Foresight: European Chemical Pesticide-Free Agriculture in 2050

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Foresight: European Chemical Pesticide-Free Agriculture in 2050

The impacts of chemical pesticides on the environment, including biodiversity, water, air and soil, and 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.

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'[1] 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 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 implemented 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 in working backwards from a desirable future to the present to determine what actions and public policies would be required to reach that future[2]. Based on the scenarios, backcasting analysis 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.

[1] https://www6.inrae.fr/cultiver-proteger-autrement/
[2] From Robinson (1982)

The 10 key messages from the foresight study

1 The entire food system, committing all its actors, must be considered to build a European chemical pesticide-free agriculture in 2050.

2 In addition to the shift towards chemical pesticide-free agriculture, the 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[3] 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.

An original foresight method mixing scenario planning, modelling and backcasting

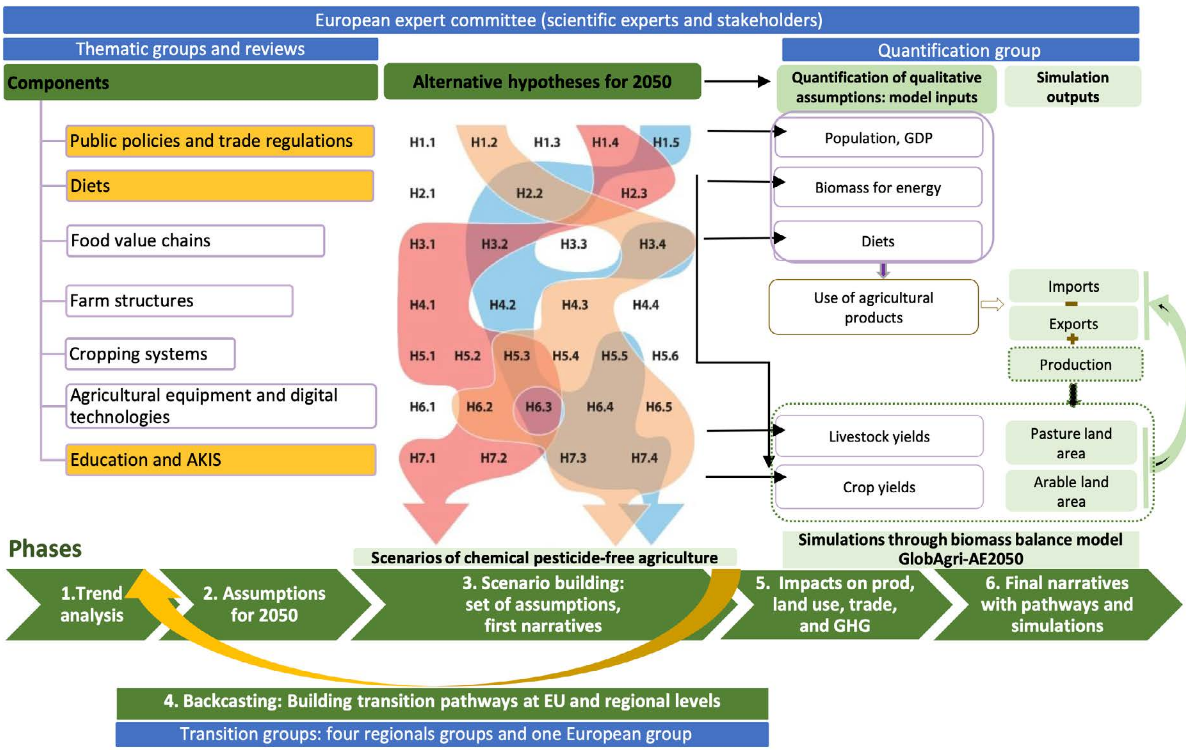

Figure 1. *General method of the foresight study based on a morphological table (central panel) articulating a scenario approach (left-hand and central panel, based on components in white, Phases 1-2-3), a simulation approach (right-hand panel, Phase 5) and a backcasting approach (bottom panel, based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

Efficient crop protection without chemical pesticides in 2050

Main issues for protecting crops without using chemical pesticides

From a literature review, the expert groups identified six modes of action (Fig. 2) to ensure crop protection without chemical pesticides, divided into control actions and prophylactic actions on pests (animal pests, pathogens and weeds): **(1)** Biocontrol; **(2)** Physical control; **(3)** Temporal management through cropping practices; **(4)** Spatial management of crop diversity within fields; **(5)** Management of landscape; **(6)** Plant breeding. Epidemiological surveillance **(7)** is not a mode of action but is a tool that triggers one (or several) mode(s) of action.

Three generic issues emerged for crop protection when withdrawing chemical pesticides: (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.**

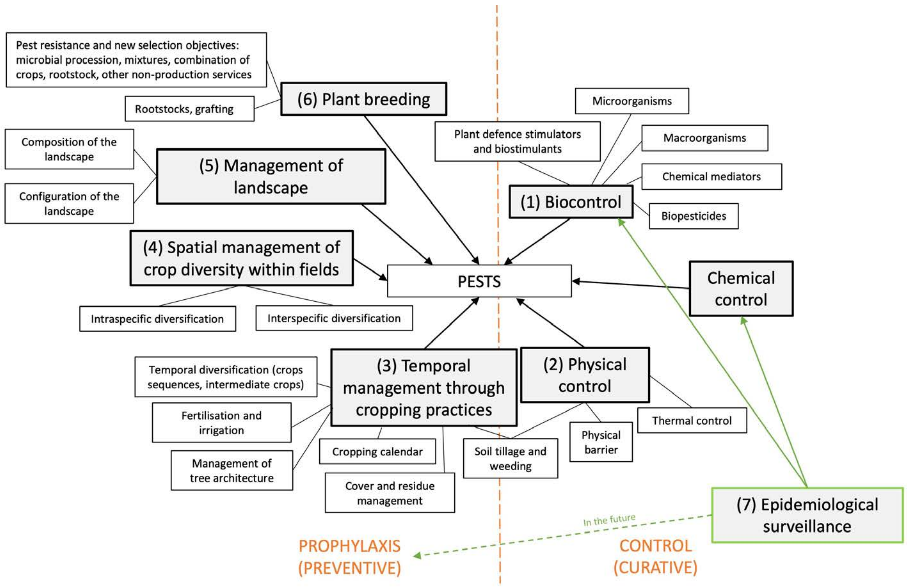

Figure 2. *Summary diagram of crop protection strategies including the six modes of action. Each mode of action (grey boxes) is associated with different levers (white boxes). Epidemiological surveillance (7) - a tool currently mainly used for implementing chemical control and biocontrol - could be used,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

Building disruptive strategies for crop protection in 2050

These reflections were used to build a conceptual diagram (Fig. 3), where cultivated plants and pests interact with other species within the landscape through food webs and within the soil through the microbiome and higher food webs. By making these interactions visible at different levels (plant, soil, crop, landscape), this conceptual diagram points out interaction mechanisms and potential levers for crop protection, in particular those based on biological regulations at the soil or crop and landscape levels. This enabled us to explore three different avenues (see Fig. 3) for imagining three rupture hypotheses for crop protection without chemical pesticides in 2050: (i) working on the relationship between the plant and pests, particularly plant **immunity** *(purple box)*, (ii) working at the l**andscape** design and on biological regulations at this scale *(green box)*, (iii) rethinking the relationship between the plant and the microbiota, through the **holobiont** perspective (i.e. the plant and its microbial communities) *(brown box)*.

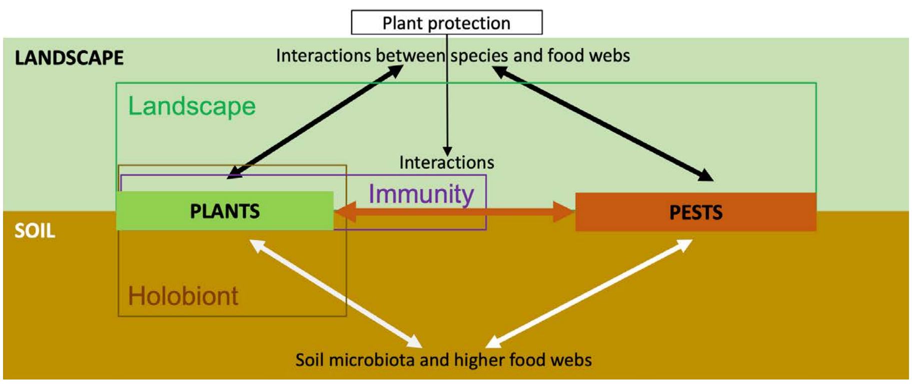

Figure 3. *Redefinition of pests and their interactions with plants and the environment and identification of rupture hypotheses for crop protection [for convenience, climate and cropping practices are not represented in the figure]*

3 CHEMICAL PESTICIDE-FREE CROP PROTECTION STRATEGIES IN 2050 WERE BUILT:

• Strengthening the immunity of cultivated plants:
directly by using plant defence stimulators, biostimulants and through plant breeding; indirectly through interactions with microbiota, other crops and plant services.

• Managing the crop holobiont by strengthening host microbiota interactions:
by strengthening the adaptability of the holobiont and the functions of microbiota by modulating the existing microbiome in a systemic, integrative and historical way; and by redesigning the holobiont through inoculations of microorganisms and plant breeding.

• Designing complex and diversified landscapes adapted to local contexts and their evolution:
by increasing biodiversity and agrobiodiversity from the landscape to the field level, and over space and time, and through plant breeding; and by building on a complex landscape with a changeable mosaic of diversified cropping systems embedded in a stable matrix of natural and semi-natural habitats (20% of the land).

Scenarios and transition pathways towards chemical pesticide-free agriculture in 2050

A systemic approach of the food system is necessary to imagine scenarios of chemical pesticide-free agriculture. Building chemical pesticide-free agriculture by 2050 involves the transformation of different components of the food systems, beyond **cropping systems**. It impacts the downstream of **food value chains**, questioning the values of consumers driving the production of chemical pesticide-free food, the governance and organisation of activities within food value chains, the information on food provided to consumers, as well as the storage and preservation of food between harvesting and consumption. It also involves major transformations in **agricultural equipment and digital technologies**, to participate in the implementation of the cropping systems, through changes in the observation and modelling systems designed to monitor and anticipate pest presence and plant health, the development of specific equipment adapted to new cropping systems, and the innovation dynamics defining their use. Last, the changes in **farm structures**, in their governance, the organisation of production factors (labour, capital, land) and the distribution of diverse farming models will influence the future conditions for implementing chemical pesticide-free agriculture.

The transition towards chemical pesticide-free agriculture could be supported by consumers' changes of **dietary patterns**, driving food demand and agricultural practices, by changes in **Agriculture Knowledge and Innovation Systems (AKIS)**, and also by changes in **public policies** related to pesticide use and risk regulation, to human health and nutrition, to transition of cropping systems and beyond, to international trade.

The scenarios were built by the European expert committee (Fig. 1), combining hypotheses of change consistently.
A morphological table (Tab. 1) gathers the hypotheses of change in 2050 for four components: food value chains, farm structures, agricultural equipment and digital technologies, and cropping systems. A scenario is defined by a combination of hypotheses of change in 2050 of each component of the system. The choice of the combination of hypotheses meets a certain number of criteria including the consistency of the hypotheses, the plausibility of the combination, and the contrast between combinations. For cropping systems, several hypotheses were mixed for a single scenario, with a dominant hypothesis and one or two secondary hypotheses.
Then, 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 from today to 2050. The transition pathways include *ad hoc* hypotheses on public policies, education and AKIS, and dietary changes.
In parallel, the three scenarios were tested and illustrated through regional case studies in four European countries: Italy, Finland, Romania and France.

Hypotheses of change in 2050

Food value chain	Global value chains producing pesticide-free food as a food safety standard	Local, European and global value chains producing healthy foods for a healthy diet	Territorial and regional value chains for food preserving human and environmental health and contributing to diversified landscapes
Farm structures	Specialisation and financialisation of farm structures with residual family farms	Regional diversity of farm structures	Territorialisation and diversification of farm structures
Cropping systems	Strengthening 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

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 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, advice and monitoring services to farmers.

In cropping systems, the crop protection strategy focuses on strengthening the immunity of each cultivated plant by anticipating the arrival of pests 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 who could not achieve the investment needed.

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
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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

2050 scenario for durum wheat production in Tuscany (Italy)

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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Scenario 2 (S2) and its transition pathway:

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

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 nuts, 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 (organic amendments, requiring maintaining some livestock production, residue management, diversification, rotation, tillage, cover crops) and inoculation of key microorganisms modulate microbiota, 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 support to the shift to chemical pesticide-free cropping systems and to the development of agricultural productions in line with dietary targets.

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
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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

2050 scenario for vegetable production in South-East Romania

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.

Scenario 3 (S3) and its transition pathway:

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

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 has 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. 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 sizes. 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.

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
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2050 scenario of cereals and oilseeds production in South Finland

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.

2050 scenario for wine production in Bergerac-Duras (France)

The wine sector succeeded its agro-ecological transition by mobilising all the stakeholders in the region. Ecological processes at the landscape level are favoured and the vineyard is valued for its oenological and environmental qualities and as an element of cultural heritage. Mosaics of crops (vineyards, fruit trees, hazelnut trees, cereals, pastures) and semi-natural habitats (hedgerows, copses, flowering strips, wetlands) create complex and resilient landscapes, where pests are regulated. These landscapes are totally integrated into the Bergerac-Duras territory. A social contract binds together the actors of Bergerac-Duras - winegrowers, wine producers, cooperatives, local authorities, residents' associations, industries - around the same territorial project.

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Will we be able to build cropping systems without chemical pesticide by 2050?

Diverse cropping systems are possible…

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. The cropping systems in 2050 can be characterised along diverse gradients of intensity in terms of exogenous inputs (such as biocontrol products, plant defence stimulators, and fertilisers), ecosystem services as well as temporal and spatial diversification (Fig. 4).

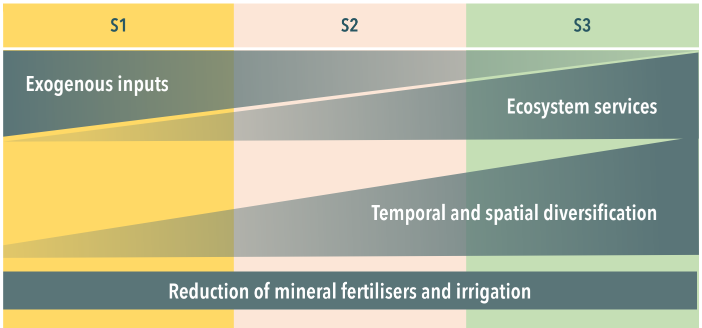


Figure 4. *The characteristics of cropping systems in each scenario*

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.

… with diverse resilience to pests under climate change

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, and also by humidity and wind. It will also influence pathogens whose entire life cycle is mainly influenced by temperature and humidity. 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. 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[4] of cropping systems, which can be assessed through their robustness and their adaptability (Tab. 2) to pests under climate change by 2050.

… with diverse knowledge and technological gaps

The current level of knowledge varies from one hypothesis of crop protection in 2050 to another [5]. The hypothesis 'Strengthening the immunity of cultivated plants' is supported by current knowledge on molecular mechanisms of action and on partial resistance to pests (plant defence stimulators, service plants, or UV-C flash). The research needs to cover the interactions between the various levers to stimulate plant immunity, the identification of plant immunity markers, and the mapping of resistance genes to the main pests on a broad range of plant species. The hypothesis 'Managing the crop holobiont by strengthening host-microbiota interactions' requires the development of knowledge to better understand the link between a specific microbial community structure and its functional traits, to identify the microbial communities that are important for the different crops and their dynamics, and to determine the ways to modulate the soil microorganisms. To support the hypothesis 'Designing complex and diversified landscapes adapted to local contexts and their evolution', a large corpus of knowledge already exists on the principles and mechanisms linked to crop diversification and landscape design; several research projects are ongoing to understand how to implement them. Modelling tools for anticipating the quantitative impacts of pests on crops are needed as well as working out solutions for perennial crops.

	Robustness	Adaptability
S1	• 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, microbial communities to plants and soil
S2	• 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
S3	• 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 beneficial	• Temporal evolution of crop mosaics and cropping practices according to anticipated risks • Anticipation of stresses and shocks through monitoring systems (pests, plants, weather)

Table 2: *Factors of robustness and adaptability of the cropping systems in the three scenarios (S1, S2, S3)*

[4] 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).

[5] These elements result from the assessment of researchers involved in projects of the French Priority Research Program 'Growing and Protecting crops Differently', about current knowledge and knowledge gaps for implementing the chemical pesticide-free crop protection hypotheses.

Are the scenarios of chemical pesticide-free agriculture compatible with **Europe food sovereignty?**

Scenarios have contrasting impacts on European agricultural production. Compared with 2010, European domestic production in calories varies from -5% to +12% in 2050, depending on scenarios and retained assumption on crop yields (lower-bound, lb, or upper-bound, ub, yields).

Furthermore, production patterns differ from one scenario to another because European agriculture is embedded in completely different food systems in the three scenarios. Production patterns largely mimic food diet patterns. This means that while production patterns in 2050 are not significantly different from those observed in 2010 with scenario S1, they are radically different in scenarios S2 and S3 (Fig. 5). In particular, as food diets in S2 and S3 are less rich in animal products, European livestock production decreases noticeably, as does the production of feed ingredients, including quality forages, and the use of grass from permanent pastures. European permanent pasture area decreases significantly in S2 (-28% in 2050 compared to 2010) and especially in S3 (-51%, Fig. 6), with freed pastureland shifting to shrublands or forests.

A transition towards chemical pesticide-free agriculture in Europe in 2050 could be possible without transforming the European food diets, but to the detriment of European exports (S1). Facing a constant cropland area and a trend diet, a reduction in the production volume of the European agriculture (lb yield assumption) would result in a sharp reduction in European exports: in comparison with S2 and S3. If Europe would wish to keep its export position on world markets, higher yields or expansion of croplands would be necessary.

The adoption of healthy diets (S2) or of 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 scenarios S2 and S3, Europeans consume less calories, with less animal-based foods. This more frugal diet results in decreasing both the domestic food use (-13% in S2, -20% in S3) and the domestic feed use (-24% and -43%, respectively) relative to 2010 (Fig. 7). In such scenarios, even with a reduction in the volume of production, domestic uses would decrease more than domestic production and Europe would shift from net importer in 2010 (200 10^{12} kcal) to net exporter in 2050 (almost 40 10^{12} kcal in S2 and near-

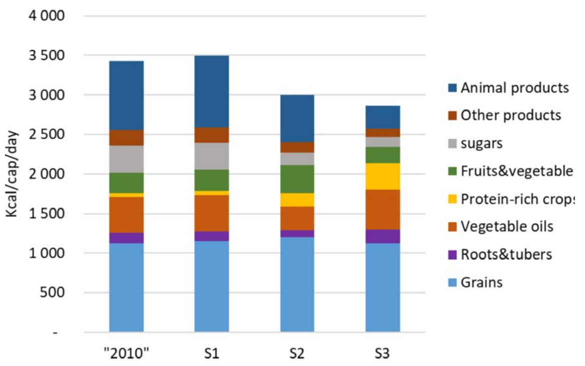


Figure 5. *Diet in "2010" and in 2050 in S1, S2 and S3 (kcal/cap/day), 8 European sub-regions average*

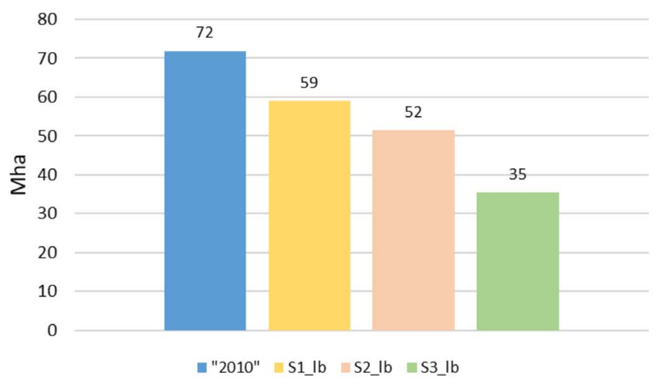
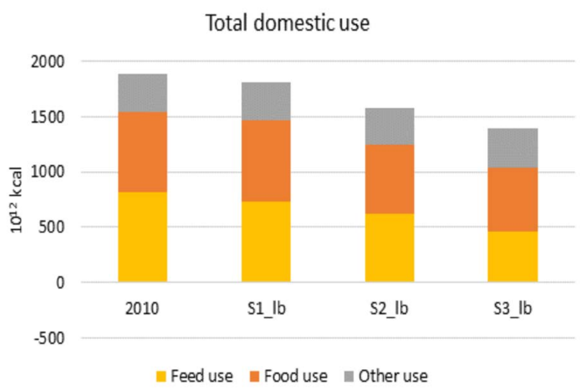


Figure 6. *Permanent pasture area in Europe in "2010" and in 2050 with S1, S2 and S3 (Mha). "lb" means lower-bound assumption on crop yields.*



Figures 7 and 8. *European use-resource balance in "2010" and in 2050 with S1, S2 and S3 (10^{12} kcal)*

How could the scenarios contribute to the European Green Deal?

To overcome climate and environmental challenges threatening Europe and the world, the European Green Deal aims at transforming the EU into a resource-efficient and competitive economy, ensuring zero net emissions of greenhouse gases by 2050, economic growth decoupled from resource use, and no person and no place left behind.

The three scenarios (except S1 with ub yield assumption) **would contribute positively to decrease European agricultural greenhouse gas (GHG) emissions and to increase carbon storage in soils and biomass.** Under the lower-bound yield assumption, the three scenarios induce a decrease in agricultural GHG emissions in 2050 compared to 2010: from -8% in S1 to -20% in S2 and -37% in S3 (Fig. 9). Whatever the scenario, the decrease in total agricultural emissions comes to a greater extent from emissions reduction of livestock production. With the upper-bound yield assumption, the decrease in agricultural GHG emissions is lower in all three scenarios, and could even turn into an increase in S1 (+9%). Furthermore, compared to 2010, the three scenarios lead to a decrease in land-use change emissions in Europe, which reinforces the capacity of Europe to store carbon throughout the projection period, from 9 million tons CO_2 equivalent per year in S1, to 17 million tons in S2 and up to 43 million tons in S3 (Fig. 10).

The three scenarios would likely contribute to improve terrestrial biodiversity in Europe. The first positive impact results from the removal of chemical pesticides in all three scenarios. The second positive impact comes from the 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, which, on average, should have a positive impact on biodiversity (no cropland expansion, increased area dedicated to semi-natural habitat in S3, and potentially the transformation of permanent pasture into forests). This improved status of the biodiversity could reinforce the natural regulations occurring in all three scenarios, making the pesticide-free objective even more feasible.

Figure 9. *Agricultural GHG emissions in Europe in "2010" and in 2050 with S1, S2 and S3 (Mt CO_2 eq.)*

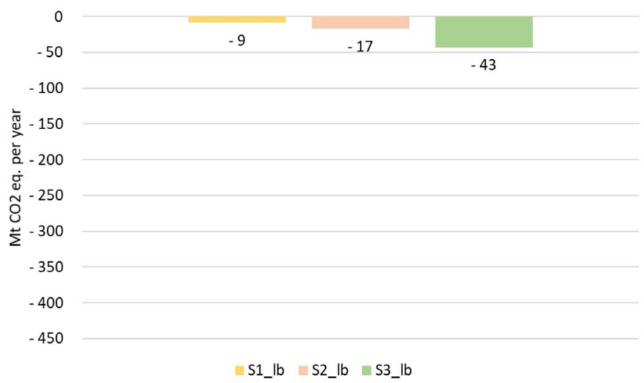
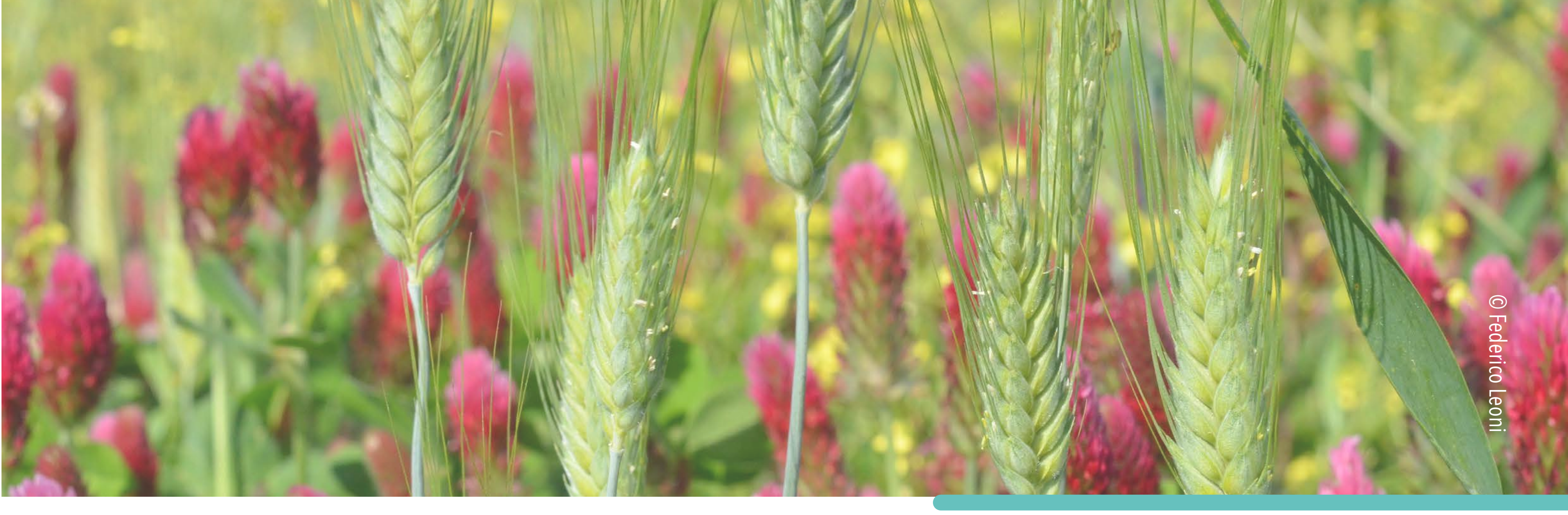


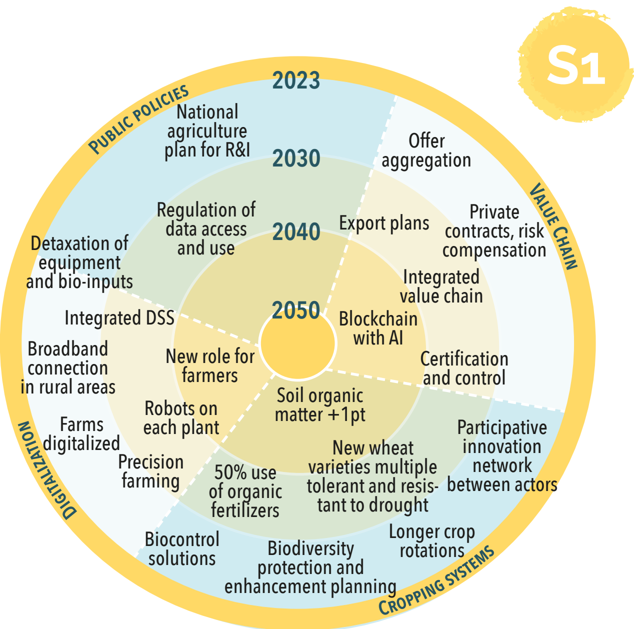
Figure 10. *Land-use change emissions in Europe with S1, S2 and S3 (Mt CO_2 eq. per year), under the assumption that freed permanent pastures become shrublands*



How to build a **transition** towards chemical pesticide-free agriculture in Europe by 2050?

Mobilising local scientists, stakeholders and the scenarios to imagine possible transition pathways in four European regions

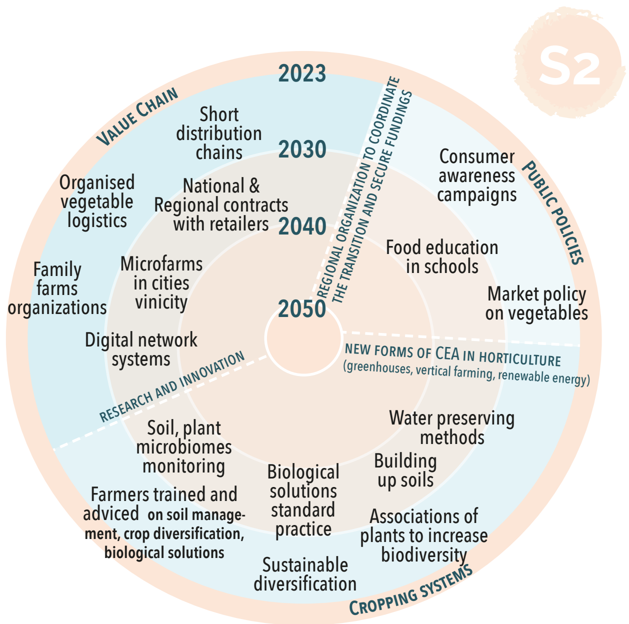
Participatory foresight workshops, gathering 15 to 20 local stakeholders and researchers each (scientists, farmers, technicians and consultants, representatives from non-governmental organisations, food and agroequipment companies, and local authorities), were conducted in four European regions, to build transition pathways towards chemical pesticide-free sectors by 2050, using the backcasting methodology. They illustrate how the three scenarios can be mobilised by local public and private actors, including farmers, to build together paths towards a common vision of pesticide-free agriculture, and identify key milestones and actions required to reach it.



Tuscany & durum wheat production

Key transition steps : Global food companies and retailers set production standards including on the use of chemical pesticides, and contract with Tuscan 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 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



Romania & vegetable production

Key transition steps : Consumers' adoption of healthy diet is facilitated by market policies for vegetables affordability, and by school curriculum evolution with courses on nutrition. Family farms, supported by national policy and EU funds, join forces to share agroequipment and data. They contract with national, regional retailers, and develop short chains. Farmers benefit from public-funded trainings on holobiont, and from public specialists advice to implement diversification, use of green manure and increased biodiversity in horticulture. They use new tools to monitor the soil nutrient and micro-ecosystems, and adapt their cropping systems to maintain healthy soils. CEA horticulture, working on renewable energy, develops progressively and includes new forms such as vertical farming.

CEA : controlled environment agriculture

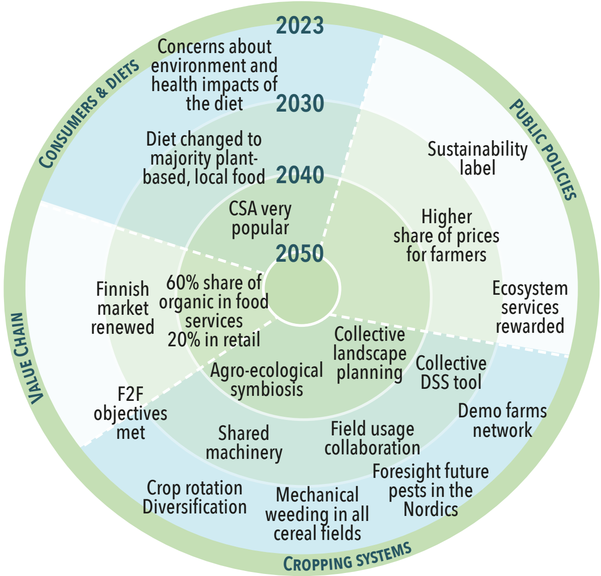
Figures 11 and 12. *Target diagrams summarising the key transition steps of the regional transition pathways in Tuscany and in Romania from 2023 to 2050*

Mobilising local scientists, stakeholders and the scenarios to imagine possible transition pathways in four European regions

South Finland & cereals and oilseeds

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.

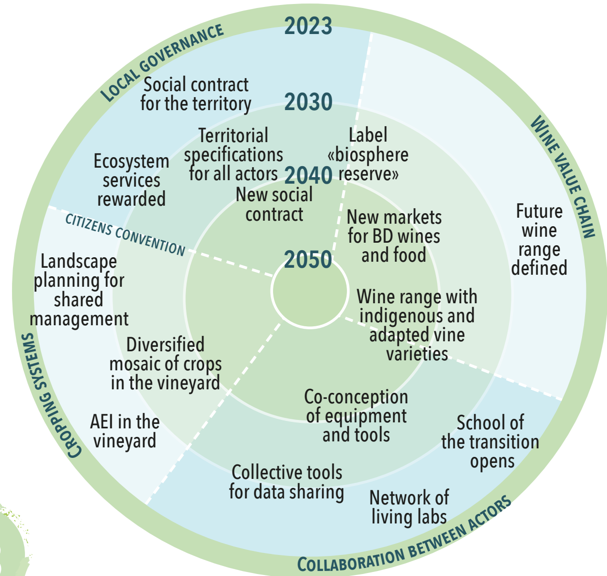
CSA : community supported agriculture ; F2F : farm to fork ; DSS : decision support system



Bergerac Duras & wine

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



S3

Figures 13 and 14. *Target diagrams summarising the key transition steps of the regional transition pathways in South Finland and Bergerac Duras from 2023 to 2050*

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For more information

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Is there a highway for the transition towards chemical pesticide-free agriculture by 2050?

Transitioning towards chemical pesticide-free agriculture requires many initiatives and transformations, from several actors, at various scales. Nevertheless, analysing the pathways built for each of the three European scenarios, some robust elements of a transition emerge, which are common milestones and actions including public policies, changes in value chains and education and AKIS.

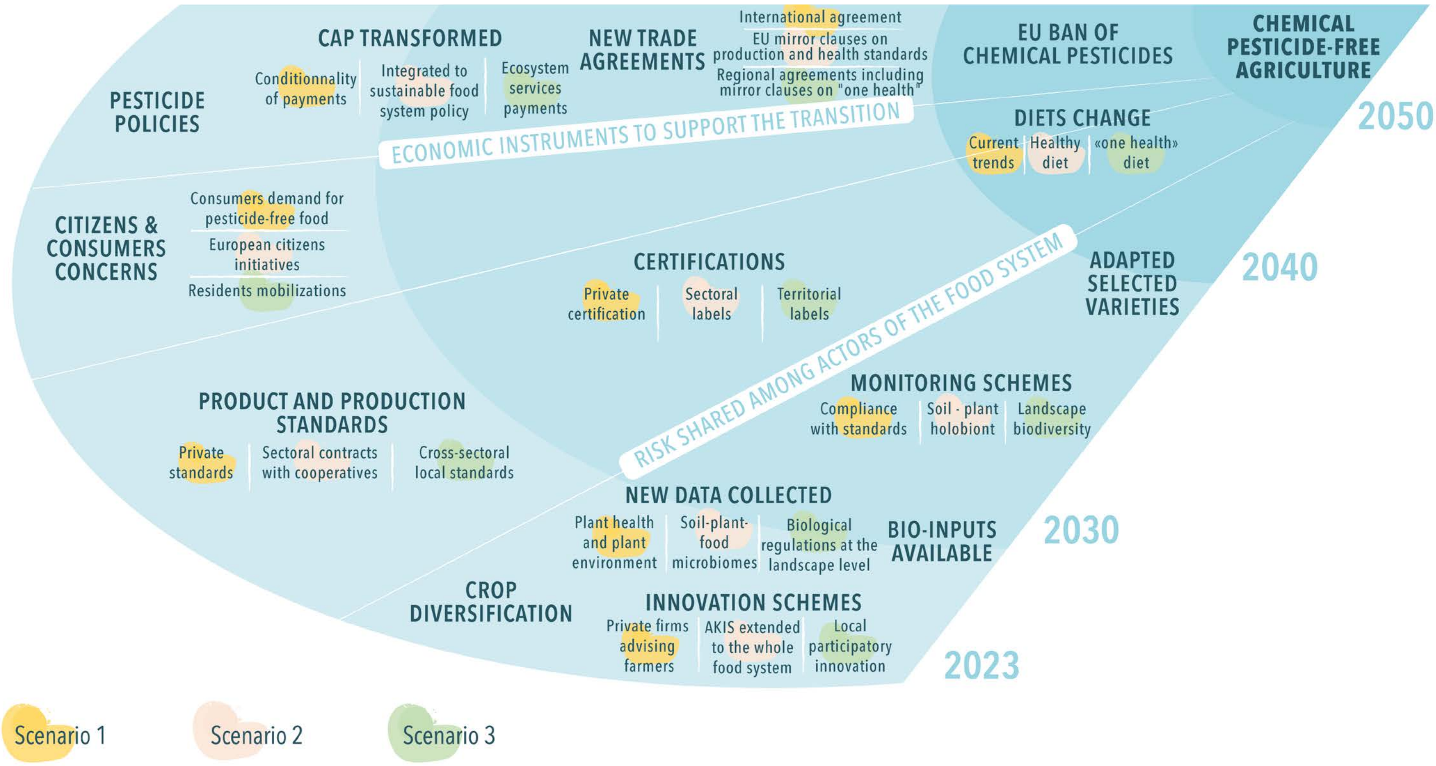

Figure 15. *Robust elements of a transition pathway towards chemical pesticide-free agriculture*

In all the scenarios, strong and coordinated measures are required for a successful transition:

- Commitment from consumers, citizens and inhabitants, who 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, the shift of their food behaviours and dietary patterns will support the transition (S2 and S3).

- The articulation of regulatory policies for reducing and ultimately banning chemical pesticides, public policies for supporting farmers (and other actors) in the transition towards chemical pesticide-free systems, with a transformation or a redesign of the Common Agricultural Policy, and food policies to support transition to healthy diets (S2 and S3).

- New trade agreements with non-European partners in order to apply the same production standards to every product present in the European market.

- New production standards, enabling the certification of productions, and their valorisation through food labels.

- Mechanisms for sharing the risks among the different actors involved in the value chain through market contracts, or in the territory.

- Agricultural, knowledge and innovation systems for knowledge creation and co-conception, with farmers, of chemical pesticide-free cropping systems.

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