal diet results in decreasing both the domestic food use (-13% in S2, -20% in S3) and the domestic feed use (-24% and -43%, respectively) relative to 2010. In such scenarios, even with a reduction in the volume of production, domestic uses would decrease more than domestic production and Europe would shift from net importer in 2010 (200 10^{12} kcal) to net exporter in 2050 (about 40 10^{12} kcal in S2 and nearly 240 10^{12} kcal in S3).

[2] These freed grassland and rangeland could also remain in 2050, and be used for extensive livestock or other uses (energy production for example).

How could the scenarios contribute to the European Green Deal?

To overcome climate and environmental challenges threatening Europe and the world, the European Green Deal aims at transforming the EU into a resource-efficient and competitive economy, ensuring zero net emissions of greenhouse gases by 2050, economic growth decoupled from fossil resource use, and no person and no place left behind (EC, 2019[3]).

The three scenarios (except S1 with ub yield assumption) **would contribute positively to decrease European agricultural greenhouse gas (GHG) emissions and to increase carbon storage in soils and biomass.** Under the lower-bound yield assumption, the three scenarios induce a decrease in agricultural GHG emissions in 2050 compared to 2010: from -8% in S1 to -20% in S2 and -37% in S3. Whatever the scenario, the decrease in total agricultural emissions comes to a greater extent from the reduction of emissions from livestock production. With the upper-bound yield assumption, the decrease in agricultural GHG emissions is lower in all three scenarios, and could even turn into an increase in S1 (+9%). Furthermore, compared to 2010, the three scenarios lead to a decrease in land-use change emissions in Europe, which reinforces the capacity of Europe to store carbon throughout the projection period, from 9 million tons CO_2 equivalent per year in S1, to 17 million tons in S2 and up to 43 million tons in S3.

The three scenarios would likely contribute to improve terrestrial biodiversity in Europe. The first positive impact results from the removal of chemical pesticides in all three scenarios. The second positive impact comes from the increasing crop diversity involved in the three scenarios, with a likely more important impact with the scenario S3 relative to scenarios S1 and S2. The strong focus given to soil and plant microbiomes, especially in S2 will have a strong positive effect on microbial biodiversity and indirectly to the whole biodiversity. Other impacts result from land-use changes induced by the three scenarios, which, on average, should have a positive impact on biodiversity (no cropland expansion, increased area dedicated to semi-natural habitats in S3, and potentially the transformation of permanent pasture into forests). This improved status of the biodiversity could reinforce the natural regulations occurring in all three scenarios, making the pesticide-free objective even more feasible. However, a negative impact could be induced by the uncertain fate of the permanent grasslands under S2 and S3. If turned into the production of renewable energy, this could be detrimental to biodiversity.

[3] EC (European Commission) (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM(2019), 640 final.

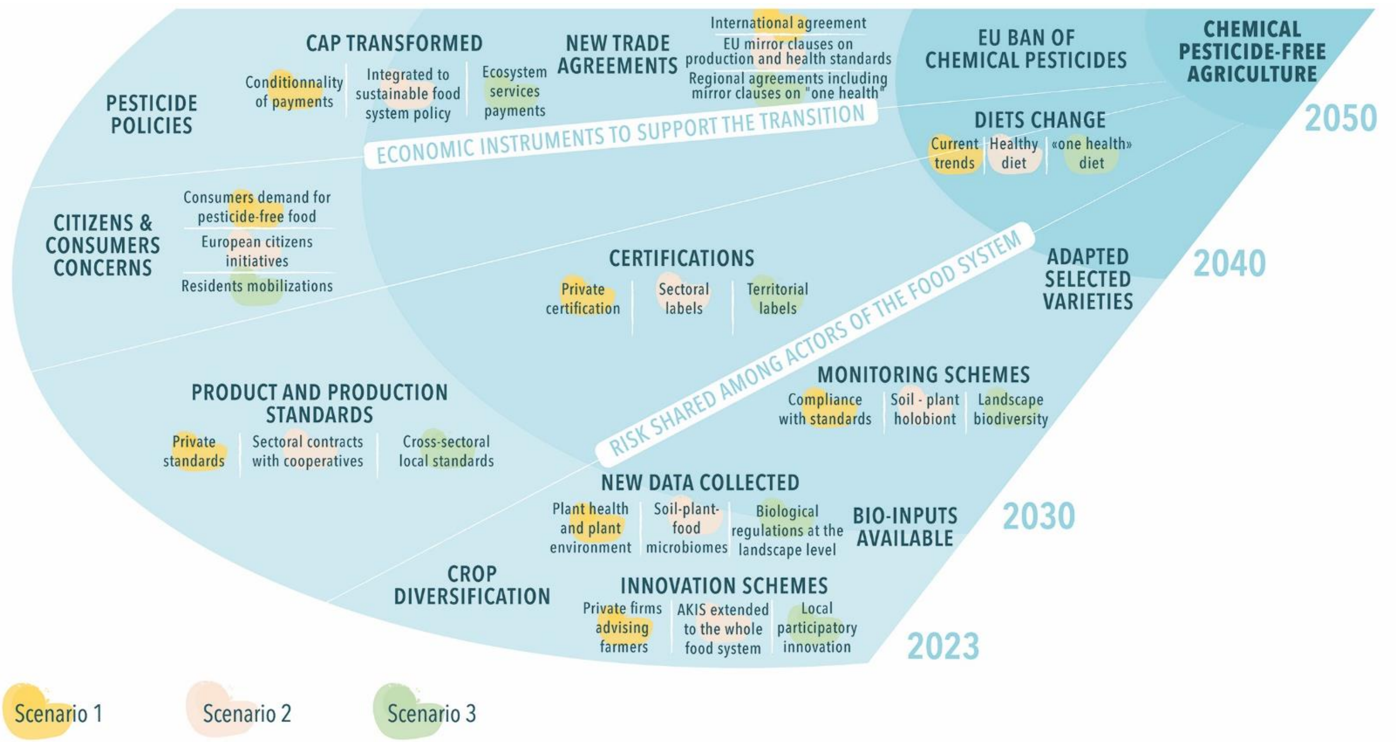
6.4. Robust elements for a transition towards chemical pesticide-free agriculture by 2050

Section 4.1 of the report presents the three scenarios for European chemical pesticide-free agriculture in 2050, together with their transition pathways, built within the group of experts on the transition and with the international expert committee of the foresight.

The transition pathways are specific to each scenario, in terms of actions required, actors involved and milestones identified. However, by analysing the transition pathways of the three scenarios, some **robust elements of the transition can be identified**. Kok *et al.* (2011)[4] define robust elements as "*elements [that] would survive several kinds of external developments […], strategies [that] appear robust because they would be effective in all exploratory scenarios that were developed, […] strategies [that] are robust because they could be successful independent of which exploratory scenario becomes a reality*".

We have worked with members of the international expert committee of the foresight to identify these robust elements of the transition pathway during a participatory workshop. We asked them, first, to make a **list of elements that are common to** all transition pathways, and then, to define the **specific elements** for each of the three transition pathways. Then, by combining these insights, we were able to compile the robust elements of the transition towards chemical pesticide-free agriculture (Figure 6-2), and to highlight the specificities of each transition pathway (Table 6-4).

Figure 6-2: Robust elements of the transition pathways, represented in a timeline from 2023 to 2050



Credits: Lucile WARGNIEZ

[4] Kok, K., van Vliet, M., Bärlund, I., Dubel, A., Sendzimir, J. (2011). Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. Technological Forecasting and Social Change, 78 (5), 835-851.

Table 6-4: Specificities of each transition pathway

	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)
Data	Data privately owned (but open to all) Data collected on plant health and its environment	Data from soil to food is shared all across the value chain Data collected on soil health, soil – plant – food microbiomes	Data is publicly owned and shared within actors of the territory including civil society Data collected on landscape regulations, agroecological infrastructures
Knowledge creation and innovation processes	Knowledge building and innovation with a top down approach: from private companies (digital equipment, Artificial Intelligence) to farmers. Create new job opportunities in new technologies	Knowledge building and innovation created across the food chain by the actors involved (can also be through living labs) Based on farmers and science and education actors	Knowledge building and innovation co-created through living labs involving farmers and local organizations Systemic, adaptive and participatory approach
Technological innovations	Technological development oriented towards robotisation, sensors, drones	Technological development oriented towards soil microbiome monitoring Develop infrastructures for enabling crop and products diversification (storage and logistic)	Technological development oriented towards machinery addressing the needs of farmers (co-development) and actors of the value chain, product diversification and landscape monitoring
Plant breeding	Breeding focused on plant immunity, multiple tolerance to pests	Breeding focus on the ability of plants to interact with the soil microbiome, production of seeds adapted to the local environment (at the field level)	Participatory breeding, varieties adapted to mixtures, 'population varieties' or species adapted to associations and to local contexts
Leading actors connected with farmers	Transition led by private sector and European public regulation of markets Based on private actors, and technical advisors	Transition led by public policies designed by European and national governments, and food value chain actors	Multi-actors transition pathway. Transition led by local, regional and European governments, civil society and local farmer networks

First, in every transition pathway, there must be a political willingness and **relevant public policies implemented** to favour and support the transition. In parallel to the set-up of regulatory policies for reducing and ultimately banning chemical pesticides, **policies must support farmers (and other actors from the value chains)** in the transition towards chemical pesticide-free schemes, all along the transition. This means **transforming the Common Agricultural Policy as of the end of the 2020's, creating economic instruments to financially support** the transition, such as risk coverage, and implementing food and nutrition policies to support transition to healthy diets (S2 and S3). All across the transition, there must also be mechanisms for **sharing the risks** based on the food chains or on the actors of the territories.

The transition also requires **new trade agreements** to be settled with non-European market partners, from 2030, in order to apply similar production standards (mirror clauses) to every product present in the European market. In every transition, **consumers have a key role to play**. At the beginning of the transition, they voice their concerns about chemical pesticides and their impacts on human health, the environment and biodiversity. Later in the transition (in the 2040's), the shift of their food behaviours and their dietary patterns will support the transition (S2 and S3). All the transitions also require the definition of new products and **production standards** in the 2025's, enabling in the 2030's the **certification** of farmers, of their productions, and their **valorisation** through food labels. Early in the transition, the innovation schemes, knowledge creation, co-conception and living labs, are central and take different forms depending on the scenario. In all transitions, **new data must be collected** by the end of the 2020's and then **monitored** at different scales and shared among actors, for the monitoring of various parts of the environment.

There is also, very early in every transition, a necessary milestone regarding **diversification of crops**, although it then has different intensities depending on the scenario. The development and availability of **bio-inputs** around 2030 are also required in every transition pathway, as the development and use of new cultivated varieties in the 2030's - 2040's adapted to each scenario and cropping systems. This also requires **adapted and committed regulations**.

6.5. The 10 key messages of the foresight study

1. The entire food system, committing all its actors, must be considered to build a European chemical pesticide-free agriculture in 2050.

2. In addition to the shift towards chemical pesticide-free agriculture, the scenarios would contribute to improving the greenhouse gas balance, biodiversity and overall ecosystem health; two scenarios (S2 and S3) would contribute to improving food sovereignty in Europe, human nutrition and health.

3. European consumers play a key role in the transition towards chemical pesticide-free agriculture, notably through their dietary changes. A transition without dietary changes is also possible but would deteriorate the European agricultural trade balance, or otherwise would require either to reach higher yields or to expand the European cropland area.

4. A balance must be found between reducing the consumption of animal products and preserving grasslands and associated services.

5. The diversification of crops in time and space, the development of biocontrol products, bio-inputs, adapted selected varieties, agricultural equipment and digital tools, and monitoring schemes of pest dynamics and the environment are key elements to be combined for an efficient chemical pesticide-free crop protection. Biological regulations at the soil, crop and landscape levels should be favoured, as well as preventive actions.

6. Several chemical pesticide-free cropping systems are possible depending on whether they rely on a high level of external inputs, or on a high level of diversification and ecosystem services.

7. The resilience of each scenario to climate change can be assessed through its robustness (linked to internal factors, *e.g*. diversification and ecosystem services) and adaptability (linked to external factors, *e.g*. external inputs).

8. For building efficient crop protection strategies without chemical pesticides, knowledge on biological processes, data and simulation tools are needed to conceive anticipatory tools for pest management, to design landscapes, and to understand the soil microbiome, the plant holobiont and plant immunity mechanisms.

9. The transition towards chemical pesticide-free agriculture requires a set of coherent public policies related to pesticide use, articulated with other policies such as food policies. This requires a transformation of the Common Agricultural Policy (CAP) and economic instruments to support the transition; finally, trade agreements at the borders of the European Union must be set up to ensure the development of chemical pesticide-free markets.

10. The transition must also involve risk sharing among actors, co-conception of technologies and cropping systems, and transformations in the upstream and downstream agricultural sectors.

European Chemical Pesticide-Free Agriculture in 2050

Appendix

Experts involved in the European Expert Committee, in the thematic groups and experts interviewed

List of the Tables

NB: The following tables presents the expert's affiliations at the time of the foresight study.

Table A1: Members of the European Experts' Committee

Name and first name	Organisation
Autio Sari	TUKES (Finish Safety and Chemicals Agency, Finland)
Barberi Paolo	Sant'Anna School of Advanced Studies (Italy)
Bergeret Pascal	CIHEAM (Mediterranean Agronomic Institute of Montpellier, France)
Bujor-Neniţa Oana	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Carlesi Stefano	Sant'Anna School of Advanced Studies (Italy)
Christensen Henriette	PAN (Pesticide Action Network Europe, Belgium)
Ciceoi Roxana	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Deguine Jean-Philippe	CIRAD (French Agricultural Research Centre for International Development, France)
Enjalbert Jérôme	INRAE (National Research Institute for Agriculture, Food and the Environment, France)
Fintineru Gina	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Huber Laurent	INRAE, Ecosys (France)
Jeanneret Philippe	Agroscope (Swiss centre of excellence for agricultural research, Switzerland)
Kolb Steffen	ZALF (Leibniz Centre for Agricultural Landscape Research, Germany)
Lamine Claire	INRAE, Ecodéveloppement (France)
Martin Guillaume	INRAE, AGIR (France)
Messéan Antoine	INRAE, Eco-Innov (France)
Mosnier Aline	FABLE consortium (Food, Agriculture, Biodiversity, Land-use and Energy, France)
Oustrain Savine	Vivescia (Agricultural cooperative, France)
Porcher Emmanuelle	MNHN (French National Natural History Museum, France)
Raineau Yann	INRAE, ETTIS (France)
Röös Elin	SLU (Swedish University of Agricultural Sciences, Sweden)

Table A2: Members of the thematic experts' groups

Name and first name	Organisation
Group 'Reducing pest pressure'	
Aubertot Jean-Noël	INRAE, AGIR, Toulouse
Barot Sébastien	IRD (Institut de Recherche pour le Développement / French National Research Institute for Sustainable Development), iEES, Paris
Bedoussac Laurent	INRAE, AGIR, and ENSFEA (École nationale supérieure de formation de l'enseignement agricole / French national school for agricultural training), Toulouse
Charles Raphaël	FIBL (Institut de recherche de l'agriculture biologique / Research Institute of Organic Agriculture), Suisse
Delière Laurent	INRAE, SAVE, Bordeaux
Garcia Vega Diego	IDDRI (Institut du Développement Durable et des Relations Internationales / Institute for Sustainable Development and International Relations), Paris
Lavigne Claire	INRAE, PSH, Avignon
Morris Cindy	INRAE, PV, Avignon
Rusch Adrien	INRAE, SAVE, Bordeaux
Thérond Olivier	INRAE, LAE, Colmar
Valentin-Morison Muriel	INRAE, Agronomie, Thiverval-Grignon
Group 'Strengthening plant resistance'	
Ballini Elsa	SupAgro (French school for higher education and research in agriculture, food and environment), BGPI, Montpellier
Corio-Costet Marie-France	INRAE, SAVE, Bordeaux
Desclaux Dominique	INRAE, DIADE, Montpellier
Julier Bernadette	INRAE, URP3F, Lusignan
Lemarié Stéphane	INRAE, GAEL, Grenoble
Moënne-Loccoz Yvan	Université Lyon (University of Lyon), Biosciences, Lyon
Moreau Delphine	INRAE, Agroécologie, Dijon
Mougel Christophe	INRAE, IGEPP, Rennes
Rameau Catherine	INRAE, IJBP, Versailles
Ricroch Agnès	AgroParisTech (French school for higher education and research in life and environmental sciences), Paris
Roby Dominique	CNRS (Centre national de la recherche scientifique / National Center for Scientific Research), LIPM, Toulouse
Rolland Bernard	INRAE, IGEPP, Rennes
Savary Serge	INRAE, AGIR, Toulouse
Selosse Marc-André	MNHN, ISYEB, Paris
Simonin Marie	INRAE, IRHS, Angers
Verdier Jérôme	INRAE, IRHS, Angers
Group 'Agricultural equipment and digital technologies'	
Baret Frédéric	INRAE, EMMAH-CAPTE, Avignon
Gilliot Jean-Marc	AgroParisTech, Ecosys, Thiverval-Grignon
Leclerc Melen	INRAE, IGEPP, Rennes
Lenain Ronan	INRAE, TSCF, Clermont-Ferrand
Ienco Dino	INRAE, TETIS, Montpellier
Naud Olivier	INRAE, ITAP-PEPS, Montpellier
Reboud Xavier	INRAE, Agroécologie, Dijon
Rizzo Davide	UniLassalle (French school for higher education and research on life sciences), Beauvais
Vaudour Emmanuelle	AgroParisTech, Ecosys, Thiverval-Grignon

Table A2 (continued): Members of the thematic experts' groups

Name and first name	Organisation
Group 'Cropping systems' (meeting February 11th&12th, 2021)	
Aubertot Jean-Noël	INRAE, AGIR, Toulouse
Ballini Elsa	SupAgro, BGPI, Montpellier
Chauvel Bruno	INRAE, Agroécologie, Dijon
Charles Raphaël	FIBL, Suisse
Corio-Costet Marie-France	INRAE, SAVE, Bordeaux
Delière Laurent	INRAE, SAVE, Bordeaux
Desclaux Dominique	INRAE, DIADE, Montpellier
Enjalbert Jerome	INRAE, GQE Le Moulon, Gif-sur-Yvette
Julier Bernadette	INRAE, URP3F, Lusignan
Lavigne Claire	INRAE, PSH, Avignon
Lemarié Stéphane	INRAE, GAEL, Grenoble
Moënne-Loccoz Yvan	Université de Lyon, Biosciences, Lyon
Moreau Delphine	INRAE, Agroécologie, Dijon
Morris Cindy	INRAE, PV, Avignon
Mougel Christophe	INRAE, IGEPP, Rennes
Rameau Catherine	INRAE, IJBP, Versailles
Ricroch Agnès	AgroParisTech, Académie Agriculture, Paris
Selosse Marc-André	MNHN, ISYEB, Paris
Simonin Marie	INRAE, IRHS, Angers
Therond Olivier	INRAE, LAE, Colmar
Verdier Jérôme	INRAE, IRHS, Angers
Group 'Cropping systems' (meeting April 29th, 2021)	
Ballini Elsa	SupAgro, BGPI, Montpellier
Bedoussac Laurent	INRAE, AGIR, and ENSFEA, Toulouse
Chauvel Bruno	INRAE, Agroécologie, Dijon
Corio-Costet Marie-France	INRAE, SAVE, Bordeaux
Desclaux Dominique	INRAE, DIADE, Montpellier
Enjalbert Jerome	INRAE, GQE Le Moulon, Gif-sur-Yvette
Ienco Dino	INRAE, TETIS, Montpellier
Julier Bernadette	INRAE, URP3F, Lusignan
Latruffe Laure	INRAE, GREThA, Bordeaux-Pessac
Leclerc Melen	INRAE, IGEPP, Rennes
Lemarié Stéphane	INRAE, GAEL, Grenoble
Moënne-Loccoz Yvan	Université de Lyon, Biosciences, Lyon
Morris Cindy	INRAE, PV, Avignon
Naud Olivier	INRAE, ITAP, Montpellier
Reboud Xavier	INRAE, Agroécologie, Dijon
Ricroch Agnès	AgroParisTech, Académie Agriculture, Paris
Rizzo Davide	UniLassalle, Beauvais
Roby Dominique	CNRS, LIPM, Toulouse
Rolland Bernard	INRAE, IGEPP, Rennes
Simonin Marie	INRAE, IRHS, Angers

Table A3: Members of the transition experts' group

Name and first name	Organisation
Bujor Oana	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Carlesi Stefano	Sant'Anna School of Advanced Studies (Italy)
Ciceoi Roxana	University of Agricultural Sciences and Veterinary Medicine of Bucharest (Romania)
Christensen Henriette	PAN EU (Belgium)
Lamine Claire	INRAE, Ecodéveloppement (France)
Loconto Allison	INRAE, LISIS (France)
Matt Mireille	INRAE, LISIS (France)
Möhring Niklas	CNRS, CEBC (France)
Raineau Yann	INRAE, ETTIS (France)
Robinson Douglas	INRAE, LISIS (France)

Table A4: Members of the expert group on quantification

Name and first name	Organisation
Aubertot Jean-Noël	INRAE, AGIR (France)
Barreiro-Hurle Jesus	JRC (Joint Research Center) (Spain)
Bartoli-Kautsky Claudia	INRAE, IGEPP (France)
Mitter Hermine	BOKU (University of Natural Resources and Life Sciences), (Austria)
Mosnier Aline	FABLE consortium (France)
Munier-Jolain Nicolas	INRAE, Agroécologie (France)

Table A5: Members of the "knowledge gaps" expert group (from the Priority Research Programme "Growing and Protecting crops Differently")

Name and first name	Organisation – PPR Research Project affiliation
Aigrain Patrick	France Agrimer (National Establishment of Agricultural and Seafood Products) – VITAE
Barret Matthieu	IRHS (Institut de Recherche en Horticulture et Semences / Institute of Research in Horticulture and Seeds) – SUCSEED
Brugière Françoise	France Agrimer – VITAE
Carpentier Alain	INRAE, SMART – FAST
Enjalbert Jérôme	INRAE, GQE Le Moulon – MOBIDIV
Fadhuile Adelaïde	Université de Grenoble Alpes / University Grenoble Alps, GAEL – FAST
Fugeray-Scarbel Aline	INRAE, GAEL – MOBIDIV
Gautier Hélène	INRAE, PSH – CAPZEROPHYTO
Hannin Hervé	SupAgro Montpellier – VITAE
Jacquet Florence	INRAE - Scientific Coordinator of the French Priority Research Program 'Growing and Protecting crops Differently'
Perchepied Laure	Université d'Angers / Angers University – CAPZEROPHYTO
Poisson Anne-Sophie	GEVES (Groupe d'étude de contrôle des variétés et des semences / Variety and Seed Study and Control Group) – SUCSEED
Sauvion Nicolas	INRAE, PHIM – BEYOND
Scorsone Emmanuel	CEA (Commissariat à l'énergie atomique et aux énergies alternatives / French Alternative Energies and Atomic Energy Commission) – PHEROSENSOR
Vailleau Fabienne	INP-ENSAT (Institut National Polytechnique-Ecole Nationale Supérieure d'Agronomie de Toulouse / Engineering Faculty of Life Sciences), LIPM – DEEPIMPACT

Table A6: Experts participating to the workshop of the regional case studies

Name and first name	Organisation
Tuscany (Italy)	
Carlesi Stefano	Sant'Anna School of Advanced Studies (SSSA) – case study coordinator
Pecchioni Giovanni	SSSA – case study coordinator
Antichi Daniele	UNIPI (Università di Pisa / University of Pisa)
Barberi Paolo	SSSA
Berti Giaime	SSSA
Bigi Alessandro	Cooperativa L'Unitaria / Agricultural cooperative
Bigongiali Federica	Fondazione Seminare il Futuro (seeds and varieties selection)
Casanovi Luigi	ODAF Pisa, Lucca e Massa Carrara (Ordine dei Dottori Agronomi e Dottori Forestali)
Cupelli Francesca	Terre dell'Etruria (Società Cooperativa Agricola tra Produttori / Agricultural cooperative)
Ferroni Franco	WWF (World Wildlife Fund) Italia
Fontanelli Marco	UNIPI
Gori Stefano	Confcooperative FedAgriPesca Toscana / Agricultural cooperative
Frasconi Christian	UNIPI
Leoni Federico	SSSA
Mantino Alberto	SSSA
Nardi Giacomo	ODAF Pisa, Lucca e Massa Carrara (Ordine dei Dottori Agronomi e Dottori Forestali)
Ricottone Giovanni	ODAF Pisa, Lucca e Massa Carrara (Ordine dei Dottori Agronomi e Dottori Forestali)
Tramacere Lorenzo	UNIPI
Volpi Iride	AEDIT s.r.l. (Company developing ITC tools to support Integrated Pest Management)
Finland	
Autio Sari	Tukes (Finnish Safety and Chemicals Agency) – case study coordinator
Laitala Emilia	Tukes – case study coordinator
Jalli Marja	Luke (Natural Resources Institute Finland) – case study coordinator
Anttila Heli	Tukes
Jern Tove	Ministry of Agriculture and Forestry
Kallio-Mannila Kaija	Tukes
Kämäri Tiiti	Häme University of Applied Sciences
Korkman Rikard	Ombudsman, Central Union of Swedish-speaking Farmers and Forest Owners in Finland
Lamminparras Aura	Finnish Organic Food Association Pro Luomu ry
Livonen Sari	Finnish Organic Research Institute
Malin Eliisa	Baltic Sea Action Group
Nevala Noora	Tukes
Pouta Eija	Luke
Roitto Marja	University of Helsinki
Ronkainen Ari	Luke
Ruuttunen Pentti	Luke
Additional participants to the case study, involved in the post-workshop discussions	
Ahlberg Juho	Tukes
Jukkala Jaana	Tukes
Laamanen Tuija	Lukes
Peltonen Sari	Pro agria (rural advisory organisation)

Table A6 (continued): Experts participating to the workshop of the regional case studies

Name and first name	Organisation
Romania	
Fintineru Gina	Bucharest University of Agronomic Sciences and Veterinary Medicine (UASVM) – case study coordinator
Lagunovschi Viorica	UASVM – case study coordinator
Butcaru Ana	UASVM – case study coordinator
Ciceoi Roxana	UASVM – workshop co-facilitator
Bianca Zamfir	Genetic Resource Bank
Blaga Lucian	Fructavit SRL (fruit and vegetable producer)
Bogoescu Marian	Academy of Agricultural and Forestry Sciences
Bratu Camelia	Genetic Resource Bank
Bujor Oana	Research center for quality study of agri-food products
Certan Ion	Research center for quality study of agri-food products
Constantinescu Dan	Nasu Roșu - organic products, distribution
Dragoi Corlățan Marius	Andermatt SRL - Company for research, development, marketing of organic products
Gabriel Corbu	Gradina corbilor (vegetable producer)
Gheorghe Coman	Enten System, sensors and crop monitoring equipment
Ivan Elena	Research center for quality study of agri-food products
Mihu Mihai	Peasant Mall
Sima Mihaela	Ilfov Agricultural Directorate - Service for the implementation of policies, strategies in agriculture and food industry
Stan Mihaela	Committee on Agriculture in the Chamber of Deputies
Stan Andreea	Research center for quality study of agri-food products
Stanciu Tudor	Beleza Store Srl (vegetable producer and store)
Serbuta Ciprian	Enviro-naturals (organic inputs store)
Teodor Joițaru	BioAgriCert - Inspection and certification body in organic farming
Tudor Cristi	Microgreens (vegetable producer)
Udriște Viorica	Green Agency - implementation of agri - environment projects
Bergerac Duras (France)	
Lelabousse Cécile	Interprofession des vins du Bergerac Duras – Interbranch organisation of Bergerac and Duras wines – case study coordinator
De Rochambeau Hubert	INRAE, « Living Lab »/VitiREV – case study coordinator
Raineau Yann	Région Nouvelle Aquitaine, VitiREV – INRAE, ETTIS – case study coordinator
Darriet Philippe	Institut des Sciences de la Vigne et du Vin - Institute of Vine and Wine Science
Dayer Coralie	Chambre d'agriculture de Dordogne - Chamber of Agriculture of Dordogne
De Resseguier Laure	Bordeaux Sciences Agro - Institute of Agricultural Sciences
Duperret Daniel	Viticulteur – Winegrower
Elia Natacha	Chambre d'agriculture de Gironde, innovations collaboratives - Service Vigne et Vin - Chamber of Agriculture of Gironde, collaborative innovations, wine and vine sector
Gouty-Borges Claire	INRAE, ETTIS
Haas Salomé	Conseil d'architecture d'urbanisme et d'environnement de la Dordogne - Council for Architecture, Urbanism and Environment Dordogne
Lobry Christine	Chambre d'agriculture de Dordogne - Chamber of Agriculture of Dordogne
Salles Denis	INRAE, ETTIS
Vanquathem Mathilde	Interprofession des vins du Bergerac Duras - Interbranch organisation of Bergerac and Duras wines

Table A7: Experts interviewed for the retrospective analysis

Name and first name	Affiliation
Farm structures	
Balmann Alfons	Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Department of Structural Development of Farms and Rural Areas (Germany)
Piet Laurent	INRAE, SMART (France)
Food value chain	
Abdoun Elsa	UFC-Que Choisir, consumers organisation (France)
De Tilly Grégoire	La Ruche qui dit Oui !, online food platform (France)
Fardet Anthony	INRAE, UNH (France)
Gassie Julia	CEP (Centre d'études et de Prospective / Center for studies and foresight), ministry of agriculture and food sovereignty (France)
Lepiller Olivier	CIRAD, MoISA (France)
Perrot Jean-Luc	Pôle de compétitivité Valorial, network of food innovation cluster Valorial (France)
Public policies	
Christensen Henriette	PAN Europe (Belgium)
Grimonprez Benoît	University of Poitiers (France)
Mantovani Alberto	Istituto Superiore di Sanita (Institute for Public Health) (Italy)
Möhring Niklas	CNRS, CEBC (France)

Table A8: Experts interviewed for the quantification work

Name and first name	Affiliation
Cheptea Angela	INRAE, SMART (France)
De Clerck Fabrice	CGIAR (global research partnership for a food-secure future) (France), SRC (Stockholm Resilience Centre) (Sweden), Eat Lancet commission
Gaigné Carl	INRAE, SMART (France)
Guilpart Nicolas	AgroParisTech (France)
Helming Katharina	ZALF (Germany)
Jean Sébastien	CNAM (Conservatoire national des arts et métiers) and CEPII (French center for research and expertise on the world economy) (France)
Kesse-Guyot Emmanuelle	INRAE, CRESS (France)

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