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Foresight: European Chemical Pesticide-Free Agriculture in 2050

Extended Summary - April 2023

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April 2023

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Introduction and method

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The negative impacts of chemical pesticides on the environment, including biodiversity, water, air and soil, as well as on human health, have become a major concern for civil society and consumers. They are also a major issue for the sustainability of agricultural systems. Recently, the Farm to Fork and Biodiversity European strategies set an ambitious target of reducing the use and risks of chemical pesticides by 50% by 2030.

Is it possible, in the mid-term, to withdraw chemical pesticides from agriculture while ensuring a good crop protection? The pesticide reduction target in the Farm to Fork strategy already opened an intense and controversial debate about the feasibility of such a target: some consider that it will have negative impacts on European production and food sovereignty, while others highlight the need to consider, in the impact assessment, changes in agricultural practices, food diets and animal feed imported for livestock.

In the foresight study, chemical pesticides are defined as synthetic pesticides and other substances that have a significant impact on the environment or on human health[1].

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 would like to go one step further in terms of target and horizon by examining the feasibility of an efficient crop protection in a pesticide-free agriculture in Europe in 2050 and how a transition to such agriculture would be achievable. 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’[2] and in connection with the European Research Alliance ‘Towards a Chemical Pesticide-Free Agriculture’. It proposes 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 biophysical impacts in Europe.

Two main principles guided this foresight study. Firstly, the idea that the limited impacts of past European policies aimed at reducing pesticide use in agriculture raise the need for a **paradigm shift** from an incremental approach of pesticide reduction to a **disruptive approach** for building innovative cropping systems without chemical pesticides. Secondly, the idea that cropping systems are **strictly embedded** in food systems, which needs to be taken into account when building scenarios of chemical pesticide-free agriculture. This foresight study assumes a **systemic approach**, considering that the transition to chemical pesticide-free agriculture would require a simultaneous transformation of different components of the food systems.

An original foresight method mixing scenario planning, modelling and backcasting

The foresight method is an original approach combining a scenario planning method based on morphological analysis, a modelling approach based on the GlobAgri-AE2050 model, and European and regional backcasting. The "backcasting" approach consists of

[1] A 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 from organic production notably in two ways: the absence of constraints on mineral fertilisation, and the absence of any chemical pesticides, including for example copper.

[2] https://www6.inrae.fr/cultiver-proteger-autrement/

working backwards from a desirable future to determine the possible conditions for achieving this future and the actions and public policies needed to achieve it[3]. Based on the scenarios, backcasting analyses were conducted at the European level and in four European regions. 144 European experts, including scientists and stakeholders (non governmental organisations, consultants, cooperatives, farmers, trade associations, food and agroequipment companies, local public authorities), were involved in the different phases of the process through eight expert groups (in blue in Fig.1).

The scenario building was based on a retrospective analysis of each component of the system (left-hand side panel in Fig. 1) identifying major trends, weak signals and potential ruptures through literature reviews, interviews and expert groups. Based on these analyses, expert groups developed alternative hypotheses describing possible changes of these components by 2050 (gathered in the morphological table, corresponding to the matrix in the central panel in Fig.1), and combined them to build the qualitative scenarios (arrows in the central panel in Fig. 1). Then, simulations using the GlobAgri-AE2050 model (right-hand side panel) assessed the impacts of each scenario. Finally, scenarios were backcasted at the European level and in four European small regions (bottom panel) in order to elaborate transition pathways that could lead to such scenarios in 2050.

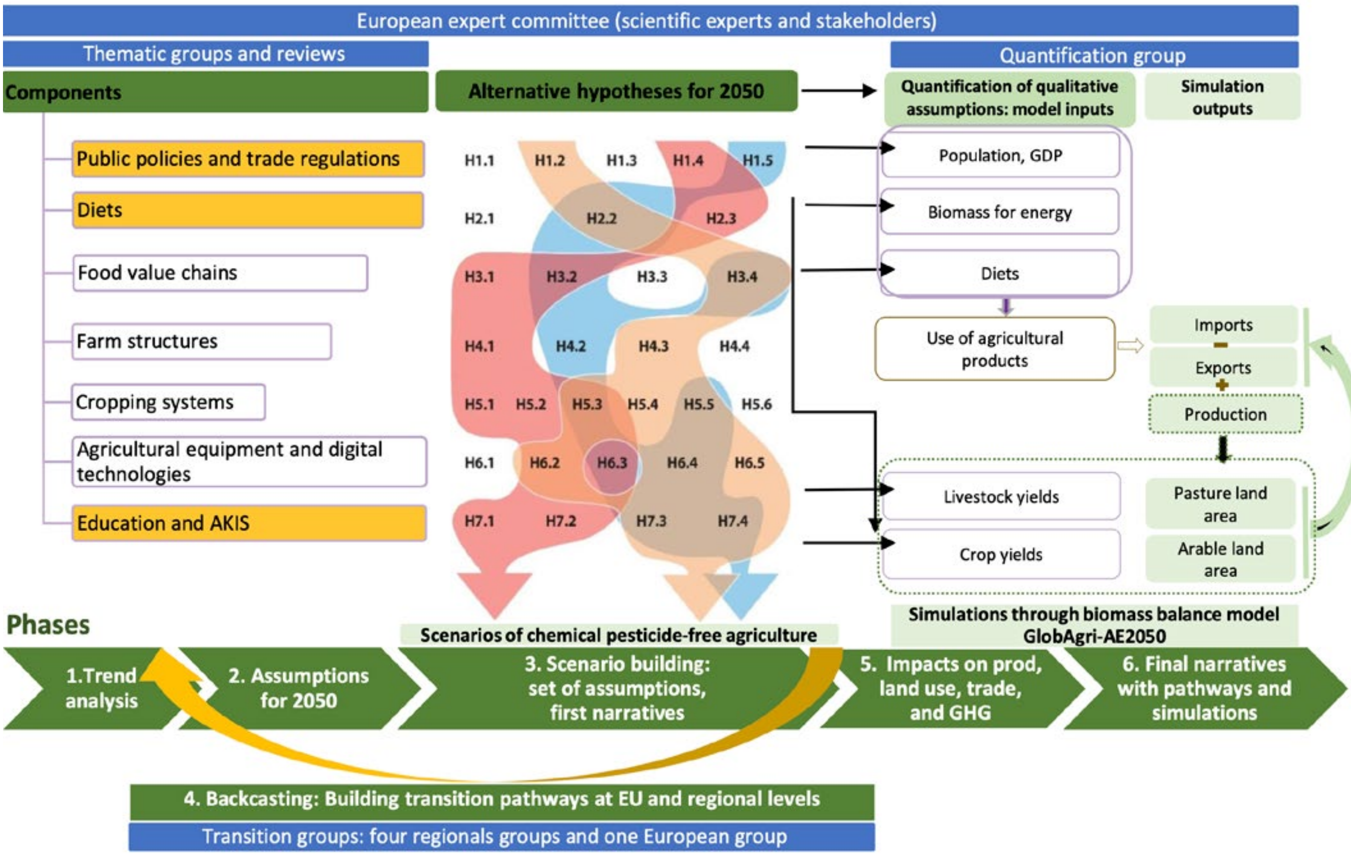

Figure 1. *General method of the foresight study based on a morphological table (central panel) articulating a scenario approach (left-hand and central panel, based on components in white, Phases 1-2-3), a simulation approach (right-hand panel, Phase 5) and a backcasting approach (bottom panel, based on components in yellow, Phase 4).*

In the central panel, the coloured arrows represent the combinations of hypotheses that form the scenarios. The foresight method was based on a 'system' (left-hand panel) 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).

[3] From Robinson (1982)

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Building efficient chemical pesticide-free crop protection strategies in 2050

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The first component we explored when building chemical pesticide-free agriculture is the cropping system, with the aim to draw hypotheses of crop protection strategies without chemical pesticides in 2050.

Since the 1950s, chemical pesticides have become a major management tool in European cropping systems. They have greatly transformed cropping systems and made possible an important increase in agricultural production. Since the 1990s, the negative impacts of pesticides on human and environmental health have led to a rethinking of crop protection strategies to limit their use and impacts, e.g. with the development of integrated pest management strategies which aim at reducing pesticide use by using them as a last resort. Unfortunately, these strategies have not reached their objectives and pesticide use has not decreased since the 1990s. This is why we have elaborated crop protection strategies without chemical pesticides in 2050.

With the aim of developing efficient crop protection strategies without chemical pesticides in 2050, **six modes of action** were identified during exploratory workshops with expert groups. These modes of action (Fig. 2, grey boxes) are associated with different levers (Fig. 2, white boxes). **They are divided into control actions on pests** (animal pests, pathogens and weeds), on the right-hand side (apart from chemical control, biocontrol (1) and physical control (2), and **prophylactic actions** on the left-hand side (temporal management through cropping practices (3), spatial management of crop diversity within the field (4), management of landscape (5) and plant breeding (6), Fig. 2). Finally, epidemiological surveillance (7), at the bottom right (green box), is not a mode of action in itself but a tool that triggers one (or several) mode(s) of action. Epidemiological surveillance is currently used mainly for chemical control and biocontrol, but the foresight approach aims at analysing how to use epidemiological surveillance for prophylaxis.

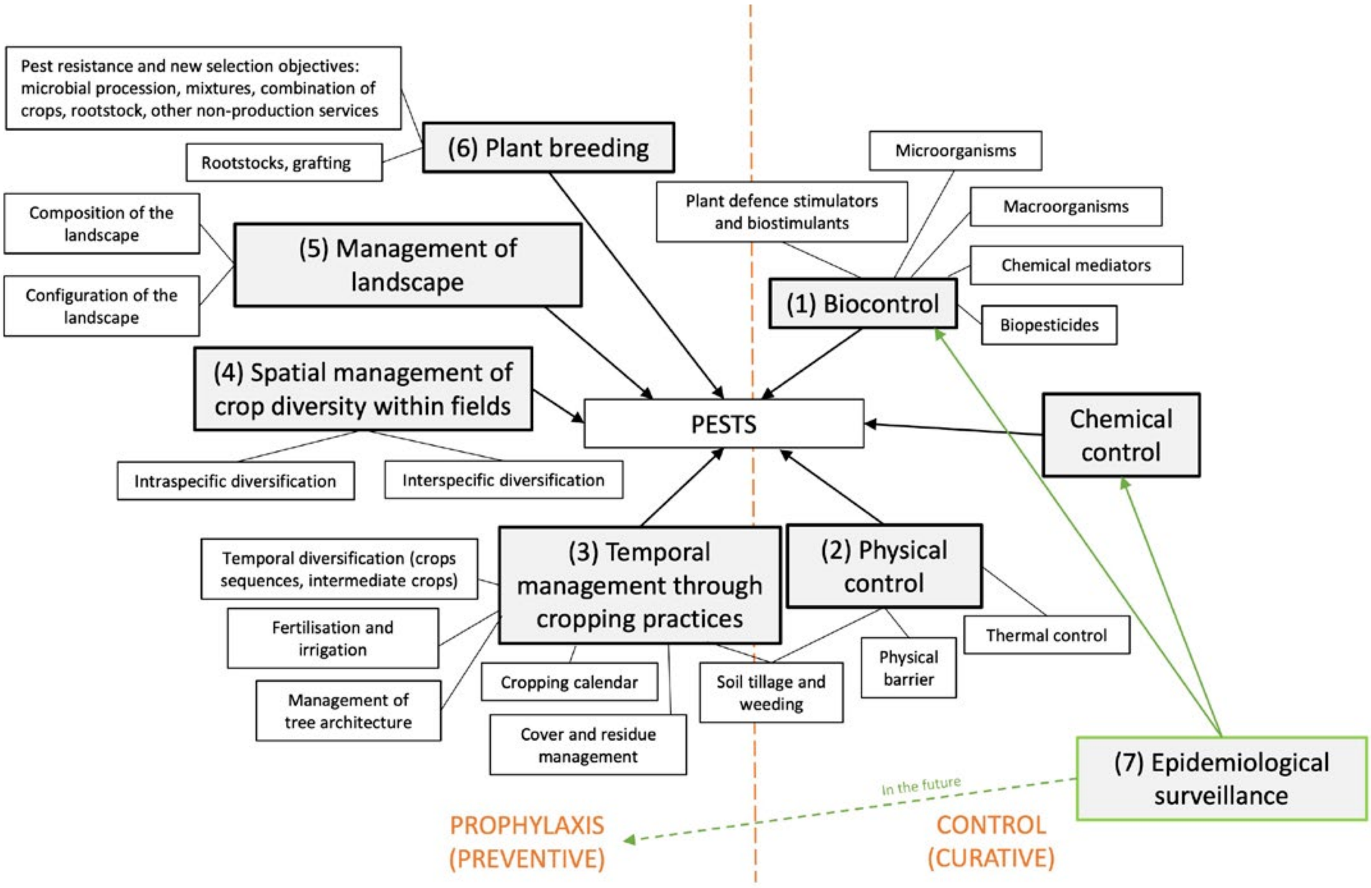

Figure 2. *Summary diagram of crop protection strategies including the six modes of action. Each mode of action (grey boxes) is associated with different levers (white boxes). Epidemiological surveillance (7) - a tool currently mainly used for implementing chemical control and biocontrol - could be used, in the future, for prophylaxis.*

From this diagram, we mobilised the approach of innovation through withdrawal[4] to explore what happens when we withdraw chemical control through chemical pesticides. **Three issues emerged for crop protection:**

(i) a redesign of crop protection and cropping systems as it is not possible to simply substitute one chemical pesticide with one alternative mode of action;

(ii) a shift from curative to prophylactic crop protection, based on the monitoring of pest dynamics;

(iii) a greater emphasis on specific entities related to biological processes used for pest regulation such as landscapes, crops and soils.

Based on these considerations, crop protection could be analysed with a new perspective (Fig. 3). First, crop protection should not only focus on pests, but also on cultivated plants and the **interactions between plants and pests.** Secondly, the term 'pest' refers to an assigned role, but pests, like plants, are biological entities which are part of an ecosystem within **wider networks of interactions** at different levels: plant, **soil**, crops and **landscape**. Plants and pests interact with other natural species or cultivated plants and with the soil and plant microbiomes, and they are embedded into food webs. In the conceptual diagram (Fig. 3), we have a triptych of interactions within the landscape and the soil that highlights interaction mechanisms and potential levers for plant protection, in particular those based on biological regulations at the soil or landscape level.

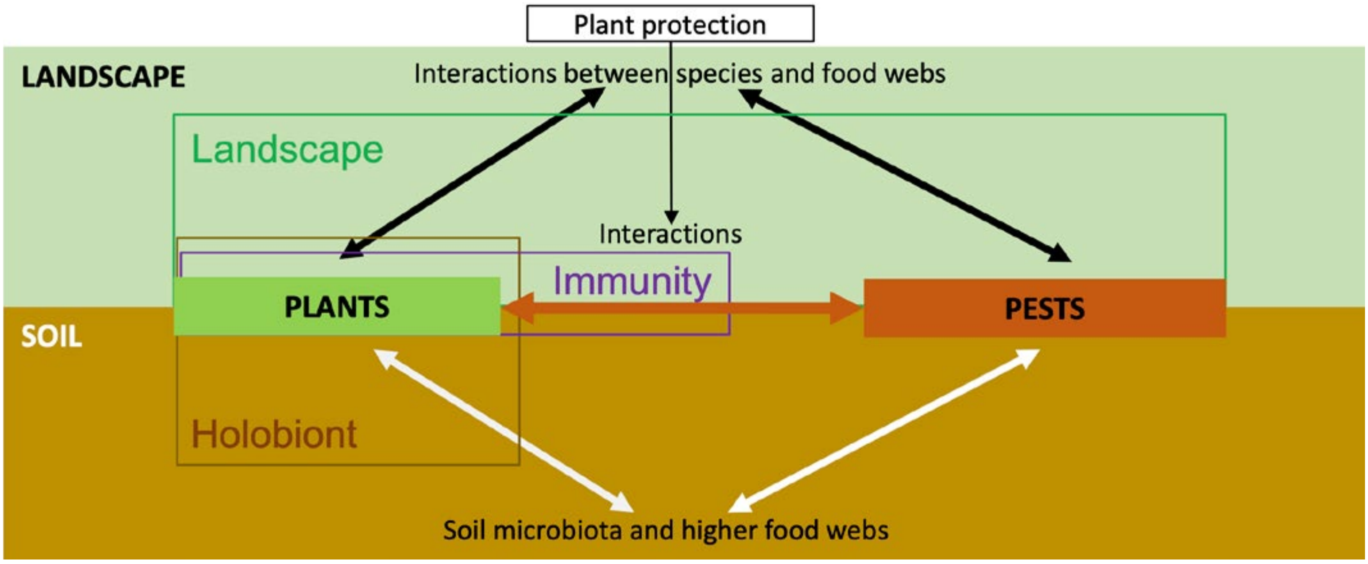

Figure 3. *Redefinition of pests and their interactions with plants and the environment and identification of rupture hypotheses for crop protection [for convenience, climate and cropping practices are not represented in the figure]*

This enabled us to define three different avenues (Fig. 3) to reconsider crop protection and design future crop protection systems without chemical pesticides:

(i) working at the landscape scale and on biological regulations at this scale **(Fig. 3, green box)**,

(ii) rethinking the relationship between the plant and the microbiota, through the **holobiont**[5] perspective (i.e. the plant and its microbial communities) **(brown box)**,

(iii) working on the relationship between the plant and pests, particularly plant **immunity** **(purple box)**.

Based on these avenues, three hypotheses of crop protection strategy without chemical pesticides in 2050 were developed during the workshops of experts groups.

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[4] See Goulet and Vinck (2015).

[5] The holobiont is a natural living entity made up of a superior organism called the host, such as a plant, and its microbiota, or the cohort of micro-organisms closely associated with it.

Three hypotheses of crop protection strategies in 2050

Designing complex and diversified landscapes adapted to local contexts and their evolution

Crop pests are managed through **spatial and temporal interactions in the plot and beyond (i.e. within the agricultural landscape).**

Biodiversity and agrobiodiversity are mobilised to influence biological regulations at the landscape level. This rupture hypothesis is based on **landscape and crop diversification**. Diversified and complex landscapes and cropping systems are designed **(i)** to be adapted to local contexts and their changes, and **(ii)** to create, in terms of habitats and resources, discontinuities for pests and continuities for beneficials and other living organisms. In this hypothesis, landscapes are composed of a **stable matrix of semi-natural habitats (20% of the land, including pastures)** and a **mosaic of crops that can be shaped**, which requires coordination of actor practices at the landscape level. **The cropping systems are diversified over space and time. Crop fields are small** and bordered by interfaces constituting semi-natural habitats.

Managing the holobiont by strengthening host-microbiota interactions

Host-microbiota interactions are mobilised in order to boost the protection of cultivated plants against pests. It relies on controlling or directing the holobiont. The holobiont is defined as an assemblage of cultivated plants and their associated microorganisms in the rhizosphere, phyllosphere, and endosphere; the plant and the plant-associated microorganisms form a single evolutionary unit. To meet its needs, the **plant recruits** from its environment **microorganisms from a reservoir of microbial diversity** with which it establishes stable relationships. Crop protection seeks to strengthen the **functions of the microbiota**, in order to enhance protection and pest resistance, and also 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 (such as the inoculation of key microorganisms/communities), as well as a complete articulation with the cropping system (such as cropping practices and the selection of varieties adapted to develop plant-microbiota interactions).**

Strengthening the immunity of cultivated plants directly and indirectly

Crop protection **acts on the individual plant** to strengthen its immunity to pests, or **at the population level** to avoid exceeding an immunity threshold. This strategy relies on **genetic control**, exogenous inputs, allelochemistry, pest anticipation and system adjustment using remote sensing and precision equipment to spread exogenous inputs. Direct strengthening of individual plants is achieved through genetic control by selecting genotypes resistant to pests and adapted to agro-pedoclimatic conditions. This is also done through **direct stimulation of the immune system via exogenous inputs of plant defence stimulators** (PDS). The objective is to find a trade-off between plant growth (via biostimulants) and plant immunity (via PDS). Indirect strengthening of plant immunity **promotes positive interactions between the plant and its environment**, through plant-microbiome interactions and diversification of resistance (variety mixtures and species associations including the introduction of service plants).

Hypotheses of change in 2050 for cropping systems

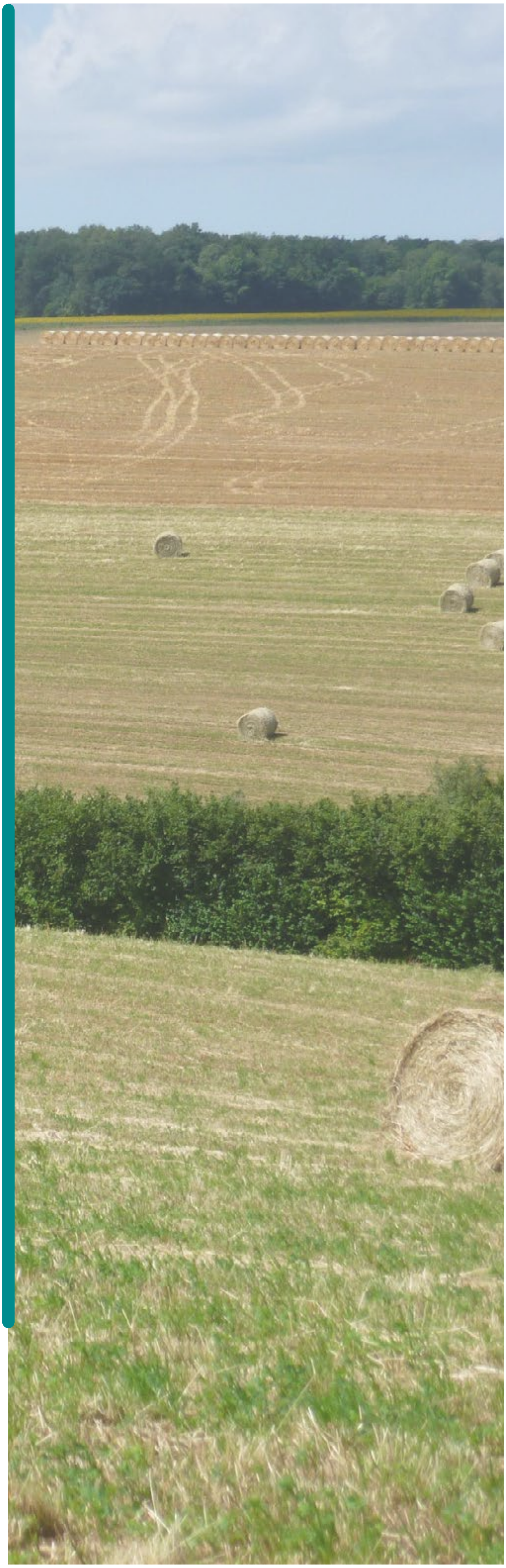
Strengthening the immunity of cultivated plants	Managing the crop holobiont by strengthening host microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their evolution

Importance of fertilisation and irrigation

In all three hypotheses of crop protection, **fertilisation and irrigation** must be adjusted to reduce pest virulence and strengthen the plant capability to recruit microorganisms, while maintaining plant growth. Moreover, organic fertilisation is preferred as a way to promote soil life, especially soil microbiomes.

Monitoring pest dynamics

In addition to the three hypotheses, we also thought about monitoring and anticipating pest dynamics at the landscape and soil scale, rethinking epidemiological surveillance and the role it can play in adapting cropping systems (Fig. 3, brown box). Indeed, in the three hypotheses we move from epidemiological surveillance focused on pests to a **monitoring system at a broader level of space and time to anticipate the dynamics of pest populations.** All three hypotheses have in common the monitoring of the status of the environment. In addition, each hypothesis also has its own specific monitoring requirements, which focus on the status of biological regulations at the landscape scale in the 'Designing complex and diversified landscapes' hypothesis, on microbiota diversity and holobiont health in the 'Managing the holobiont' hypothesis, and on the health status of plants in the 'Strengthening the immunity of cultivated plants' hypothesis.



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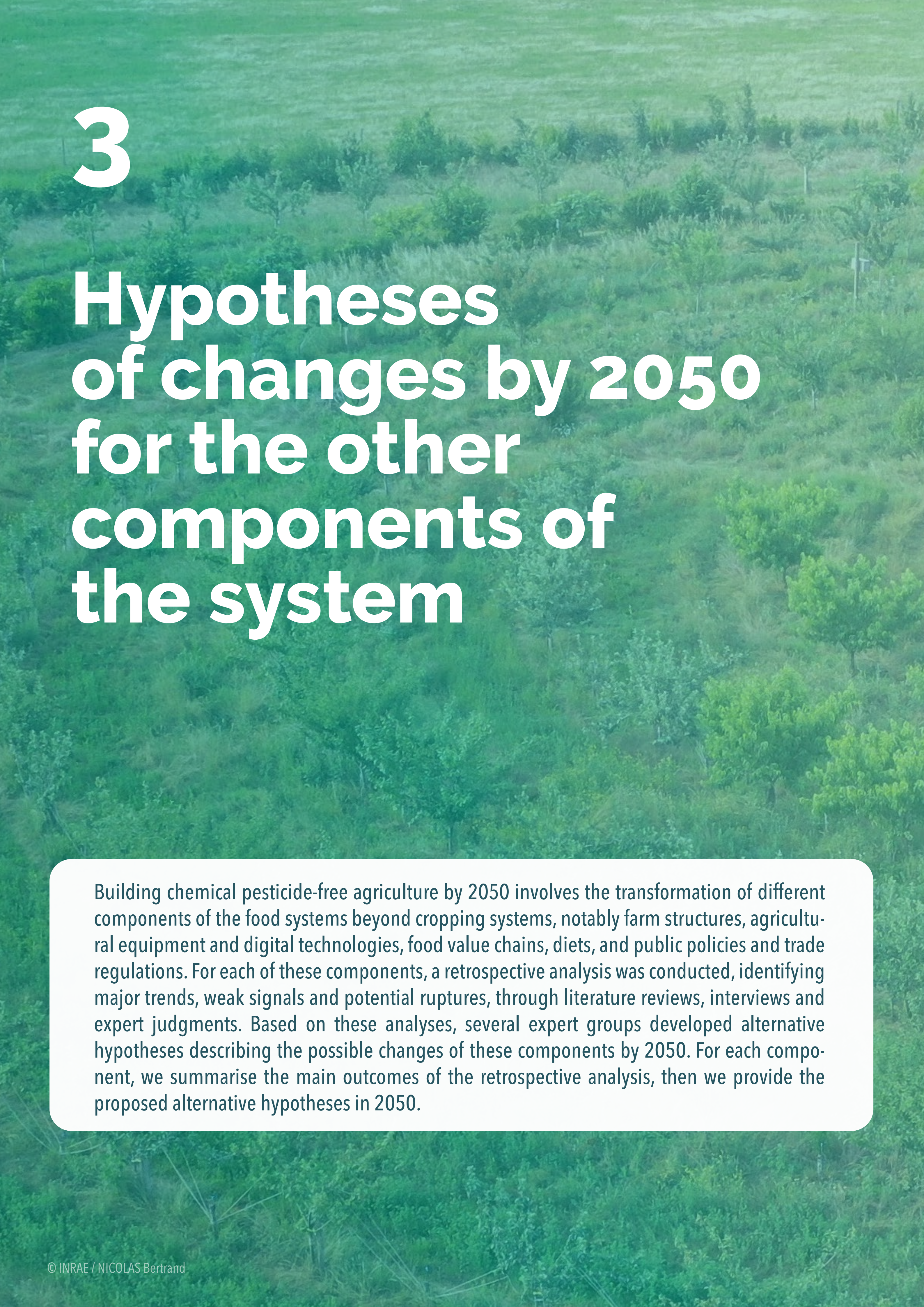

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Hypotheses of changes by 2050 for the other components of the system

Building chemical pesticide-free agriculture by 2050 involves the transformation of different components of the food systems beyond cropping systems, notably farm structures, agricultural equipment and digital technologies, food value chains, diets, and public policies and trade regulations. For each of these components, a retrospective analysis was conducted, identifying major trends, weak signals and potential ruptures, through literature reviews, interviews and expert judgments. Based on these analyses, several expert groups developed alternative hypotheses describing the possible changes of these components by 2050. For each component, we summarise the main outcomes of the retrospective analysis, then we provide the proposed alternative hypotheses in 2050.

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Changes in farm structures in Europe by 2050

Although there are major differences among farm structures in Europe, almost all EU regions are undergoing long-term structural change in farming corresponding to a steady increase in average farm sizes and a concentration of production on fewer and larger farms.

Coexistence of agricultural structures in Europe

Farms in Europe are very diverse in terms of size, organisation and type of production reflecting the coexistence of different farming models across the continent. Over the past decades, farm number has been declining while farm size increased, reflecting **land concentration**. This led to a **dual distribution of farm structures in Europe**, with 13% of the largest farms that occupy 80% of utilised agricultural area (UAA), while 80% of the smallest farms only used 13% of the UAA, in 2016. Moreover, **European farms have become increasingly specialised** (reduction in mixed crop-livestock farms, specialisation of production with less diversification and spatial concentration of production). This came with **a specialisation in European regions with a geographical concentration of production**. This strong specialisation of farms and regions generates many negative externalities (pollution, health risk, landscape simplification and biodiversity loss).

Governance of farm structures in Europe

The most widespread European farm **model is family farm**, with mostly family labour. Nevertheless, this model is changing, to include other actors in the farm governance. Farmers gather under **collective organisations**, to face different challenges, especially through **cooperatives** that have become key actors of the food value chains. They also organise collectively to promote production, to pool production tools, to share intangible assets and to adopt new practices. **Local actors and consumers** can also take part in governance of farm structure (e.g., direct sale, community-supported agriculture, etc.). **Agro-industrial companies** are also involved through vertical coordination, contracting, standards and labels. More recently, **financial actors** have been investing in agricultural land and can influence farm governance. This led to two different logics of farm governance: a patrimonial logic based on family and a corporate logic based on shareholders.

Organisation of production factors (labour, land and capital)

European agricultural **labour is decreasing, and remains primarily family labour.** However, the use of hired labour and **delegation** of operations is increasing. Recently, new form of full delegation of farms is developing. Moreover, agricultural **population is ageing** and establishment of young farmers is increasingly difficult, questioning the renewal of agricultural population. For **land and capital**, it is still **mainly family-hold** in Europe. Nevertheless, the use of **external capital** has been increasing with new financial actors investing in agricultural land and in farms. Even if European farms are mainly family-based, production factors tend to be **increasingly segmented.** A new form of farm organisation is emerging in Europe, the **familial agroholdings** where capital is still in the hand of extended family, but hired workforce manages and works on the farm. **Corporate farming** is also developing with highly segmented production factors: capital and land are owned by shareholders and operational management and labour delegated to hired workforce.

Based on this analysis, **three alternative hypotheses for farm structures in 2050 have been drawn:**

- Farm structures are highly specialised and financialised, with large and specialised corporate farms concentrating agricultural land. Production factors are segmented and mobile. Residual family farms coexist alongside those corporate structures. This leads to a dual organisation of farm structure and regional specialisation.

- Limits and criticisms of regional specialisation have pushed value chain actors, especially cooperatives, to promote the diversification of production within the major European regions. Farms are heterogeneous, with familial agroholdings, dealing with processors and distributors, and smaller family farms integrated into cooperatives. There is a diversity of production at the regional scale, although each farm structure remains highly specialised.

- Farm structures are linked with the actors and activities in their territory. Farms are family-based, land concentration is limited and the establishment of new farmers is supported. Farms are diverse in size. Farmers have diversified their production and are organised collectively.

Hypotheses of change in 2050 for farm structures

Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures

Changes in agricultural equipment and digital technologies for cropping systems without chemical pesticides in 2050

The **main transformations in agricultural equipment and digital technologies** likely to participate in the implementation of a chemical pesticide-free cropping system can be summarised under three main areas.

Observation and modelling systems

The first area refers to **observation and modelling systems** designed to monitor and anticipate pest presence and the health of plants. 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. Then, **modelling** and simulation tools rely on big data, deep learning or mechanistic modelling to anticipate the future presence of pests.

Specific equipment

The second area relates to **specific equipment** adapted to chemical pesticide-free cropping systems. These are the ongoing development of a**gricultural equipment** adapted to new crop management approaches (for example, the mixing of crops), precision agricultural equipment for the application of biocontrol products and the empowerment of equipment through to full **autonomy** (robots).

Dynamics of innovation

The third area is about the **innovation dynamics** that define the use of this equipment and technology. This innovation should be **co-constructed** with multiple actors, from farmers to equipment manufacturers, including local stakeholders. Data should be generated and processed on a **supra-farm scale**, which requires **data sharing** and **open data management.** 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**. 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.

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Based on these trends, **three alternative hypotheses of agricultural equipment and digital technologies in 2050 have been drawn:**

- **A modularity of equipment for their adaptation to agricultural practices.** The development of an architecture of modular equipment allows the farmer to combine and adapt machinery by considering the specificities of his/her cropping system. This strategy aims at solving problems resulting from both larger agricultural machinery that induces field (and farm) size increase, and heavier farm vehicles that cause subsoil compaction. In addition it aims at reversing 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 central to the management of cropping systems. The farmer mobilises observation tools such as sensors, remote sensing instruments, crowdsourcing (sharing 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 developped in places like living labs or third places that allow co-conception and experimentation of machinery, and involve a diversity of actors of the value chain.

- **A pooling of equipment, sensors and data at the scale of landscapes or of stakeholder organisations.** This hypothesis is based on the sharing of data and modelling tools for understanding the spatial dynamics of pests, and the pooling of equipment for intervention at the farm scale and beyond. The sharing of agricultural equipment is rooted in a specific organisation at landscape level or based on existing stakeholder organisations. 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 sharing 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.

- **Autonomous robots able to act on each plant.** It involves mainly intermediate actors such as equipment manufacturers to build robots, 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 capital investment of farmers, leaving many farmers aside. The use of robots have raised major regulatory issues such as the competition with human work and the energy balance of digital technologies, and societal concerns about autonomous drones and robots.

Hypotheses of change in 2050 for 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

Changes in dietary patterns in Europe by 2050

Overall, in Europe, there has been a **nutritional transition** over the past decades, favoured by increased incomes, urbanization and availability of cheap, industrially processed foods. 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. This dietary change has been achieved through the transformation of the food chain that promoted ultra-processed, energy-dense manufactured foods and sugar-sweetened beverages. In the past decade, only minor changes in European dietary habits have occurred, mostly confirming past trends: 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 continue to increase, driven by consumption of manufactured foods, and exceed World Health Organisation (WHO) recommendations. Wholegrain consumption is low, except in Northern countries.

There are discrepancies across European regions, although all, including the Mediterranean area, are experiencing a "westernization" of their diets.
Also, food security and affordability remain an issue in EU with millions of people who cannot afford a quality meal every second day, and requiring food assistance.

Overall, these trends indicate that current dietary habits in Europe are not in line with dietary recommendations for healthy diets. In the EU, unhealthy diets are a leading risk factor of death, **contributing to cardiovascular diseases, diabetes and some cancers**. As cardiovascular diseases remain the leading cause of death in the EU, dietary risks are responsible for 49% of all the years lost due to cardiovascular death or disability (men and women combined) in the EU. **Unhealthy diets contribute to increase overweight and obesity**. Over the last 40 years, obesity has increased threefold in several European countries. In 2019, 53% of the adult population were overweight while 17% of the adult population were obese (OECD, 2022). The cost of unhealthy diets in EU is significant. In the EU, non-communicable diseases (often linked to obesity and unhealthy diets) represent 70–80% of healthcare spending by Member States, an estimated cost of €700 billion annually[6]. This dietary pattern (high-energy consumption per day and consumption of resource-intensive foods) **also have an impact on the environment** by contributing to the global increase of greenhouse gas emissions, the pollution of waters, soil, air, and losses in biodiversity.

In order to shift dietary behaviours towards better adherence to dietary guidelines, **countries across Europe have implemented nutrition and health policies since the 2000's**, with various and complementary instruments (e.g., incentives, taxes, education, food information, public procurement). More recently, the EU Farm to Fork Strategy set the objective of "ensuring food security, nutrition and public health, making sure that everyone has access to sufficient, nutritious, sustainable food".[7]

There are also consumer's movements towards healthier diets, diets more respectful of the environment and reduced consumption of animal products.
For example, there is an increase of vegetarian and vegan diets (e.g., in Germany) and consumer choices for local products or short supply chains, with lower environmental or climate impacts.

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[6] https://ec.europa.eu/health/newsletter/169/focus_newsletter_en.htm#:~:text=70%25%20to%2080%25%20of%20all,suffer%20from%20a%20chronic%20condition

[7] European Commission Farm to Fork Strategy, 2020: https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

Based on these trends, **three hypotheses of changes to 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 composition of these three alternative diets in 2050 is presented in **Box 1** in section 5.

- In a *business as usual hypothesis*, food diets in Europe follow current trends. European diets in 2050 are characterized by high and stabilized (compared to 2023) consumption of animal products (such as meat, eggs and dairy foods), and of fat and added sugars and salts. These diets have high levels of daily calorie consumption. Combined with low levels of physical activity in urban environment, they led to an increase of obesity and diet-related non-communicable diseases.

- European consumers evolve towards adoption of healthy diets as described in Agrimonde-Terra foresight and AE2050 study[8]. Given the increasing costs of treating the consequences of overnutrition and malnutrition, public health measures were taken at European level to shift food consumption towards healthier and more diversified diets and to address the major issue of malnutrition. A healthy diet is characterized by an improvement in the energy balance with reduced energy intakes, 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 low consumption of ultra-processed foods.

- European consumers shift towards diets that are both nutritionally and environmentally sustainable ("one health"), as described in the FLEX diet of the EAT-Lancet Commission[9]. The transformation to "one health" diets by 2050 required strong dietary shifts, towards a diet with reduced caloric intake, which is rich in diversified plant-based foods (including fruits, vegetables, legumes and nuts) and with fewer animal-source foods, contains unsaturated rather than saturated fats, and limited amounts of refined grains, ultra-processed foods and added sugars.
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[8] For Agrimonde-Terra foresight, see Mora et al. (2020); for AE2050 study, see Tibi et al. (2020).

[9] For EAT-Lancet Commission on Food, Plant, Health, see Willet et al. (2019).

Changes in food value chains in Europe towards chemical pesticide-free agriculture by 2050

Imagining alternative crop protection strategies involves considering changes in the downstream of food value chains of which farms are part. It means 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.

Dynamics of interrelations between actors of the food value chain

Food value chains include the activities of storing, processing, retailing and disposing and/or reusing, and involve material and information flows. In Europe, a diversity of food value chains coexists.

Over the past decades, there has been a concentration – horizontal and vertical – at various stages of the food chain. Globally and in Europe, companies are merging at and across levels of food value chains, capturing larger market shares, and creating ever-bigger players in the processing and retail sectors, with a huge bargaining power. Such a bargaining power erodes farmers and consumers' ability to choose how to farm and what to eat. In 2011, the largest five retailers in thirteen EU Members States had a combined market share of over 60%. Retailing is the food chain stage where the biggest corporations operate, and have the highest financial power in comparison with other stages of the value chain. To differentiate themselves to consumers, large-scale general retailers and food processors apply higher private health and environmental standards than conventional standards on topics such as animal welfare, crop production practices and nutritional composition. These standards can include criteria on pesticides, and with conditional support to farmers. Large-scale processors have also developed or acquired private organic brands.

Regional and local SMEs (small and medium-sized enterprises), employing 58% of persons in the food and drink industry, 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.

Challenging the current market dynamics, and 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, some consumers support local short food value chains through direct purchases and partnerships with farmers.

The purchase of food products and catering services plays an important role within public procurement. It provides the opportunity to drive local and regional economies towards more sustainable paths by, e.g., procuring organic or local food for consumption in public schools, kindergartens, hospitals and residential. 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.

Another important recent development is the digitalization and emergence of the online sale platforms, accelerated by COVID-19 pandemic. Ordering through digital platforms ("click and collect" services) has expanded a lot, and this new delivery method has reached diverse supply chain actors including large platforms, traditional retailers, restaurants, farmers for direct selling. Big Tech transformation into Big Food is also raising concerns as advancements in technology have expanded companies' ability to communicate with consumers, but also to store and analyse data on consumers.

Technologies to store, process, preserve food in a pesticide-free agri-food system

Historically, food processing has played a key role in extending the shelf life and transportability of food, avoiding food losses and ensuring food safety. There is a continuity in the use of pesticides and preservatives along value chains, from production to consumption of unprocessed, processed or ultra-processed food. Besides, some substances are considered as both a pesticide and a preservative. European rules for organic products already apply throughout the value chain and include a limited list of approved pesticides and of chemical preservatives. 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, a number of alternative technologies using physical control or biocontrol are being developed. The food industry has been working on progressively reducing or phasing out from the use of food additives, including food preservatives. Solutions across the value chain include novel techniques for storage (i.e., prophylaxis, natural mineral products, and air circulation in cereals silos to avoid insecticides), minimal food processing with classic and more novel methods in food preservation through packaging (aseptic packaging, controlled/modified-atmosphere, active packaging with antimicrobial activities, bio-based and biodegradable edible films and coatings). Solutions also include natural antimicrobials (among which essential oils and microbial antagonists), and/or the management of the food microbiome.

Changes in consumers' attitudes towards food and purchasing behaviours

According to recent surveys, European consumers prioritise taste, food safety and cost in their food purchases. In 2022, the most important concern in food safety among Europeans is the presence of pesticide residues in food. Sustainable food products and diets are primarily associated with nutrition and health, but also with little or no use of pesticides. There are ongoing changes of consumers towards environmentally, socially responsible and healthy products, with an increasing trend of consumption of 'health and wellness' food products both in Western and Eastern Europe. Additionally, there is also a growing interest in locally-produced food, a well-established consumer trend, intensified by the COVID-19 pandemic. Authors reports also an increasing interest for vegan and vegetarian diets in some European countries.

In parallel, convenience appears as a major driver affecting food choices from consumers, which translates into increasing trend of online purchases of food products since 2007 in the EU, and increasing trend of industrialised processed food products sales.

Multiplication of food information to consumers

Food scandals, reported by media, highlight 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. In reaction, civil society organisations emphasise on gaps between stated objectives of labels and their actual impacts, and recommend developing evidence-based labels. Public authorities call for more education on food and greater transparency in food value chains. More generally, the literature points to the need to overcome information gaps and build trust among actors of food value chains, to foster changes in consumption behaviour. Different means of informing, accompanying or influencing consumer's choices have been developed or are being developed by different actors: civil society organisations, and public and private actors. Labels have appeared on front-of-pack or on the back-of-pack of a food product[10]. Labels are supposed to give consumers the opportunity to consider, 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 so-called cleanliness (e.g., Zero pesticide residue) considerations when making food choices. However, the growing number of private and public labels on food products may be confusing and bring mistrust from consumers. Researchers also emphasise on the lack of legal definitions and regulations of some labels and the misleading picture they can provide, especially the labels arguing the "cleanliness" of food[11].

In addition to the information conveyed through labels on the products themselves, recent progress in technology and communication have enabled the development of food digital platforms, intended to assess food products based on several criteria such as the nutritional quality, acceptability of additives, degree of processing, or the impacts of food products on the environment.

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[10] In line with the provisions of EU regulation 1169/2011 on Food Information to Consumers.

[11] To address this, the European Commission has planned, within the Farm to Fork Strategy, to examine ways to create a sustainability labelling framework, to better inform and empower consumers to make informed and sustainable food choices.

By 2050, actors of the food value chain will play a key role in the transition towards chemical pesticide-free food systems. **The change of the food value chain will likely shape the future for chemical pesticide-free agriculture.** Therefore, based on above-described past and current trends, and imagining how food value chains could evolve to enable the development of chemical pesticide-free agri-food systems in Europe, **three alternative hypotheses have been drawn for 2050:**

- **Chemical pesticide-free food** has become a **food safety standard** on the European food market. **Global food value chains** are dominant and vertically integrated, with large-scale retailers and/or food processors applying production standards on chemical pesticide-free food production through their contracts with farmers. They have a monopolistic access to big data all along the agri-food chain, and use them to optimise the allocation of production factors, to adapt their processing processes and optimise storage conditions, and to provide information to consumers through retail platforms.

- Consumers are increasingly concerned about the negative impacts of unbalanced and unhealthy diets on their health. They changed their diets towards **healthy diets** with healthier foods (including chemical pesticide-free foods), **turning away from unhealthy foods**. Public authorities and consumers' organisations empower consumers in making informed choices through campaigns and third party web applications. There are strong interrelations between actors of the value chains, allowing **the management of microbiomes from farm to fork. Food is preserved by closely monitoring and managing the food microbiome**. Minimal processing combined with biological control is favoured, maintaining the quality and nutritional value of food. Food is supplied at a diversity of scales – local, national, European and global.

- The civil society is concerned about **human and environmental health (including biodiversity loss),** and consumers consume chemical pesticide-free food to address these. A diversity of value chains produce **a diversity of food, rooted within territories and small regions**. Actors interact and collaborate across different levels of value chains, and between value chains (eg. crop value chains with livestock value chains). Data on the environmental footprint of food, including biodiversity, are provided by **evidence-based labels or on third party web applications**. Food is preserved by using minimal processing combined with biological control. **Logistic is adapted to crop diversification and to the seasonality of products.**

Hypotheses of change in 2050 for food value chain

Global value chains producing pesticide-free 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

Changes in public policies and trade regulations in Europe towards chemical pesticide-free agriculture by 2050

Transitioning towards chemical pesticide free agriculture requires public policies to enable, set goals, and support actors in their changes of practices. Based on the analysis of past and current trends, we drew *ad hoc* hypotheses of how public policies and their instruments could evolve to enable the development of chemical pesticide-free agri-food systems in Europe in 2050.

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 regulatory framework for pesticides uses in Europe and its changes over the last decades. Then, taking into consideration that many policies affect pesticide use, we studied public policies affecting pesticides through the topic angle, by considering the following 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 certification policies address the issue of pesticides?

Legislative framework for regulating pesticides use on the European market

The procedure for placing plant protection products in the EU market is currently regarded as one of the most stringent in the world. It has evolved over years, and continues to, by regularly including new criteria for the safety and environmental assessment of active substances.
Examples of possible future criteria include the assessment of the effects on populations of organisms, the toxicity of multiple residues, of pesticides metabolites. This has, and should continue to lead to bans of active substances, limiting the possibilities for chemical pest management.
Also, the pesticide registration regulatory framework should evolve to adapt to innovations in crop protection, including non-chemical substances such as biocontrol products.

Based on these observed trends, we hypothesize that by 2050 the pesticide registration regulatory framework will become stricter, leading to less chemical active substances available for crop protection.

Diverse EU policies dealing with chemical pesticides use reduction in agriculture

Since the 2000's, there has been a multiplication of policies to manage, reduce the use and/or risks of pesticides in the EU, designed independently of each other. These include water policies that set objectives of good chemical and good ecological status for waters in each river watershed, and maximum levels in drinking water. Then, in 2009, with the Sustainable Use Directive (SUD), the application of Integrated Pest Management principles became mandatory, and each Member State had to draw national action plan with measurable goals, targets and indicators. In practice, SUD and the national action plans have had limited effects on reducing pesticides use and risks across Europe. In 2020, the European Commission set in the Farm to Fork strategy the objective to reduce the overall use and risk of chemical pesticides by 50% and the use of more hazardous pesticides by 50% by 2030. Furthermore, in June 2022, the Commission adopted a proposal for the revision of SUD into a regulation, turning these objectives into legally binding reduction targets. Nutrition and health policies also address the topic of reducing pesticide use and risks for human health, by setting maximum residue limits for food and feed, protecting the users of pesticides from occupational exposure and associated risks, and by encouraging consumption of organic food, to reduce consumer's exposure to pesticides.

Many scientists and organizations have called for a common and holistic food system policy for Europe. The Green Deal, Farm to Fork and Biodiversity Strategies go into that direction by covering, among other, environmental, food, agriculture, health and social dimensions. Further, the European Commission is currently working on a legislative proposal for a framework for a sustainable food system, addressing comprehensively the challenges of the food system.

Simultaneously, territorial initiatives are triggered by increased societal concerns about the impacts of pesticides used in agricultural production and in urban amenities areas. Since the early 2000s, local level actions by residents have successfully influenced the establishment of municipal, territorial, or regional policies regarding pesticide uses, which go beyond the national regulatory framework. The territorial coordination of actors can facilitate collective action, development of solutions adapted to the local specificities and issues, more transparency and dialogue, and ultimately reconnect local food system actors with their consumers.

Based on these trends, three hypotheses of changes by 2050 were drawn:

- Iterative reduction objectives of pesticides use and risk 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 holistic food system policy, where pesticides reduction measures are embedded in a single Food System Policy framework with clear long-term policy goals for all actors in the value chain.
- Territorial/local and cross-sectoral policies managing sustainable food system policies including pesticides policies (but also covering land use, landscape design, water and soil protection, production, value chain and market), led by local authorities and local actors.

Agricultural policy and economic instruments to support the adoption of alternatives to chemical pesticides

Since the 90's, there has been a progressive "greening" of the Common Agricultural Policy (CAP), to incentivise changes of practices by introducing voluntary schemes, with limited effects. Therefore, in order to support the transition towards chemical pesticide-free agriculture, the CAP could be redesigned.

In line with the three above hypotheses of changes in policies managing or reducing the uses and/or risks of pesticides, and based on current trends in the CAP, we built three alternative hypotheses of re-design of the CAP by 2050:

- Enhanced conditionality of CAP payments to the compliance with pesticide reduction and then pesticide-free targets.
- Integration of agricultural policy into a holistic food system policy and oriented towards nutrition and health goals, and sustainability targets (water, biodiversity, soil).
- Payments for ecosystem services provided by all actors including farmers, within a territory.

In addition, there is in the literature a number of works where authors propose to complement such re-design of the CAP by various combinations of economic instruments, in order to make the whole policy package more impactful Examples of efficient mixes of instruments include: covenants (agreements between parties) and subsidies for transition, certification and subsidies for transition, subsidies for transition and regulation (ban) in the long term, advice on alternatives combined with insurance systems (private, mutualisation fund), taxes on pesticides and subsidies on alternatives, subsidies on consumers and certification (products without pesticides).

International trade policies and pesticides

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 with Codex Alimentarius food maximum residue limits, or OECD testing standard protocols for toxicological studies. Within the World Trade Organization (WTO), pesticides are covered under the Sanitary and Phytosanitary measures agreement, which allows countries to set their own standards, provided that they are applied only to the extent necessary to protect human, animal or plant life or health, and that they do not discriminate between countries where identical or similar conditions prevail. Several collaborations have been developed between countries regarding pesticide regulatory programs. Also, international private standards set specific rules regarding pesticides use in agricultural production.

Europe currently applies the EU maximum residue limits to imported food and feed products, but does not impose its requirements on the use of pesticides in the fields. This question of applying similar production standards for products produced outside and inside Europe is frequently put on the agenda of policy makers. It can be justified by health and environmental protection objectives, and could be included in the future bilateral trade agreements between Europe and some regions (reciprocity or "mirror" clauses). Europe could also lead the discussions within international organisations – WTO, Codex Alimentarius – to reach a common worldwide agreement.

Based on these trends, two hypotheses of changes by 2050 of European trade policies were drawn:

- Global harmonised regulation on pesticides in line with WTO and *Codex Alimentarius.*
- Trade agreements including mirror or reciprocity clauses related to pesticides use.

4

Scenarios and transition pathways for a chemical pesticide-free agriculture in Europe in 2050

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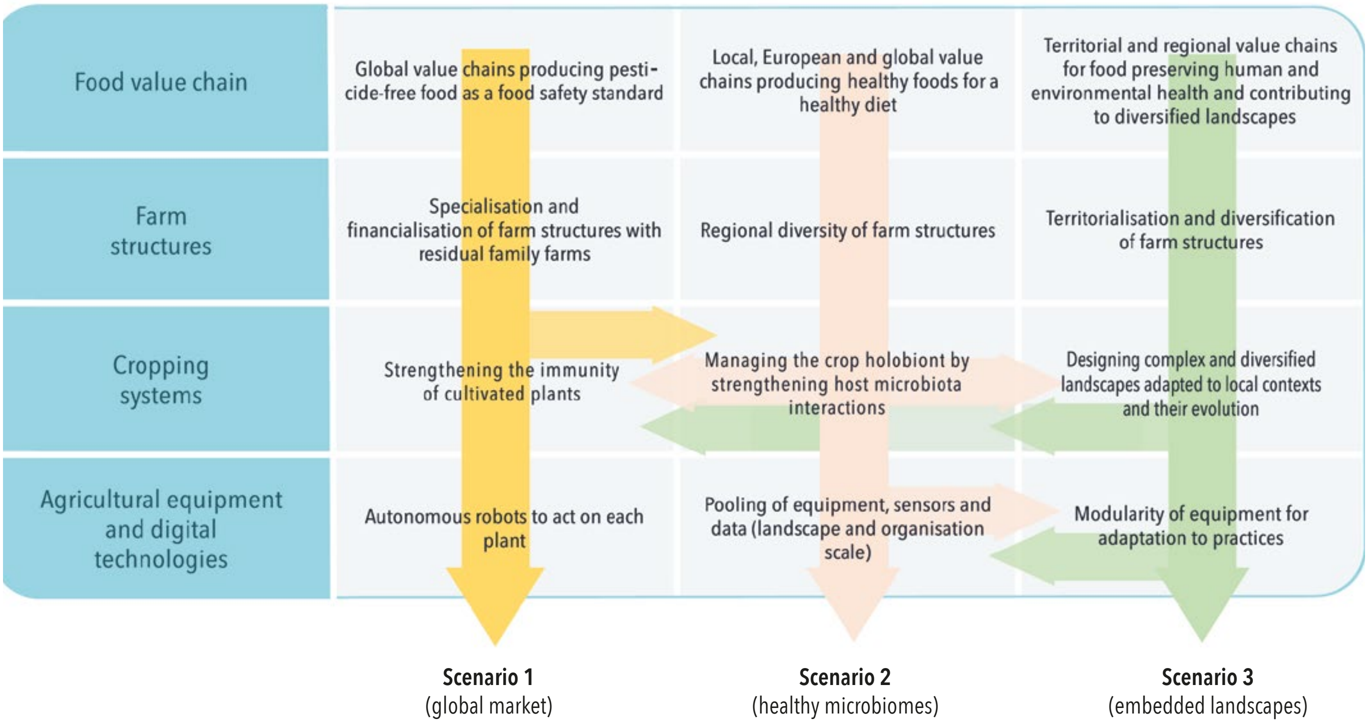
Based on the hypotheses of changes for the different components of the systems in 2050, presented previously, three scenarios and their transition pathways were built, and then were translated for specific crop systems and regions in Europe.

The scenarios of pesticide-free agriculture in Europe in 2050 were built by using a morphological table that gathers the hypotheses for 2050 developed in the previous sections for four components: food value chains, agricultural structures, cropping systems, and agricultural equipment and digital technologies. The morphological table contains the morphological space of changes of the system, i.e. the set of states of the system that can be generated from the parameters of the table (i.e. the hypotheses of changes). A scenario is defined by a combination of hypotheses of changes in 2050 for each component of the system. The choice of the combinations of hypotheses that led to the construction of the scenarios by the European expert committee meets a certain number of criteria including the consistency of the hypotheses, the plausibility of the combination, and the contrast between combinations. For the cropping systems concerned, several hypotheses were combined for a single scenario, with a dominant hypothesis and one or two secondary hypotheses. A narrative describes each scenario.

Using a backcasting analysis, we built a transition pathway for each scenario showing the sequencing of actions, their outcomes, and the interactions among system components along a pathway from today to 2050. The transition pathways include *ad hoc* hypotheses on public policies, education and agricultural knowledge and information systems (AKIS), and dietary changes that supported the transition to the scenarios. For each scenario, a transition pathway was synthetized in a circular figure. Some selected elements of the pathway were integrated into the narrative.
In parallel, the three scenarios were tested and illustrated through regional case studies in four European countries (Finland, France, Romania and Italy). The regional case studies complemented the work done at the European level by illustrating the European scenarios and their transition pathways. It was also a way to check the relevance of the scenarios for building pathways towards pesticide-free agriculture in 2050, in specific contexts.

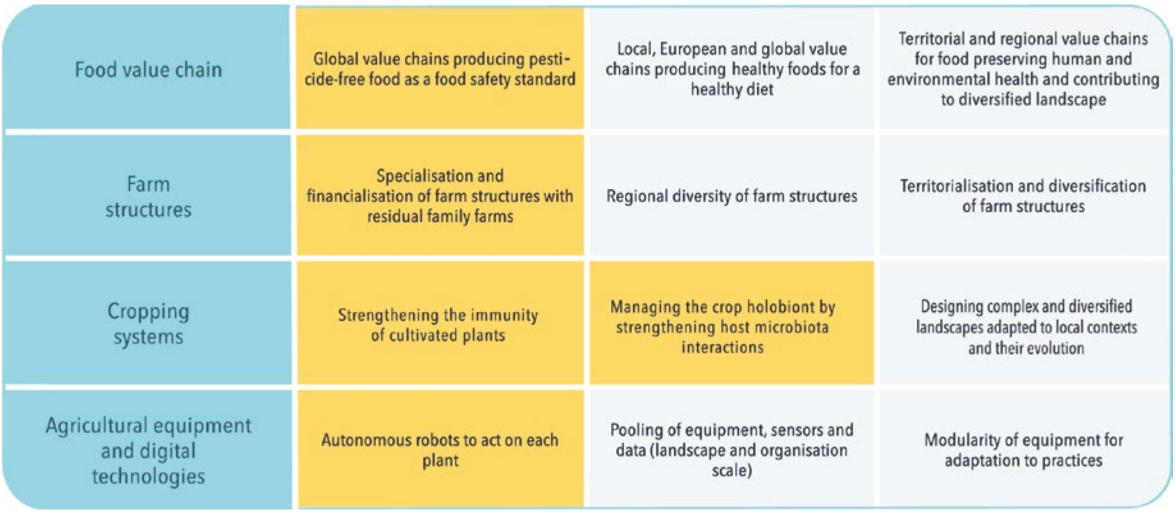


Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscapes
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 the immunity of cultivated plants	Managing the crop holobiont by strengthening host microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their evolution
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 1 (global market)	**Scenario 2** (healthy microbiomes)	**Scenario 3** (embedded landscapes)

Table 1: *Morphological table with the combination of hypotheses of change to 2050 corresponding to each scenario*

Scenario 1 (S1) and its transition pathway:

Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market



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 the immunity of cultivated plants	Managing the crop holobiont by strengthening host microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their evolution
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

Table 2: *Morphological table with the combination of hypotheses of change in 2050 corresponding to scenario 1*

In 2050, international market standards guarantee that food products come from chemical pesticide-free agricultural systems. The building of a transnational pesticide-free food market has been achieved through the inclusion of chemical pesticide-free specification of food products, in bilateral agreements between the European Union (EU) and trade partners. European and global value chains that are highly concentrated, highly capitalistic and intensive in technology, have promoted private certifications and contracts with farmers based on price premium. Large-scale retailers and processors govern value chains, control the different stages of food value chains from production and input supply (seeds, biological inputs, and equipment) to logistics.

Under the pressure of the food value chains, farm transition to pesticide-free production occurred through digitalisation and automation including the monitoring of pests, and by using high levels of external inputs. Farms have conducted massive investment in robotisation and digital infrastructures thanks to external capital, and have specialised. Private companies of the upstream sector conducted the breeding and marketing of resistant and tolerant varieties (including variety mixtures) and provided access to inputs such as biocontrol products (e.g. microorganism inoculations), plant defence stimulators and bio-stimulants. Agricultural equipment companies have developed robots based on artificial intelligence, and sell equipment, advices and monitoring services to farmers.

In the cropping systems, the crop protection strategy focuses on strengthening the immunity of each cultivated plant by anticipating pest arrival and measuring the physiological status of the plants. Based on large database, combining real-time observation via sensors, drones, remote sensing and sampling and predictive modelling, autonomous devices such as robots, companion robots and swarms of robots distinguish the different cultivated plants in the plot and implement an individualised action on each plant. The crop protection is enriched, for the weed management, by a diversification of cultivated crops through introducing service plants into crop successions. Moreover, the management of animal pests is done through biocontrol or allelochemistry products.

European public policies have supported this transition through a strong conditionality of Common Agricultural Policy (CAP) support based on the non-use of chemical pesticides in cropping systems, and through a policy of re-conversion of small farmers that could not achieve the investment needed.

Transition pathway for scenario 1

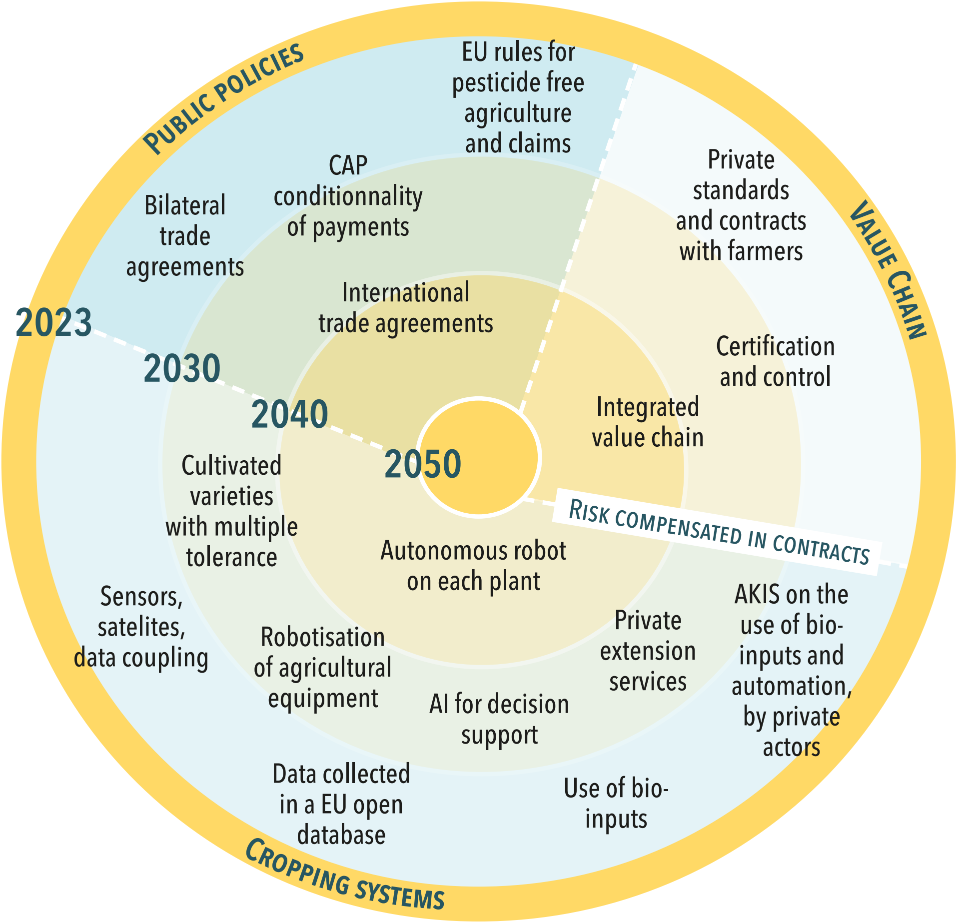


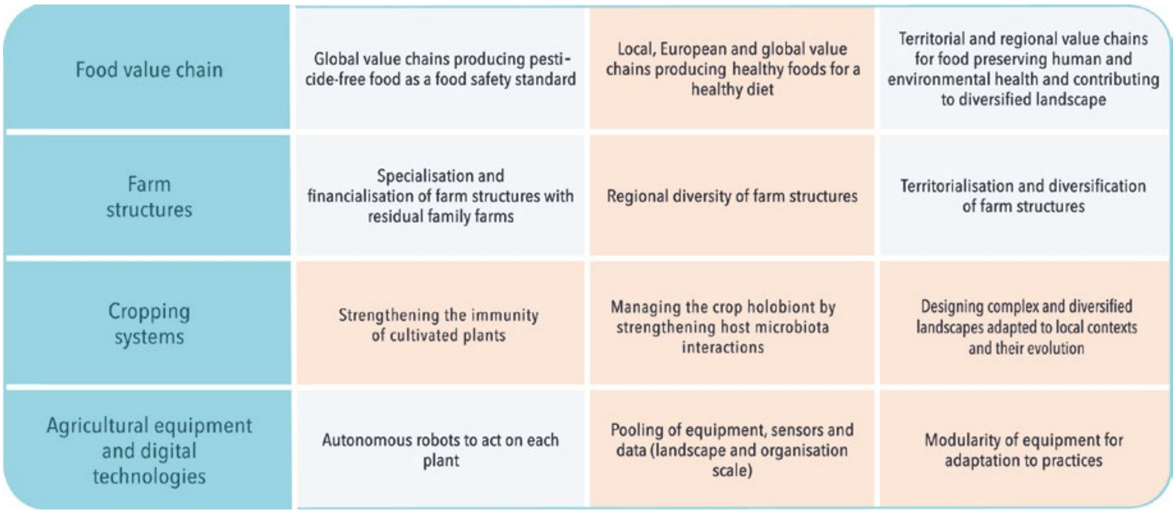
Figure 4. *Transition pathway for scenario 1, covering public policies, cropping systems (including AKIS), diet and value chain*

The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components, and ordered chronologically by decades.

- 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 to zero pesticide use
- International agreements to develop pesticide-free international markets

Scenario 2 (S2) and its transition pathway:

European food chains based on plant holobiont, soil and food microbiomes for healthy foods and diets



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 the immunity of cultivated plants	Managing the crop holobiont by strengthening host microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their evolution
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

Table 3: *Morphological table with the combination of hypotheses of change in 2050 corresponding to scenario 2*

In 2050, the demand for healthy food has led to the development of regional and European value chains and agriculture without chemical pesticides. The objective of healthy diets and pesticide-free production affected all actors of the value chain. This change was supported by the implementation of a European holistic policy linking agricultural, food chain, nutrition and health, biodiversity, soil and water policies. EU bilateral trade agreements have helped to build a European market of pesticide-free and healthy foods by including reciprocity clauses on environment and health.

European consumers, fully aware about the benefits of healthy food and the importance of microbiota, have achieved a dietary shift towards a diversified and balanced diet, helped by the implementation of subsidies on healthy foods and taxes on unhealthy ones. In 2050, European consumers eat only foods produced without chemical pesticides, avoid ultra-processed foods, and eat more fruits, vegetables, legumes, whole grains, and less sugars, fats, animal-based foods, and salt.

To increase the diversity of food available, retailers, processors and cooperatives have organised and diversified regional commodity chains, notably through the creation of certifications and labels, resulting in diversified farming landscapes. For dealing with pests, crops and food are protected and preserved by closely monitoring and managing the microbiomes from field to fork, and by favouring minimal processing combined with biological control over the use of chemical food additives (including preservatives) and biocides.

Centres of excellence on microbiome knowledge have developed new tools for the monitoring of soil microbiota and plant holobiont health at the field level, as well as food microbiomes. They have built new infrastructures of data and knowledge on plant holobiont, soil microbiome, and food microbiomes. Based on these tools, farmers have defined management strategies of cropping systems that require high level of management skills for dealing with pests.

The crop protection seeks to strengthen the functions of the soil microbiota through increasing its biodiversity, the adaptability of the plant holobiont when facing biotic or abiotic disturbances, and to enhance plant protection. Specific cropping practices modulate microbiota (organic amendments, requiring maintaining some livestock production, residue management, diversification, rotation, tillage, cover crops). Inoculation of key microorganisms and selected varieties enhance positive plant-microbiota interactions. Other levers are mobilised for crop protection: crop diversification, including rotation, and tillage for weed management, and biological regulation through beneficials at the landscape level for animal pest management.

The holistic European food system policy supported this transition by conditioning farms subsidies to the shift to chemical pesticide-free cropping systems and to the development of agricultural productions in line with dietary targets.

Transition pathway for scenario 2

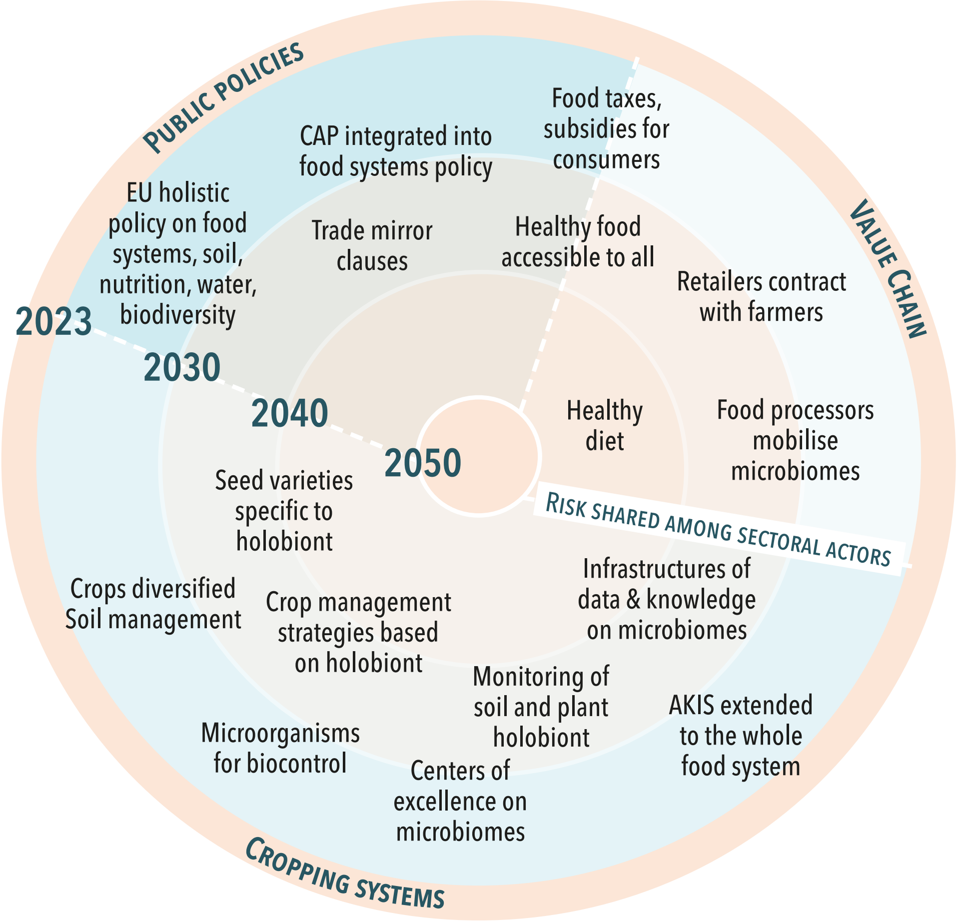


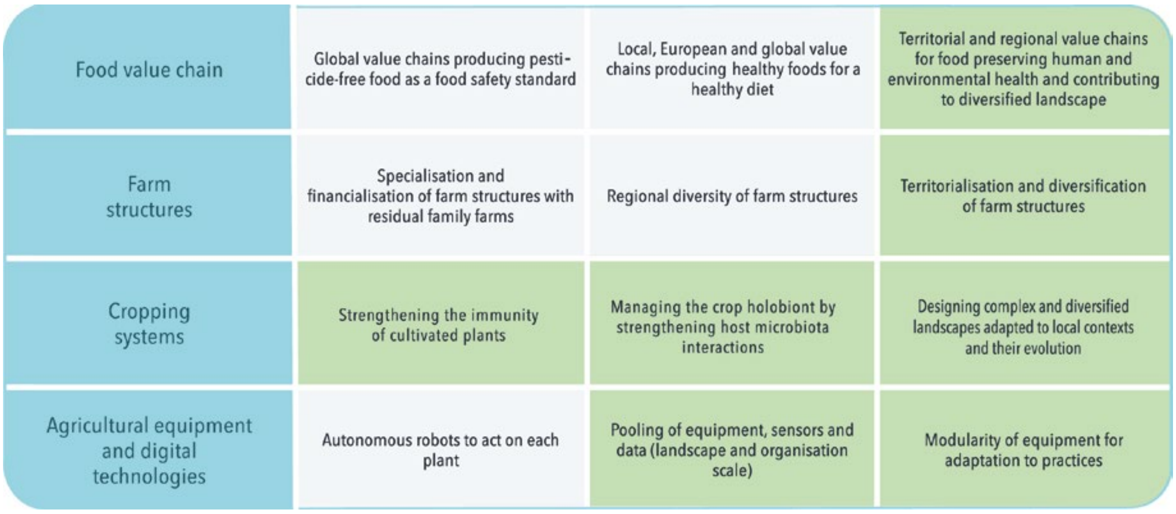
Figure 5. *Transition pathway for scenario 2, covering public policies, cropping systems (including AKIS), diet and value chain*

The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components.

- 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 the actors of the value chain
- Collective learning on microbiomes functionality, use of monitoring tools and implementation of holobiont-based crop management strategies (rotation, crop choice, fertilisation)

Scenario 3 (S3) and its transition pathway:

Complex and diversified landscapes and regional food chains for a one-health European food system



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 the immunity of cultivated plants	Managing the crop holobiont by strengthening host microbiota interactions	Designing complex and diversified landscapes adapted to local contexts and their evolution
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

Table 4: *Morphological table with the combination of hypotheses of change in 2050 corresponding to scenario 3*

In 2050, territorial and regional food supply chains produce food that preserve human and environmental health as part of a territorial-based transition towards a one health food system at European level. This transition addressed two concerns: a demand for pesticide-free local and healthy food and a global concern for biodiversity preservation and environmental health.

The transition was triggered by the coordination of farmers, private and public actors. Territorial coordination had conducted a redesign of agricultural production systems based on complex landscapes, soil microbiomes and diversified crops, and a relocation and diversification of value chains to supply consumers and inhabitants with healthy products. Cross-sectoral and decentralised policies have been set up by territorial authorities to redesign landscape, protect soil, water and biodiversity and relocate food value chains through land use planning and participatory process. Agricultural production is sold through short and long supply chains. Beside the relocation of some food chains, part of the production is traded among European 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. Food is preserved by using minimal processing combined with biological control during storage and retailing.

Cropping systems and crop protection rely on biological regulations at the landscape and soil levels with little use of external inputs. In living labs at territorial level, diverse actors including farmers and researchers have co-conceived and tested cropping systems that strengthen biodiversity and regulate pests. They include diversification strategies and landscape design.

The 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 (20% of land covered by natural and semi-natural habitats), and partial development of mixed farming with a reintegration of the animal production in farms in line with dietary change. Extensive livestock farming contributes to the closing of biogeochemical cycles, essential to European agriculture. The mosaic of crops is adapted in its composition and configuration to the issues of crop protection; it is diversified over space and time with reduced field size. The management of plant diseases relies on prophylaxis mobilising knowledge about pest and disease cycles, as well as biological regulations from soil microorganisms and landscape. The weed management strategy is handled to find a compromise between crop losses and services provided at the landscape level. Mechanical or biological control methods are used only as a last resort or transiently.

A new EU policy, replacing the CAP, aimed at rewarding ecosystem services delivered by farmers and beyond by all the actors of the territory, supported the transition of farms and territories to a one health food system. To create a conducive economic environment for the transition in food markets, EU implemented high taxes on imports of products used for human food from crops cultivated with chemical pesticides, and reciprocity clauses related to One Health in bilateral trade agreements.

Transition pathway for scenario 3

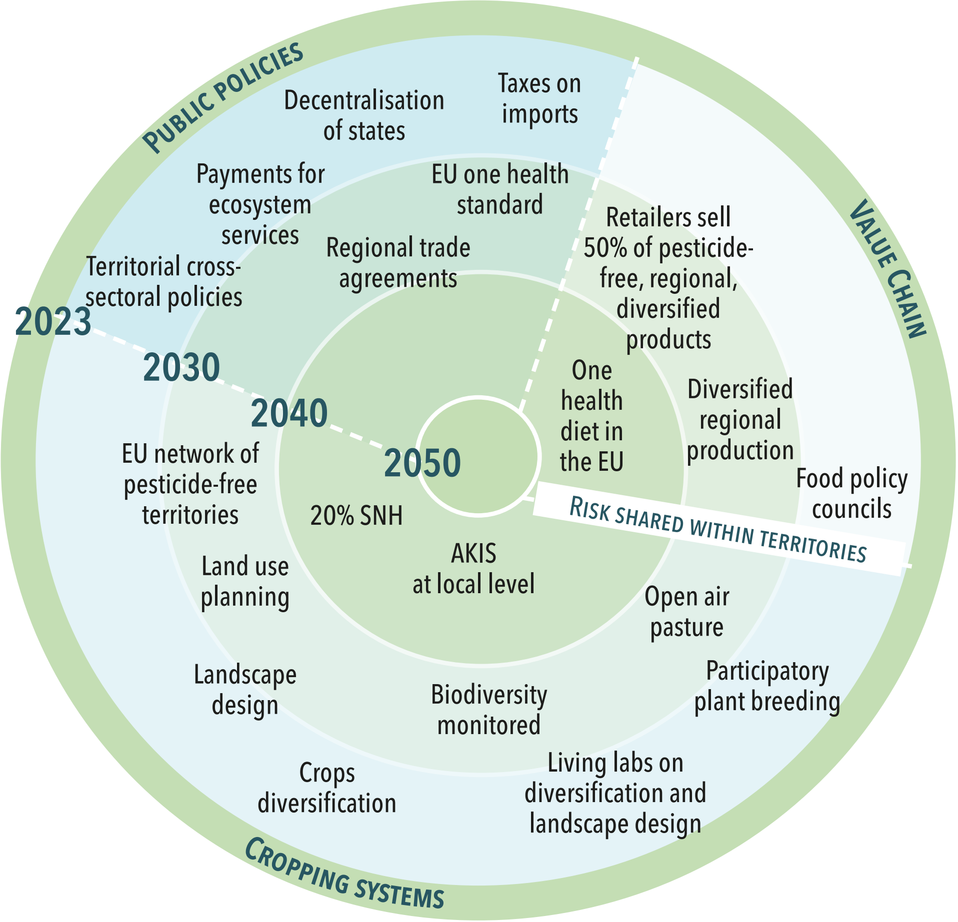


Figure 6. *Transition pathway for scenario 3, covering public policies, cropping systems (including AKIS), diet and value chain The circles represent decades: 2023-2030, 2030-2040 and 2040-2050. The main milestones of the transition are represented for each of the components.*

- Coordination of actors at territorial level: public, private, citizens. Cross-sectoral territorial policies that aim to reorganise local value chains develop the territory and 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

Downscaling scenarios and transition pathways at regional scale: four case studies across Europe

Participatory foresight workshops with 15 to 20 local stakeholders and researchers each (scientists, farmers, technicians and consultants, representatives from non-governmental organisations, food and agroequipment companies, and local authorities) were conducted in four European regions, to build scenarios and transition pathways towards chemical pesticide free sectors by 2050.

We used in the four case studies the same methodology based on backcasting, combined with the scenario of chemical pesticide free agriculture in 2050, as described in chapter 1 "introduction and method".

These case studies illustrate how European scenarios can be translated in a specific region and for a specific sector, engaging public and private actors around the elaboration of a common vision, and identifying pathways of milestones and actions to reach it.

2050 SCENARIO FOR DURUM WHEAT PRODUCTION IN TUSCANY (ITALY) BASED ON EUROPEAN SCENARIO S1

Durum wheat is produced without chemical pesticides, in compliance with market standard, and Tuscan pesticide-free wheat and pasta products are exported worldwide. Production occurs in large and specialised farms in Tuscan plains, equipped with cutting-edge technologies, allowing farmers to work at very large scale with little labour force and with a high working speed. The use of precision farming is spread and almost all the equipment used for the main operations, from sowing to mechanical weeding until harvesting, are satellite-guided.

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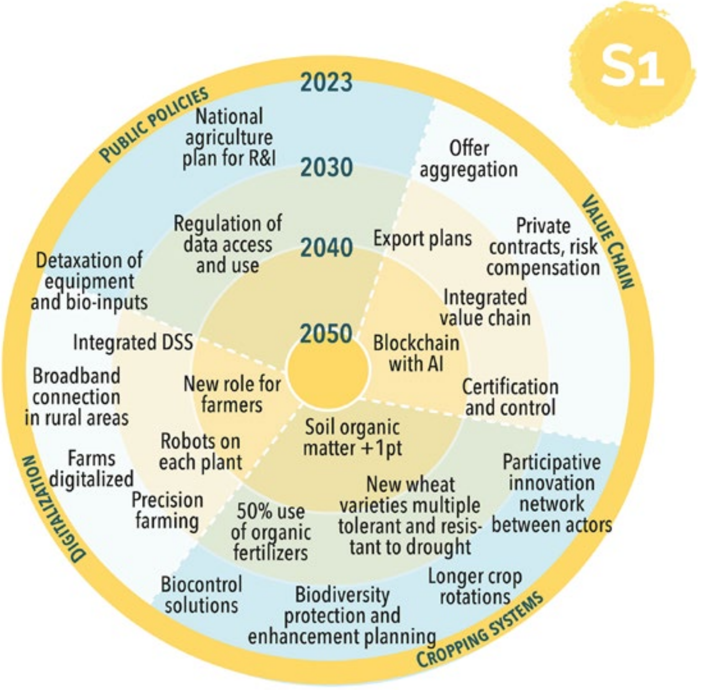

Figure 7. *Target diagram summarising the key transition steps chemical pesticide-free durum wheat production in Tuscany (Italy)*

Key transition steps

Private food companies and retailers set production standards including on the use of chemical pesticides, and contract with farmers for risk compensation. Farmers gather into big cooperatives where products offer is aggregated. They are certified against the private standards, and get access to participative innovation network and technical support. A national agriculture plan funds research and innovation into breeding, digital technologies, and their de-taxation, to facilitate farmers investments. Farmers mobilize these new technologies of precision farming to reduce progressively the use of chemical pesticides. They also manage soil health to increase its organic matter. The durum wheat chain becomes fully integrated and exports on international markets.

R&I : research and innovation ; DSS : Decision Support System ; AI : Artifical Intelligence

2050 SCENARIO FOR VEGETABLE PRODUCTION IN SOUTH-EAST ROMANIA BASED ON EUROPEAN SCENARIO S2

A diversity of vegetables are grown by organisations of farmers 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. These vegetables are distributed through short chains, local food systems, regional and national outlets. They are considered by public authorities and consumers as priority products, and have become major contributors to healthy Romanian diets.

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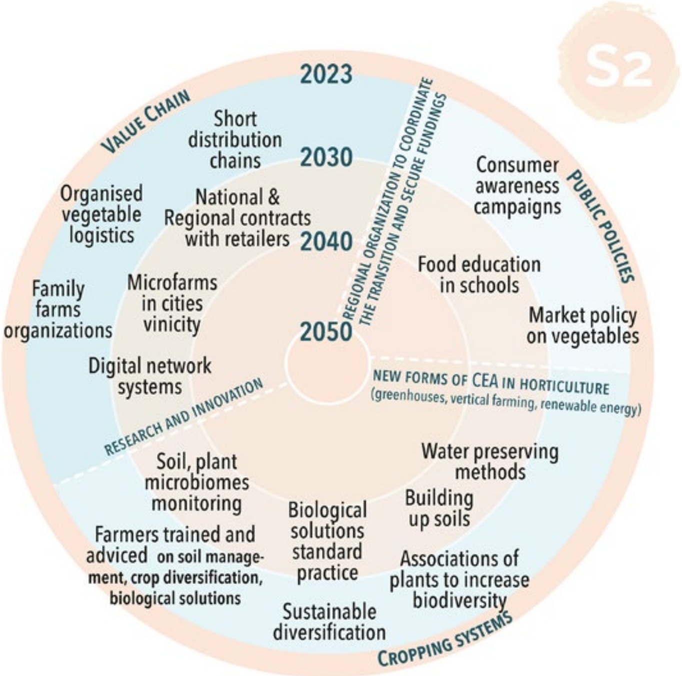

Figure 8. *Target diagram summarising the key transition steps chemical pesticide-free vegetable production in South-East Romania*

Key transition steps

Private food companies and retailers set production standards including on the use of chemical pesticides, and contract with farmers for risk compensation. Farmers gather into big cooperatives where products offer is aggregated. They are certified against the private standards, and get access to participative innovation network and technical support. A national agriculture plan funds research and innovation into breeding, digital technologies, and their de-taxation, to facilitate farmers investments. Farmers mobilize these new technologies of precision farming to reduce progressively the use of chemical pesticides. They also manage soil health to increase its organic matter. The durum wheat chain becomes fully integrated and exports on international markets.

CEA : controlled environment agriculture

2050 SCENARIO OF CEREALS AND OILSEEDS PRODUCTION IN SOUTH FINLAND BASED ON EUROPEAN SCENARIO S3

Cereals and oilseeds are produced locally, without chemical pesticides, answering Finnish concerns about environmental protection, preservation of rural areas, and food sovereignty. Diversified cereals, oilseed and legumes crops are protected from pests by preventive farming practices, leveraging biological regulations and arranging a mosaic of areas at landscape scale. 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. Farmers environmental protection services are explicitely targeted by public subsidies. There is a strong cooperation between farmers, advisory organisations, and other actors at local level in order to share equipment and, also, for monitoring weather and ecosystem dynamics.

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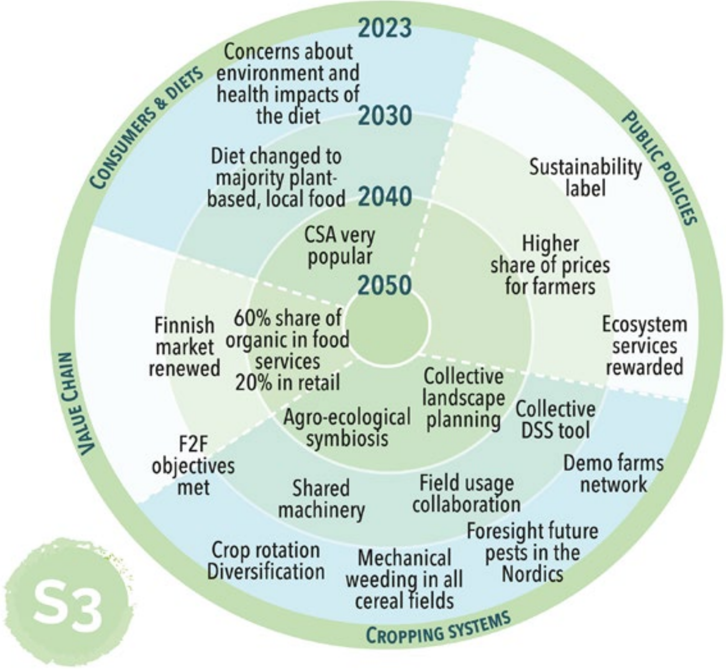


Figure 9. *Target diagram summarising the key transition steps chemical pesticide-free cereals and oilseeds production in South Finland*

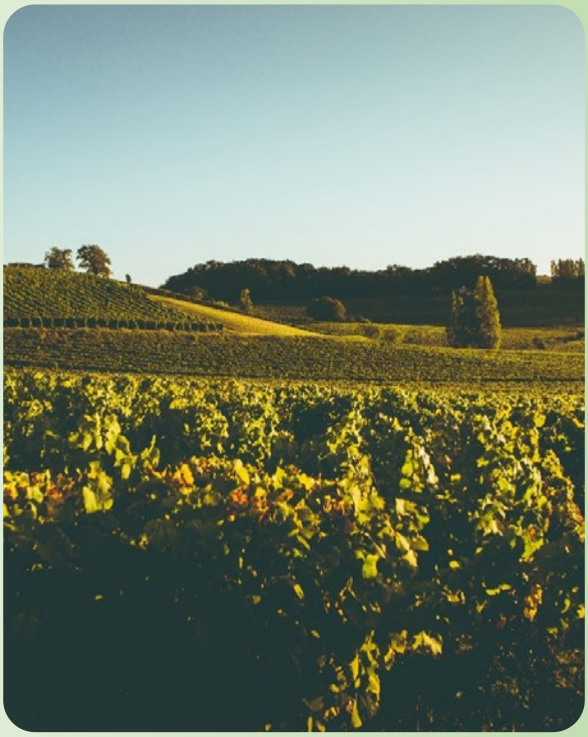
Key transition steps

Finnish consumers concerns about the impact of their diets on the environment trigger changes in the food value chain: the share of organic products increases and the food market evolves towards more diversity of local products. Finnish consumers support the transition of local agriculture, which evolves progressively towards increased organic farming, diversification of cereals, oilseeds and legumes productions. Transition in the cropping systems goes by sharing best practices through demo farm network, payments for ecosystem services, fairer share of food prices for farmers, and an increased collaboration between farmers and local actors, up until the implementation of agro-ecological symbiosis.

CSA : community supported agriculture ; F2F : farm to fork ; DSS : decision support system

2050 SCENARIO FOR WINE PRODUCTION IN BERGERAC-DURAS (FRANCE) BASED ON EUROPEAN SCENARIO S3

The wine sector succeeded its agro-ecological transition by mobilising all the stakeholders in the region. Ecological processes at the landscape level are favored and the vineyard is valued for its gustatory and environmental qualities and as an element of cultural heritage. Mosaics of crops (vines, fruit trees, hazelnut trees, cereals, pastures) and semi-natural habitats (hedgerows, copses, flowering strips, wetlands) 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. A social contract bonds together the actors of Bergerac Duras - winegrowers, wine producers, cooperatives, local authorities, residents' associations, industries - around the same territorial project.



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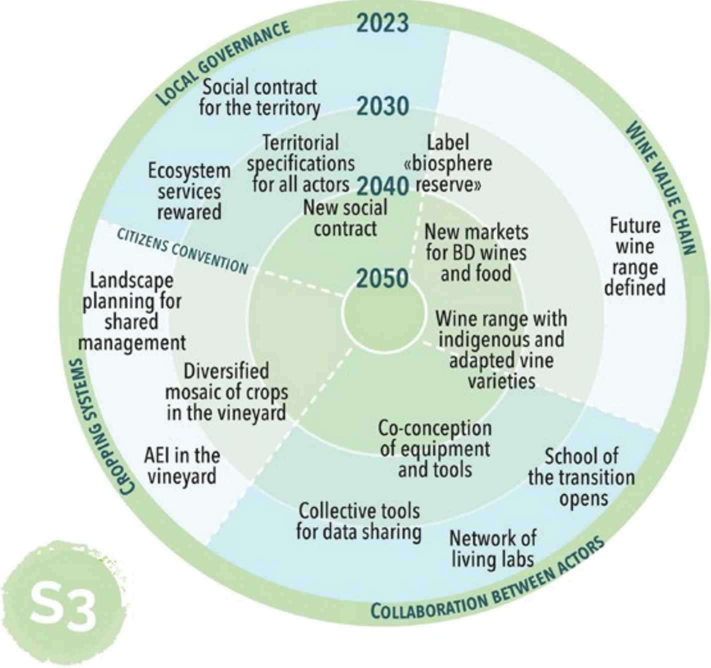

Figure 10. *Target diagram summarising the key transition steps chemical pesticide-free wine production in Bergerac Duras*

Key transition steps

The transition starts with a common agroecological project put through by local actors, followed by the set up of a participatory governance around the social contract of the territory. It organizes the transition, the landscape planning, the fundings including the payment of ecosystem services. A citizen convention monitors and gives inputs all along the transition. Actors increasingly cooperate, share knowledge, practices, results of experiments, and co-develop solutions towards the same goal: the « biosphere reserve » certification for the territory. It opens new markets for the Bergerac Duras renewed wine range and for the diversified local food products.

AEI : agro-ecological infrastructure ; BD : Bergerac Duras

5

Impacts of the scenarios on European agricultural production and trade, land-use change and greenhouse gas emissions

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The three scenarios are combinations of alternative hypotheses of change to 2050 for each component of the system. The quantitative assessment of the three scenarios with the GlobAgri-AE2050 model requires to translating each hypothesis of change for each component into quantitative values of related input variables or parameters of the model. The GlobAgri model is based on biomass balance, and does not include prices. By definition, a model is a simplified representation of the considered system and only a few components and their hypotheses of change can be considered in the quantitative assessment. Such components are "Food diets", trade regimes as part of "Public policies and trade" and "Cropping systems". Table 5 provides an overview of the assumptions adopted for the simulation of each scenario.

	Scenario S1: Global and European food chains based on digital technologies and plant immunity for a pesticide-free food market	**Scenario S2:** European food chains based on plant holobiont, soil and food microbiomes for healthy foods and diets	**Scenario S3:** Complex and diversified landscapes and regional food chains for a one-health European food systems
Diets	Trend diet (same as in the reference[1] scenario)	Healthy diet based on Agrimonde-Terra and AE2050 Including half reduction in food wastes	Flex diet of the EAT Lancet Commission Including half reduction in food wastes
Crop yields	**Lower-bound (lb)** Reference minus ½ yield gap organic vs. conventional agriculture		
	Upper-bound (ub) Lower-bound + 50% yield response to diversification	**Upper-bound (ub)** Lower-bound + 75% yield response to diversification	**Upper-bound (ub)** Lower-bound + 100% yield response to diversification
Cropping intensity[2]	+8%	+8%	+12%
Max cultivable area	No cropland expansion		Cropland decrease (-3.5 Mha) in order to save space for semi-natural habitats (SNH) (> 20% land area)
Trade	No restriction on imports	Restrictions on imports for plant products used for food and for plant and animal products used for ultra-processed foods	Restriction on imports for all products

Table 5: *Overview of the quantitative hypotheses*

[1] The reference scenario is a trend scenario. It depicts the European agri-food system in 2050 if current trends remain in place.
[2] Cropping intensity = total harvested area/total cultivated area. It may be greater than 1 (e.g., multi-cropping) or lower than 1 (e.g., fallow).

Furthermore the three scenarios are described in Box 1 through a set of graphs related to model input assumptions and model output results, that allows to draw a picture of the agri-food system in Europe in the base year "2010" (average 2009-2011), and in 2050 under our three scenarios. Based on these graphs, 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% (scenario S3 and scenario 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 decrease in European exports in comparison with 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 -16% 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[12]. 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. Sce-

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[12] These freed pastureland could also remain in 2050, and be used for extensive livestock or other uses (energy production for example).

[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.

narios 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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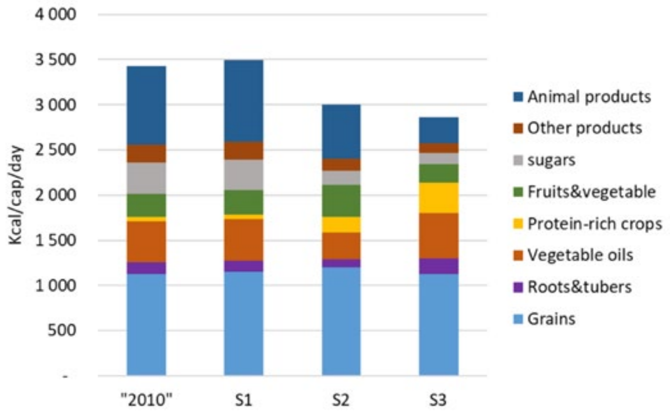
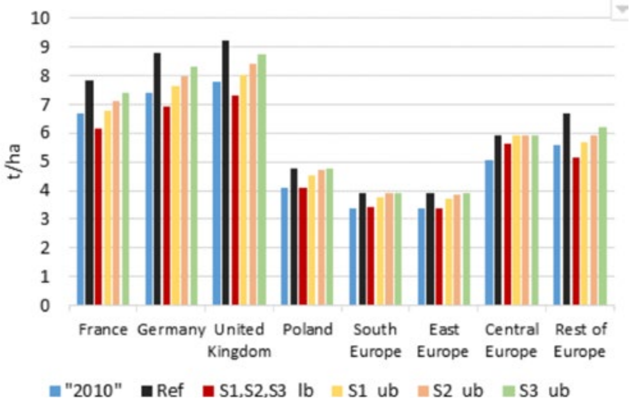
[15] Regulation COM/2021/554

Box 1. A set of graphs for describing scenarios

Hypotheses on diets and crop yields in 2050 under the three scenarios



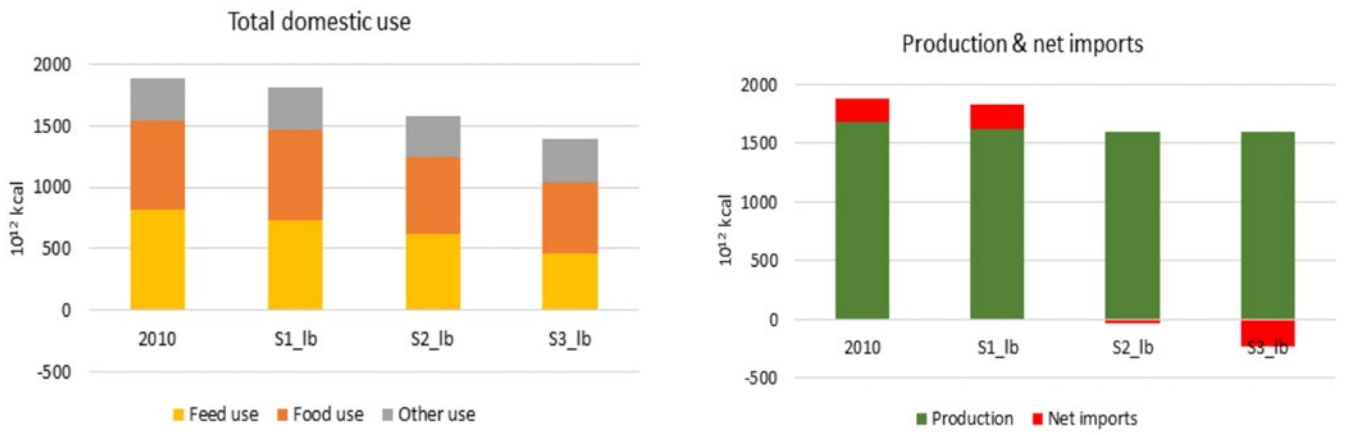
Average European diet (2010 and 2050)[1] (kcal/cap/day)



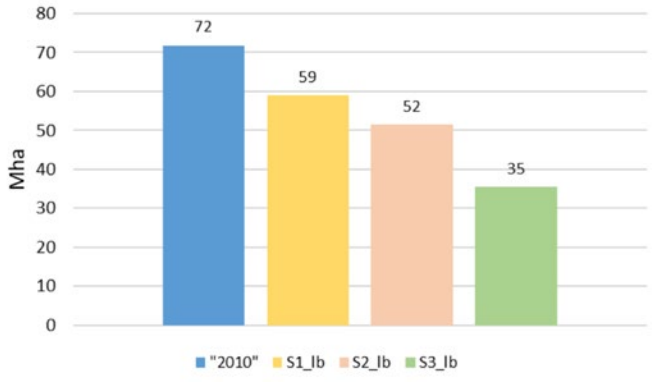
European crop yields in 2010 and 2050 (lb and ub hypotheses): the wheat example (t/ha)

[1] Diets are differentiated across European sub-regions (same assumptions apply everywhere but on differentiated 2010 diets)

Some simulation results



European resource-use balance (2010 and 2050) (10^{12} kcal)



Permanent pastureland area (2010 and 2050) (Million ha)

Agricultural GHG emissions (2010 and 2050) (Mt CO_2 eq.)

6

A transversal view of the scenarios

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In this section, we first describe the general strengths and weaknesses of the scenarios. We then present a transversal analysis of the cropping systems in the three scenarios, in terms of type of intensification, resilience in face of climate change and research needs for the implementation of such changes. Finally, we identify the robust elements, common to all scenarios, of a transition towards pesticide-free agriculture.

Strengths, weaknesses, opportunities and threats (SWOT) of the scenarios of chemical pesticide-free agriculture

Members of the European expert committee of the foresight conducted a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the three scenarios, to identify their main advantages (internally – strengths, and externally – opportunities), and obstacles to overcome (internally – weaknesses, and externally – threats).

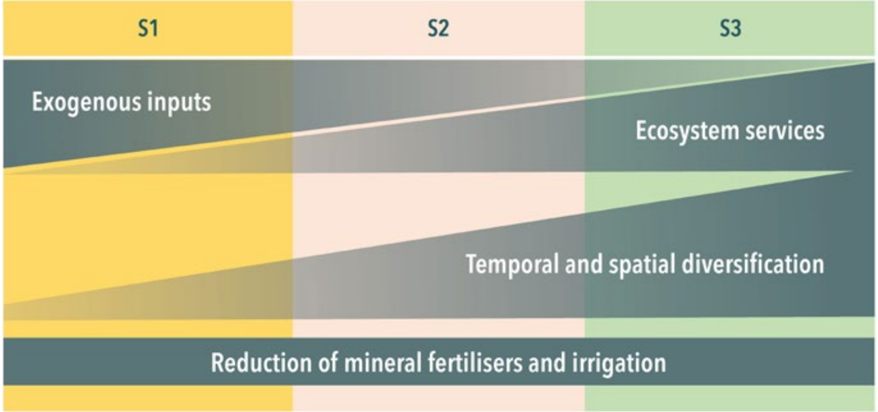
Scenario 1 main strength is that it sets a global pesticide-free food market, meaning that **the same goal will be shared across Europe.** Also, the main technologies, digital, knowledge, infrastructures for data needed for this scenario are already available, and the global firms are already in place. It **does not involve ruptures** in consumers diet and in food systems organisation. It does however require **major developments in technologies**, including digital technologies, equipment, infrastructures for data management, in line with current innovation policies implemented across Europe. Its major weaknesses are that it could **decrease the public control** on the food system, and that it will **require strong investments** by farmers to acquire these technologies, who may face difficulties to mobilise enough capital. It also raises the issue of the **ownership of data and of capital** by private companies, and on the **dependence on resources** (energy, raw materials notably). 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 farm structures, 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**, linked to 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. As a consequence, it would require **time and resources** to acquire the necessary knowledge and propose solutions, by 2050. Also, in this scenario **cooperative systems** could not be ready and willing 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 solutions such as micro-organisms, ending up creating **a dependency on this new type of pesticides**, 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 developement 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 climate change challenges: achieving GHG emissions reduction targets, 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). One of the main challenges with scenario 3 is that it requires strong coordination between farmers and diverse stakeholders within a territory for managing landscape **complexity, at different levels**. Also, it requires actors to think and implement **long-term and large-scale reasoning for farmers, and policy-makers.** Finally, the scenario requires farmers to reverse their specialisation, and to **manage different tasks and activities** (linked to crop diversification, management of semi-natural habitats…). 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 in this support. The scenario is highly **dependent on consumers willingness to change their diet.**

A comparative view of the chemical pesticide-free cropping systems in the three scenarios in terms of intensification

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 exogenous inputs (such as biocontrol products, plant defence stimulators, and fertilisers), ecosystem services, as well as temporal and spatial diversification (Fig. 11). In all three scenarios, there will be a reduction in the use of mineral fertilisers and irrigation.



On one end, in S1, cropping systems have a high level of exogenous inputs and a low level of crop diversification and ecosystem services.

On the other end, in S3, cropping systems mobilise a low level of exogenous inputs, and a high level of diversification and ecosystem services.

Figure 11. *Intensity gradients for the cropping systems in each scenario*

Climate change and resilience to pests of the chemical pesticide-free cropping systems in 2050

Climate change will be characterised by an average increase in global surface temperatures and CO_2 concentrations by 2050. Precipitation is expected to increase (resp. decrease) in Nordic and temperate (resp. in Southern temperate and Mediterranean) latitudes of Europe, with spatial and temporal variations. Climate change will affect the pressure of insect pests whose physiology and dynamics are mainly influenced by temperature (e.g. on voltinism, winter survival), and also by humidity (e.g. on winter survival) and wind (e.g. on insect dispersal). It will also influence pathogens whose entire life cycle is mainly influenced by temperature and humidity (e.g. increased precipitation may favour the dispersal of spores of certain species, the extension of the growing season could allow greater inoculum production for some species and increase the frequency and intensity of infections). Pressure from weeds will also be affected, since their growth and development depend, as for crops, on temperature, precipitation and CO_2 concentrations.

Climate change will also lead to changes in the geographical distribution of pests and crops across Europe, with an increased risk of introducing pests that may become invasive, as well as developmental synchronies between pests and their host plants (e.g. aphid eggs that emerge during host leaf fall have better fitness than those that hatch earlier or later in the season). However, the results obtained in these studies are specific to the pest, the host plant and the interactions between the pest and the host plant, as well as to the agro-pedoclimatic conditions of the study, so that extrapolations and generalisations must be considered with great caution.

Climate change will also result in an increase in climatic hazards and extreme events (heat waves and droughts, heavy rainfall and floods, storms…), which makes it difficult to predict the effects of pests on crops. It is therefore preferable to focus on the resilience[16] of cropping systems, which can be assessed through their robustness and their adaptability (Tab. 5) to pests under climate change by 2050.

Implementing crop protection strategies without chemical pesticides: what are the research needs?

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. They highlighted that, to support the hypothesis 'Designing complex and diversified landscapes adapted to local contexts and their changes', a vast body of knowledge already exists on the principles and mechanisms linked to diversification, landscape design, at field and territorial levels; several research projects are ongoing to understand how to implement them. Measurement tools (such as sensors) and modelling tools (including artificial intelligence[17]) for anticipating the quantitative impacts of pests on crops are needed, as well as working out solutions for perennial plants.

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[16] Resilience is the ability to absorb change and to anticipate future perturbations through adaptive capacity (Urruty et al., 2016, based on Darnhofer, 2010). Resilience capacity can be assessed by (i) robustness which is the internal capacity of the system to withstand unanticipated stresses and shocks, and (ii) adaptability which is the capacity of the system to modify the composition of inputs, production, marketing and risk management in response to stresses and shocks, but without modifying the structure and the feedback processes of the system (Meuwissen et al., 2019, based on Holling et al., 2002).

[17] See for example the priority research program « agroecology and digital » : https://www.inrae.fr/actualites/accelerer-transitions-agroecologique-alimentaire-3-programmes-equipements-prioritaires-recherche

		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 biostimulants, plant defence stimulators and 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 regulatory 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 beneficials	• Temporal evolution 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

Table 6: *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.*

The hypothesis 'Managing the holobiont by strengthening host-microbiota interactions' is supported by existing knowledge on mycorrhization and tools for assessment of the genetic diversity of microorganisms and their detection. It however 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 importance for the different crops and their dynamics. Then, this hypothesis needs also the creation of a tool for monitoring the microbiome, and the identification of the ways to modulate the soil microorganisms.

In the hypothesis 'Strengthening the immunity of cultivated plants directly and indirectly', the existing knowledge on molecular mechanisms of action and on partial resistance to pests allowed the development of solutions such as plant defence stimulators, service plants, or UV-C flashes. Future research should complete knowledge in particular on the interactions between the various levers to stimulate plant immunity, on the identification of the plant immunity markers, and on the mapping of resistance genes to main pests on a broad range of plant species.

Beyond research needs on mechanism understanding, tools of anticipation and new practices, research is also required on how to transition to these chemical pesticide-free crop protection strategies, in terms of cropping systems, organisation for collective action between actors at different scales, revision of the regulatory frameworks and public policies, adaptation of the food value chains, acceptability of the new solutions, to quote a few.

Transitioning towards chemical pesticide-free agriculture by 2050: is there a highway? Some robust elements for a transition pathway

By analysing the transition pathways of the three scenarios, some robust elements of the transition can be identified. They are milestones and actions, effective and necessary for achieving all scenarios (figure 12).

First, in every transition pathway, there must be a political willingness and **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)** 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 and implementing food policies to support transition to healthy diets (S2 and S3). All across the transition there must also be mechanisms for **sharing the risks among the different actors involved**. The transition also requires new **trade agreements** to be settled with non-European market partners, from 2030, in order to apply similar production standards 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** (scenarios 2 and 3). 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.

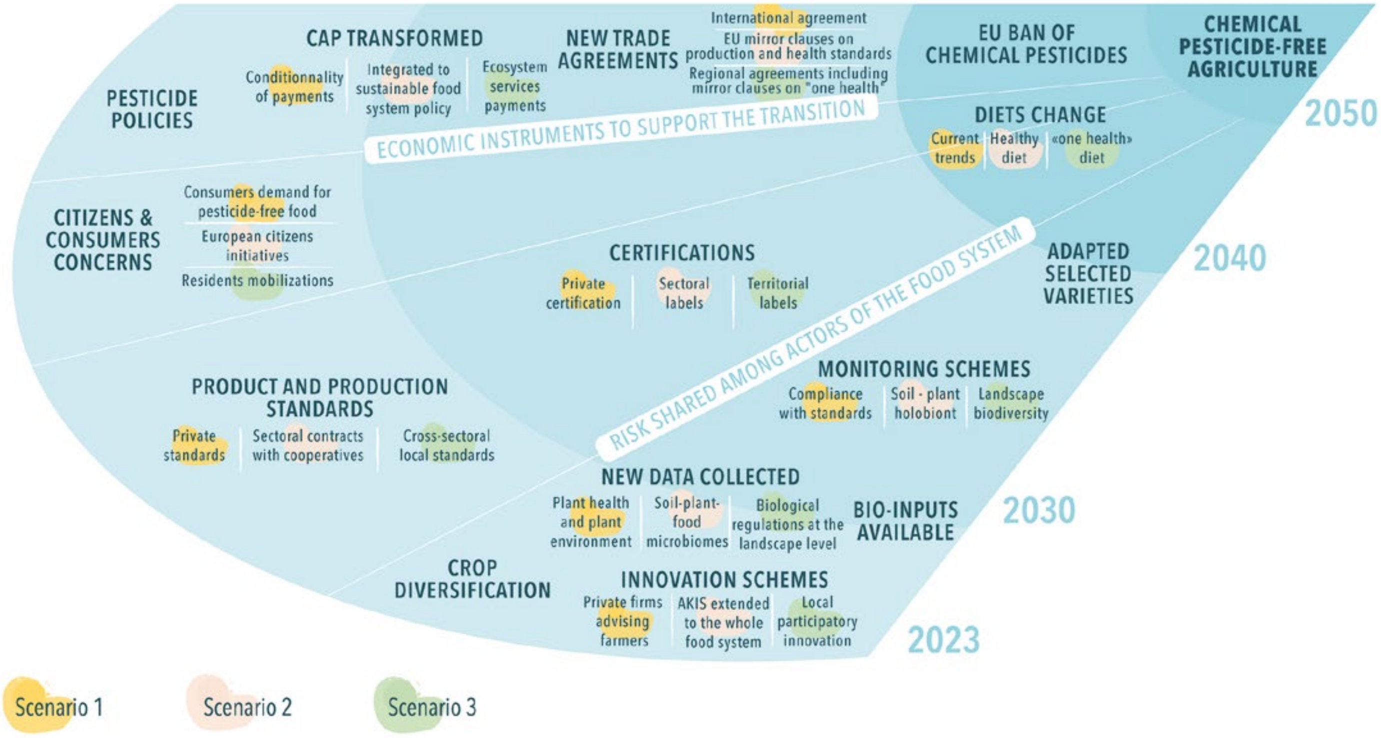

Figure 12. *Robust elements of the transition pathways, represented in a timeline from 2023 to 2050*

7

The 10 key messages from the foresight study

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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 three scenarios would contribute to improving the greenhouse gas balance, biodiversity and overall ecosystem health; two scenarios 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 maintaining pastures.

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 prophylactic 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. exogenous inputs).

8

For building efficient crop protection strategies without chemical pesticides, knowledge on biological processes, data and simulation tools are needed for conceiving anticipatory tools for pest management, for designing landscapes, and for understanding the soil microbiome, plant holobiont and plant immunity mechanisms.

9

The transition towards chemical pesticide-free agriculture requires a mix of coherent public policies related to pesticides use, articulated with other policies such as food policies; it involves a transformation of the Common Agricultural Policy (CAP) and economic instruments to support the transition; finally, trade agreements at the European Union's borders 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 sectors of agriculture.

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The foresight team would like to sincerely thank all the experts involved in the project:

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- **The participants to the regional workshops ;**
- **The experts interviewed for the retrospective analyses;**
- **The members of the Priority Research Program "Growing and Protecting Crops Differently" who participated to the research gaps identification;**
- **The scientists and stakeholders involved in the thematic experts groups on crop protection, cropping systems, agricultural equipment, European transition and quantification.**

For more information:
Mora O (coord.), Berne JA, Drouet JL, Le Mouël C, Meunier C (with the contribution of Forslund A, Kieffer V and Paresys L), 2023. European Chemical Pesticide-Free Agriculture in 2050. Foresight report - INRAE (France).

The report and summaries are available on INRAE website.

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