Protect crops by increasing plant diversity in agricultural areas. Summary report of the collective scientific assessment

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Summary report of the collective scientific assessment – Decembre 2023

Following the end of the Second World War, the advent of synthetic fertilisers and pesticides enabled farmers to specialise, choosing their most economically profitable crops and freeing themselves from both biotic constraints (pressure exerted by crop pests) and abiotic constraints (soil fertility, climate variability etc.). While this transformation of agriculture has served to increase production levels, it has induced a gradual loss of plant diversity, both of cultivated plants (accompanied by a shortening of rotations and a standardisation of fields) and semi-natural plants (removal of hedges in order to enlarge field sizes). The environmental and health impacts of this dominant model, as well as its interrelation with major global changes (climate change, erosion of biodiversity and changes in land use), have now been well established by the scientific community[1]. Faced with these challenges, France and the rest of Europe are seeing the development of a strong societal demand for agriculture that can meet our food needs in a way that is more respectful of the environment and human health, and less dependent on synthetic inputs.

This demand is being relayed through a set of European (Green Deal for Europe and Common Agricultural Policy) and national (Ecophyto plan, Future Law for Agriculture and Food and Forestry) public policies which set objectives for reductions in pesticide use and the associated risks, and more generally promote a transition towards agricultural systems that put biodiversity and ecological processes back at the heart of production factors. However, despite the growing consideration of environmental issues in public policies, it is clear that the transition to cropping systems that use fewer pesticides is far from being sufficiently advanced to achieve the targets that have been set (Guyomard et al., 2020). In addition, while plant diversification is considered in the political and scientific arenas as a major lever for this transition, there is a lack of critical hindsight and overall vision as to its effectiveness 'in the field', in particular to protect crops. Finally, plant diversification covers a very wide range of situations and practices; while some are already well known and deployed by some farmers (for example, the use of varietal mixtures), others are more restricted (for example, agroforestry in temperate environments) and many are perceived by some actors –rightly or wrongly – as not very effective or too restrictive.

Given this context, the Ministries in charge of Agriculture, the Environment and Research called on INRAE at the end of 2019 to conduct a collective scientific assessment study (known as an ESCo) evaluating the effectiveness of crop protection strategies based on plant diversification. This also involved analysing the brakes and levers for the deployment of such strategies. The request is part of the France's Ecophyto 2+ plan and feeds into the Priority Research Programme (PPR) 'Growing and Protecting Crops Differently' which encourages research to design cropping systems without synthetic pesticides.

Conducted by a multidisciplinary committee of experts, the analysis of nearly 2,000 international scientific references shows without ambiguity that increasing the level of plant diversity in fields and landscapes contributes effectively to the regulation of crop pests. Moreover, diverse systems have on average higher levels of associated biodiversity and provide more ecosystem services to society. Although most of these systems make it possible to achieve higher and/or more stable yields than less diversified systems (particularly in low-input systems), their adoption is limited by numerous obstacles at all levels of agricultural chains, both upstream and downstream of farms themselves. They often struggle to generate profitability at the farm scale, in particular because the ecological advantages of plant diversification are expressed over the long term, and in part because the advantages go beyond the limits of the farm (preservation of biodiversity, contribution to climate change mitigation etc.). Public policies therefore appear to be a central lever to encourage and support the development of plant diversification.

INRAE's collective scientific assessment approach

Collective scientific assessment (known as ESCos) are an institutional assessment activity developed by INRAE from the early 2000s and led by the Directorate for Expertise, Foresight and Advanced Studies (DEPE). It consists of conducting a critical review of the international scientific literature in response to a question of a societal nature, in order to inform public action, without formulating an opinion or recommendations. ESCos are conducted in compliance with principles that guarantee the robustness of their conclusions[2]: competence and plurality of the expert committee, impartiality, transparency of the method and traceability of the work process implemented.

This ESCo was produced by a multidisciplinary group of around 30 experts and scientific contributors from various institutional backgrounds, from complementary disciplines (ecology, economics, agronomy, genetics, management sciences, law etc.). Their work was facilitated by a project manager and two scientific managers. The experts analysed a corpus of nearly 2,000 references compiled by scientific information specialists (mainly scientific articles published in peer-reviewed international journals, to which were added study reports, books and legal literature). This exercise produces a report that brings together the contributions of the experts and the cited bibliography, and a more accessible summary for the use of decision-makers and society as a whole.

[1] For example, the INRAE-Ifremer collective scientific expert report on the ecotoxicological impacts of pesticides (Leenhardt *et al.*, 2022) and INRA on the synergies between agriculture and biodiversity (Le Roux *et al.*, 2008), as well as the work of the Intergovernmental Science and Policy Platform on Biodiversity and Ecosystem Services (IPBES).

[2] https://www.inrae.fr/actualites/quels-principes-inrae-conduit-il-expertise-ou-etude-scientifique-collective

Plant diversification and natural pest regulation: definitions

A wide range of plant diversification practices

Diversification concerns both **plants cultivated by farmers** (annual or perennial plants grown for the purpose of biomass production or ecosystem services) and **semi-natural vegetation** associated with agricultural areas (spontaneous vegetation present within plots and the landscape, most often composed of biennial, multiannual and perennial species). The scope of the ESCo covers all the spatial and temporal scales at which it is possible to consider plant diversity. The analysis therefore covers a wide range of diversification practices, which can be combined (Fig. 1).

At the **plot scale**, the aim is to increase the intraspecific diversity of the cultivated cover (by using **varietal mixtures** of certified seeds or **traditional or peasant varieties**) or interspecific diversity (through **intercropping**, by growing **service plants** during the life cycle of the crop or by setting up **agroforestry** systems).

The diversification of plants also concerns time scales, via an extension of **rotations** (for example the introduction of a new crop) or the establishment of **plant cover during the fallow period**.

At the **supra-plot scale** (farm and beyond), this ESCo considers the diversity of the landscape, both in its cultivated dimension (nature of the crops present in the **rotation** and **plot size**) and semi-natural aspects (nature of the **borders of plots**, connectivity of **hedges**, presence of fallow land, permanent grassland, thickets etc.). It should be noted that the diversity of the agricultural landscape is largely the result of individual choices that are rarely coordinated: the nature and distribution of crops in the landscape stems from the cropping plans and rotation choices of farmers; the density of semi-natural vegetation is linked to the size of the plots.

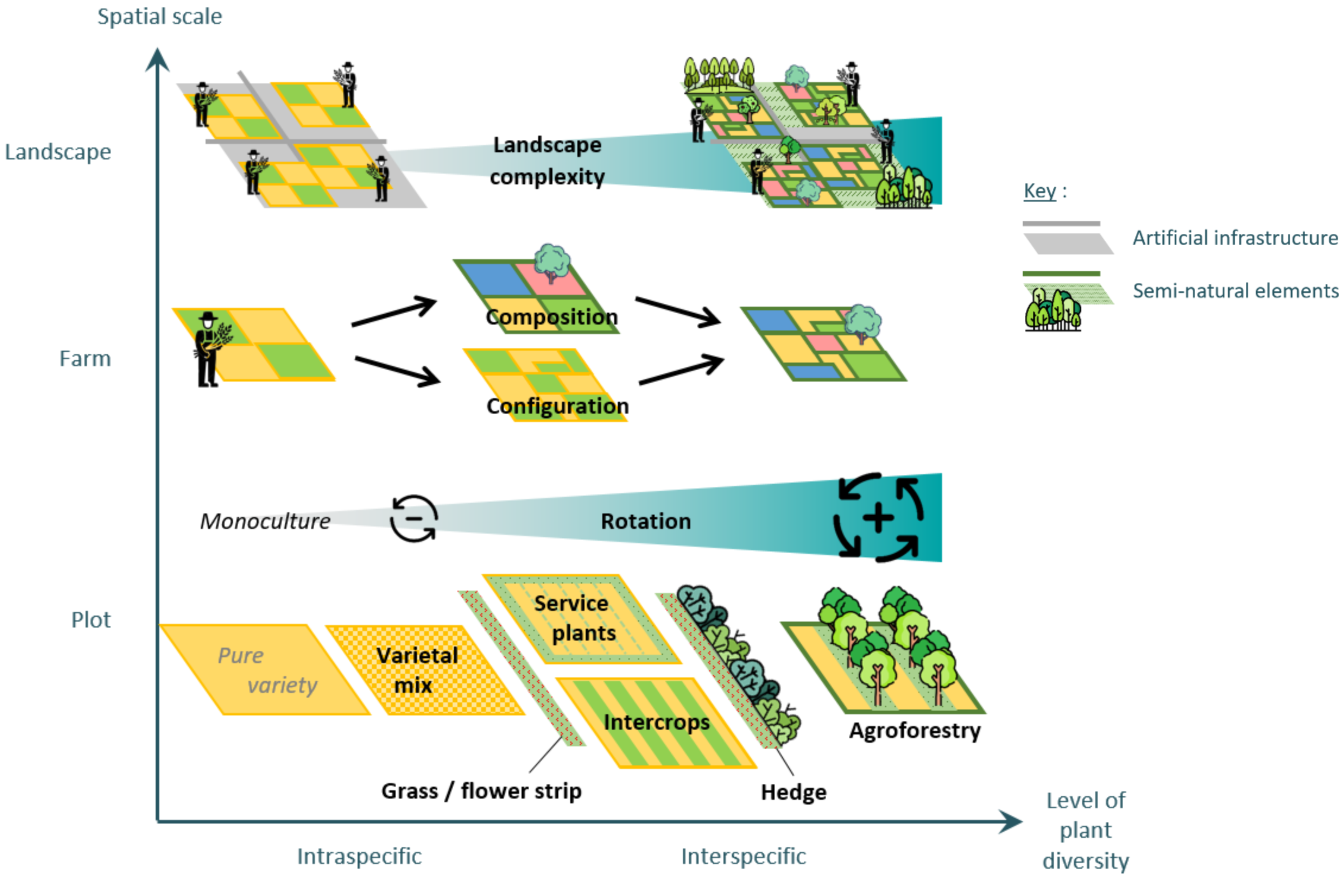

Figure 1. Schematic representation of the methods of plant diversification considered in this ESCo

Natural regulation of crop pests: a paradigm shift

Different categories of pests are likely to cause damage (symptoms observable on plants) to cultivated plants: **phytophagous arthropods** (insects, mites etc.), **weeds** (crop regrowth and spontaneous plants) and **parasitic plants**, **pathogenic microorganisms** (fungi, bacteria, viruses etc.) causing plant diseases, **gastropods**, **nematodes** and **vertebrates**. Depending on their nature, the damage can lead to quantitative or qualitative crop losses (damage) and, ultimately, economic losses for farmers.

Different crop protection strategies (curative and preventive) are used to prevent or reduce crop losses. Currently, the dominant strategy is based on **chemical pest control**, most of the time in combination with the use of varieties that are **not very sensitive or even resistant to diseases**, and certain so-called **cultural control methods** (choice of crop rotation, sowing rate and tillage). **Agroecological crop protection** gives priority to **preventive measures to regulate pest populations**. To do this, it relies on biodiversity (plant and animal) and the natural functioning of agricultural ecosystems.

In principle, this natural regulation of pests is essentially based on the fact that the same pest cannot consume or colonise all cultivated plants due to its more or less marked specialisation vis-à-vis these plants. As a result, **an increase in plant diversity 'dilutes' the pest's host plant in a plant cover or a landscape of non-host plants**. Phytophagous pests therefore have more difficulty finding their host plant (so-called 'bottom-up' regulation). For weeds, diverse plant cover provides a more competitive environment. Added to this is the intervention of **natural pest enemies** (so-called 'top-down' regulation), whose presence depends on the resources and habitats that the vegetation within and beyond the plot offers during their life cycle.

Plant diversification is a lever to protect crops

The effects of different plant diversification methods on pest populations are summarised in Table 1. Each box presents the main trend that emerges from the literature analysed. **The bibliographical review shows that each category of pest can be regulated by at least one mode of diversification**. In the majority of cases, the literature agrees on the positive effect of plant diversity. However, the level of scientific consensus varies according to the diversification method.

Table 1. Summary of the effects of different methods of plant diversification on different pest categories

	Weeds	Flying insects	Soil insects	Vector-borne diseases	Airborne pathogens	Soil pathogens	Nematodes	Other pests*
Varietal mixtures	+		?				?	?
Intercropping				?			?	?
Agroforestry			?	?		?		
↗ Diversified rotations				?				?
↘ Share of a crop/landscape	?		?	+		?	?	
↗ Diversified cropping plans			?	+		?	?	?
↘ Field size			?	+/-			+/-	?
↗ Distance between crops	+/-		+	+			+	?
↗ Semi-natural elements	+		?				?	+

Key:

* Pictograms from left to right and from top to bottom: Striga, gastropods, voles and mites.

** The level of intensity of the colour reflects the level of consensus in the literature (the darker the colour, the stronger the consensus).

- **Consensus** in the literature in favour of a positive effect on pest regulation** (= the mode of plant diversification reduces the pest population)
- **Absence of consensus in the literature: ambiguous effect**
- **Consensus** in the literature in favour of a negative effect on pest regulation** (= the mode of plant diversification favours the multiplication of the pest population)
- **No significant effect** on pest
- **Theoretical hypothesis on the direction of the effect** (in italics) without empirical evidence *+: positive effect expected; -: negative effect expected; +/-: ambiguous effect expected*
- ? **Insufficient information to draw a conclusion** (including theoretically)

The literature is more extensive on plant diversification methods at the plot scale (varietal mixtures, intercropping and rotations), for which it reports mainly positive effects on pest regulation (**green boxes**). **The effects of the cultivated (diversity of rotations) and uncultivated landscapes (semi-natural elements) are essentially the subject of theoretical expectations** but not tested experimentally (**blue boxes**). The literature suggests that the spatial arrangement of the landscape (size of plots and distribution of crops) has an effect that is at least as important as its composition (diversity of cultivated and semi-natural species).

Weeds are mainly regulated by multi-species cultivated plant cover (intercropping and agroforestry) and rotations. **Insect pests** can be regulated by all methods of intra-plot diversification (in particular intercropping) as well as by an increase in the diversity of cultivated plants in the landscape. Concerning crop diseases, the literature mainly focuses on **aerial pathogens** associated with straw cereals (wheat, barley, oats and rice). These can be regulated mainly by varietal mixtures, rotations and, to a lesser extent, by intercropping. **Other types of pests** are much less studied, with the notable exception of nematodes, which can be regulated by certain rotations.

While the literature agrees on the regulatory effect of plant diversity, cases of ineffectiveness (or even adverse effects) do exist. In addition to the gastropods favoured by agroforestry systems (**red box**), studies relating negative effects exist for all diversification methods. For some 'diversification method / pest category' pairings (for example, diversification of semi-natural vegetation / flying insects), there are as many negative effects as there are positive effects, preventing a clear consensus from being reached (**yellow boxes**). These ambiguities are essentially explained by the dependence of the effects on the context of the cases analysed:

- The results often depend on the **life traits of the organisms involved** (capacity and mode of dispersal, host specialisation, forms of resistance etc.), preventing any generalisation of the effect observed on a taxon to a whole category of pests.
- **Agricultural practices** are a major factor in the variability of effects. In particular, the literature suggests that the implementation of conventional practices (use of synthetic inputs and varieties adapted to this management approach) is likely to reduce the regulatory effects provided by plant diversity. Moreover, we often observe more **marked positive effects in low-input systems**.
- Local and seasonal **climatic conditions** are systematically mentioned as being able to modify the expression of natural mechanisms.

This means **it is not possible to derive general rules dictating which plant diversification method should be deployed to regulate which pest**. **Unlike chemical control strategies, which are characterised by the homogeneity of their implementation regardless of the agronomic and pedoclimatic context**, expertise is required to adapt the methods of plant diversification to local production conditions. The importance of the objective sought by the farmer is also underlined, in particular for rotations whose design can meet various objectives. So, a rotation designed to improve soil fertility is not necessarily effective in controlling pests.

In addition to the natural regulation of pests, plant diversification is favourable for associated biodiversity and provides other services to society

Two recent meta-syntheses aggregating the results of thousands of studies conducted around the world have examined the links between plant diversity in agricultural areas, associated biodiversity and the supply of a set of ecosystem services. This work compares the levels of biodiversity and services associated with different methods of diversification, compared to control systems that are not very diversified.

They first identify a **positive link between plant diversity (whether cultivated or semi-natural) and associated biodiversity**, but of varying intensity depending on the diversification method. The strongest links are observed in agroforestry systems, whereas they are not significant for varietal mixtures.

The vision of the links between cultivated diversity and ecosystem services is fragmentary: some services have received little evaluation (pollination and mitigation of greenhouse gas emissions) and some plant diversification methods remain little studied from the perspective of service provision (varietal mixtures, agroforestry in temperate zones and establishment of hedges). **When these links are studied, they turn out to be mostly positive**. However, again their intensity is highly variable according to the diversification method under consideration.

Overall, the different diversification methods appear more or less advantageous with regard to the preservation of biodiversity and the provision of ecosystem services (Fig. 2). **Varietal mixtures** have neutral links to biodiversity and service provision. On the other hand, **agroforestry** (as practiced in tropical environments) is the most advantageous with regard to these issues. **Cover crops**, **rotations**, **hedges** and **intercropping** are rather intermediate. Finally, the introduction of **semi-natural vegetation** (excluding hedgerows) is associated with higher levels of biodiversity and ecosystem services than undiversified systems, but there is a lack of quantitative assessments to enable this plant diversification method to be positioned in relation to the others.

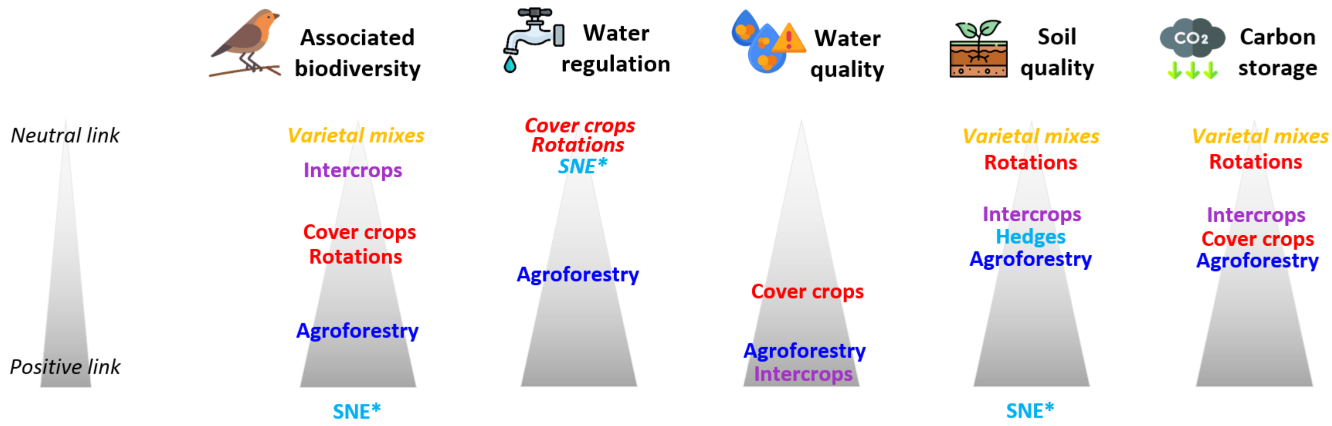

Figure 2. Ranking of diversification methods according to the strength of their links with associated biodiversity and the supply of certain ecosystem services (only the links indicated in the literature are represented)

*The positive links between the diversity of semi-natural elements (here called SNE) and associated biodiversity and ecosystem services are not quantified, preventing this diversification method from being positioned relative to the others.

Diversified systems often show higher yields than undiversified systems

Besides the losses caused by pests, yields depend on a set of factors including the genetic potential of the cultivated plant, the satisfaction of the crop's nutrient and water needs, efficiency of pollination etc.

According to the literature analysed in this ESCo, the **diversification of cultivated plants is generally accompanied by a gain in yields** (compared to less diversified systems[3]).). This gain is of the order of a few percent for **varietal mixtures** and **cover crops** in temperate environments, rising to several tens of percent in tropical **agroforestry**. **Rotations** and **intercropping** show intermediate yield gains. **The presence of semi-natural vegetation does not seem to have any impact on yields in adjacent plots**. It should be noted that varietal mixtures enable the inter-annual stabilisation of yields.

These orders of magnitude, taken from studies conducted around the world, are largely confirmed by work specifically analysing diversified systems used in agroecological and economic contexts comparable to France. However, some case studies report reduced yields. For example, lower yields have been associated with the use of **traditional or peasant varieties** (the reason for which they have historically been replaced by certified varieties resulting from varietal selection). A lack of knowledge among farmers on the management of diversified systems (for example in the case of the **introduction of a niche crop in the rotation** such as hemp or spelt etc.) can also be at the origin of yield fluctuations. Finally, the introduction of **semi-natural elements** in or around the plot tends to induce production losses, mainly due to the loss of cultivated area (provided, however, we do not consider the possible development of this vegetation: wood, fruit etc).

Plant diversification has contrasting effects on the economic profitability of farms in the short term

Given the importance of the economic dimension in farmers' decision-making, the profitability of diversified systems is one of the key factors for their adoption. **Few studies assess the economic impacts** for a farm of **adopting plant diversification practices to protect crops**. This evaluation is all the more difficult to conduct as the methods of diversification studied affect the determinants of profitability differently (Fig. 3). In addition, plant diversification is often associated with other agroecological practices, which also affect profitability.

The most studied form of diversification is **intercropping**, which generally proves to be **profitable** despite the additional costs linked to agricultural equipment (for sowing, harvesting and sorting in particular). The adoption of **varietal mixtures does not seem to significantly affect farm profitability but can stabilise income**. Although associated with lower yields, arable **traditional or peasant varieties** can prove **profitable in niche strategies**, when the farmer controls the distribution of their crops through local sales channels (see below). On the other hand, the **diversification of**

[3] The yields of mixtures of varieties or species are mainly compared to untreated controls (experimental approach), unlike the other diversification methods, which are mainly compared to references in conventional agriculture (observational approach).

rotations and cropping plans through the introduction of a new crop gives **highly variable results** (some positive effects, sometimes negative, often neutral). The lack of profitability generally comes from the fact that the new crops introduced are often, by definition, less profitable than those initially chosen by the farmer (because they are the most profitable). Similarly, the **establishment of semi-natural elements is not considered profitable** without subsidies, at least in the short term.

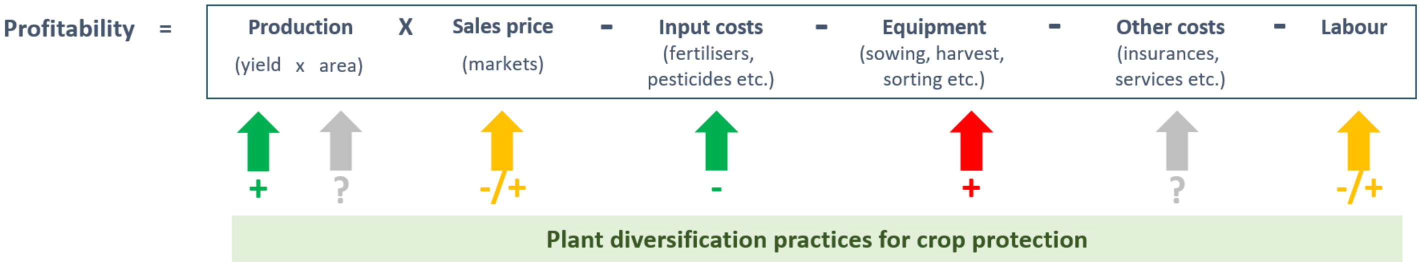

Figure 3. Schematic representation of the factors included in the calculation of the profitability of a farm and how plant diversification of a cropping system affects profitability

The symbols reflect the effect of diversification on each component: increase (+); decrease (-); ambiguous effect (+/-); effect not documented in the literature analysed (?). The colour of the arrows reflects the direction of the effect on profitability: positive effect (green); negative effect (red); ambiguous effect (yellow); insufficient information (grey).
For example: diversification tends to favour yield (+) which increases profitability (green arrow), but it can also increase the cost associated with certain equipment (+) which reduces profitability (red arrow).

Transversely, the **methods of plant diversification studied are generally more efficient economically in the context of strong pest pressure as well as in systems with low input levels, in particular organic farming**. Economic profitability is also reinforced in economic contexts where production prices are low (mitigating the effects of possible yield losses) or high input costs (reinforcing the effects of savings on inputs). However, the potential gains compared to a conventional production system are generally insufficient to encourage farmers to confront the obstacles linked to the socio-technical organisation of value chains and the interactions between actors within territories (see below).

From a methodological point of view, estimating the profitability of diversified systems suffers from the lack of consideration of various factors:

- **The delay between establishing ecological mechanisms** (fully effective after a few years in the case of landscape diversification, rotations and semi-natural vegetation) and/or the **sustainability of the agroecological effects induced by plant diversification** (for example inter-annual stabilisation of yields).
- The **multiplicity of positive externalities of plant diversification**, which are found beyond the farm's boundaries (diversification implemented on a farm can contribute to pest regulation at the landscape scale) and are not restricted to pest regulation (provision of certain ecosystem services that benefit society – see above).
- There is also the question of the **'social' profitability** of production methods, integrating into its calculation the **environmental and health impacts of crop protection strategies based on chemical control**.

To promote plant diversification, obstacles must be lifted within supply chains and territories

The production methods that prevail in the dominant conventional agricultural systems (based on the use of synthetic inputs) are the result of the co-evolution of knowledge, practices and organisations within supply chains over recent decades. These systems have become specialised thanks to the achievement of economies of scale at the farm level (choice of the most profitable crops) and within supply chains (concentration of research and development efforts and advice on these species and standardisation of food processing methods). Productivist public policies have accompanied this movement. **The current system is therefore characterised by a systemic lock-in that opposes diversification (Meynard et al., 2013)**.

Consequently, the deployment of crop protection strategies based on plant diversification requires systemic changes both upstream and downstream of agricultural production, as well as in the relationship between farmers and other actors in the territory (Fig. 4). The obstacles and levers to the deployment of such strategies are rarely specific to a particular diversification method. However, **the literature does not make it possible to rank the weight of each of them in the adoption of different diversification practices**.

Adoption factors upstream in supply chains

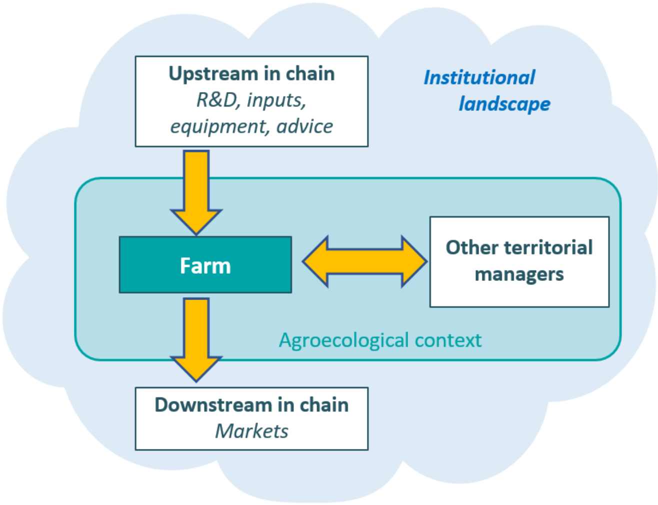

Figure 4. The different levels of socio-economic organisation considered in this ESCo

Upstream of farms, the **availability of seeds and plants adapted to diversified systems** is one of the factors most frequently mentioned in the literature. The varieties available to farmers are mainly selected for their performance grown as a pure crop with synthetic inputs. In addition to the necessary **investment in the breeding process**, the **sharing of experiences and the exchange of seeds** between farmers (possibly combined with participatory selection involving researchers and farmers) can help to remove this obstacle.

Sometimes **the supply of agricultural equipment adapted to diversified crops is also lacking**. This is particularly the case for sowing and harvesting of **combined crops** or certain **niche crops**, and for the maintenance of **semi-natural elements**. The **sharing of equipment** (group purchases or use of service providers) is mentioned as a lever, though this requires a certain coordination among users. **Self-construction of equipment** by farmers (adaptation of equipment) is also a lever for reducing equipment costs.

The literature often mentions the **lack of knowledge** (both among farmers and advisers), of **technical and economic references** and of **advice** for managing diversified systems. In addition to **increased investment in R&D and advice**, several levers are mentioned in which research has a role to play: **on-farm experimentation**, integration into **networks of farmers**, access to **decision support tools and/or assessments of the effects of diversification practices** (in particular their effectiveness against pests).

Adoption factors downstream in supply chains

Downstream, the **lack of markets for products from diversified systems is a recurring obstacle**. In the case of arable crops, the processing processes used in standard value chains impose certain characteristics (for example, varietal purity for milling) that cannot be obtained with **varietal mixtures**, **traditional or peasant varieties** and **intercropping**. In market gardening and arboriculture, products must meet strict quality standards (size and appearance) and volumes at given maturity dates to supply supermarkets. However, the **diversification of vegetable crops** can induce visual defects on produce and a change in cropping schedules.

These barriers can be removed by **promoting the specific characteristics of products obtained from diversified systems** (organoleptic, nutritional or environmental qualities, proximity, seasonality etc.) in **local supply chains and/or use labelling** to achieve higher selling prices. The lack of markets can also be circumvented by a **transition to an economic model of on-farm processing** (for example, flour for cereal crops, tinned fruit and vegetables), though this involves higher workloads. Where **semi-natural elements have been introduced** on the farm, the challenge is to be able to exploit the wood produced by hedges or tree rows in agroforestry systems, in supply chains which may be unknown to farmers.

Deploying plant diverification requires territorial coordination

Territorial coordination is necessary to deploy **diversification at the landscape scale** (spatial organisation of crops and introduction of semi-natural elements), or to guarantee the **sustainability of certain diversification methods introduced at the plot scale** (sustaining the effectiveness of varietal mixtures requires consideration of their deployment at a landscape scale).

Plant diversification projects mobilising a plurality of actors (farmers, agricultural advisers, agrifood manufacturers, cooperatives, water managers, non-agricultural associations, local authorities etc.) are emerging but remain rare. The literature testifies to the methodological difficulties in studying and managing the territory, due to the multiplicity of spatial and temporal scales that need to be considered and the actors involved. **Transdisciplinarity** is suggested to overcome these difficulties, making it possible to **develop participatory research with the actors concerned** and thereby allow solutions that are acceptable to all to emerge.

Three levers have been identified to promote territorial solutions:

- The fact that collective action generates a **collective gain** (for example eco-certification or payments for environmental services).

- The **establishment of collective organisations** to manage agricultural territories (for example, local collective institutions such as France's cooperative societies serving the general interest) or centralised planning and incentives by public authorities.
- The **certification of products, farms and landscapes**, boosting the range of possible sales channels (for example, collective catering markets).

Public policies are a key determinant in the deployment of plant diversification

Public policies, in particular the Common Agricultural Policy (CAP), have been a strong lever for initiating and supporting agricultural modernisation in the post-war period. **Escaping the systemic lock-ins of this very stable dominant model therefore requires ambitious public policies**, as well as an evolution in the legal framework governing the management of agricultural areas.

While the CAP has gradually introduced measures aimed at reducing the environmental and health impacts of conventional agriculture, the actual result on the environment and biodiversity of agricultural areas is not very visible. The case of introducing semi-natural elements is an emblematic example. From the early 2000s, public policies (particularly European ones) sought to promote their conservation and then their restoration. So, hedges and agroforestry are today at the heart of a large number of European and national plans (for example, BCAE[4], green payments, MAEC[5] and future CAP eco-schemes, France 2030, strategies for accelerating sustainable agricultural systems and equipment, regional financial programmes and the localised and experimental introduction of payments for environmental services). **While the measures adopted in the CAP 2014-2020 appeared relatively effective in avoiding the destruction or degradation of the semi-natural elements in place, they proved insufficient to promote their expansion and did not stimulate the development of agroforestry**.

The efficacy of French approaches has not been evaluated, but the scattering of aid between multiple measures appears to be an insufficient incentive. In addition, the legal context is not always consistent with public policy incentives. So, the regulations are not very favourable for the development of semi-natural elements, which collide with rural land rights. Scattered tools exist to protect them (rural leases, real environmental obligations and town planning documents) but no quantitative study has measured the effective deployment of this type of system, nor its real efficacy. Finally, agroforestry is a poorly identified legal object, combining two activities (agricultural and forestry) operating under separate legal regimes.

Several political levers exist to support the use of plant diversification rather than chemical control to protect crops. **Subsidies for the adoption of diversification practices** transfer to the community the economic burden of taking charge of environmental issues by farmers. Public policies can **directly support supply chains by targeting advice, research, investment aid and the establishment of markets**. This support can be backed by payment for environmental services, justified by the effects of diversification on biodiversity and the supply of ecosystem services. Such support is generally well received by the actors in supply chains and territories but faces budgetary constraints, as well as the technical complexity of its implementation (calculation and evaluation of environmental benefits).

Indirect support can include a **correction of market imperfections that currently favour conventional production systems** that consume synthetic inputs, pesticides in particular. This may include **banning the use of the most toxic pesticides or taxing them in proportion to the negative externalities that their use generates**. This type of environmental taxation would induce both a reduction in use and substitution mechanisms, while generating revenue that can be used to support the change towards more virtuous practices, for example. Given the low elasticity of demand with respect to pesticide prices, producing an effect would require high levels of taxation (or increase rapidly over time).

It is still too early to assess the impact that the post-2023 CAP could have on plant diversification and research is needed to assess the effect of such measures. However, it is likely that, without a strong political will defining binding objectives, crop protection strategies that are an alternative to pesticide use, including plant diversification, will find it difficult to emerge on their own and that the ambitious objectives set by the European Green Deal will not be achieved (Guyomard *et al.*, 2020).

[4] Good agricultural and environmental conditions

[5] Agri-environmental and climate measures

By crossing all the summarised knowledge, plant diversification methods can be placed along a gradient of the transformation of cropping systems that their adoption requires, compared with their expected benefits:

- **Varietal mixtures** collide with barriers at the supply chain level (seed supply and markets) but it seems possible to implement them in conventional systems without major changes in management practices or agricultural equipment at the farm level. However, their associated benefits in terms of pest regulation, yields and provision of ecosystem services are also the lowest compared to other diversification approaches.
- Through the introduction of a new crop, the **diversification of rotations** on a farm offers interesting potential for the supply of ecosystem services (including the natural regulation of pests) but faces obstacles both at the farm scale (complexity of managing a new crop and need for new equipment) and at the supply chain level (lack of varietal selection, advice and research for niche crops, plus limited markets).
- **Intercropping** with cash crops raises technical challenges (sowing, harvesting and sorting), but seems to be among the most profitable. This method of diversification exploits a combination of mechanisms (a barrier to dispersal, allelopathy etc.) which is favourable for the management of several types of pests (weeds, insects and soil pathogens).
- At the other end of the gradient, **agroforestry systems** require the most significant transformations: more fundamental redesign of the system, use of specific agricultural equipment, integration into forestry value chains and complexity of the legal status. The evaluation of pest regulation using agroforestry should be reinforced in temperate environments, but the numerous works relating to (sub)tropical agroforestry demonstrate the benefits of these complex covers in terms of the preservation of biodiversity and the supply of a wide range of ecosystem services.
- The **establishment of semi-natural elements**, which are particularly beneficial to biodiversity and the provision of ecosystem services, raises specific issues at the landscape scale. In particular, it requires coordination between different categories of actors in the territories and needs spatialised public incentive policies (for example, to establish green belts) that are complex to design and implement.

Perspectives and research needs

Plant diversification in the face of environmental issues

This ESCo provides food for thought on the contribution of plant diversification to the transition to agriculture without synthetic pesticides. Although the adoption of diversification practices is often accompanied by an (unquantified) reduction in the use of synthetic pesticides, it does not guarantee that they are abandoned, unlike regulatory constraints such as organic certification. Therefore, the combination of plant diversification (an agroecological tool) with organic certification (a regulatory tool) appears promising. Indeed, certain plant diversification methods (in particular concerning semi-natural vegetation in landscapes) are associated with higher levels of biodiversity and ecosystem services than non-diversified organic farming systems. In addition, diversifying systems often makes it possible to achieve higher yields than those recorded in organic farming (moreover, these yield gains are most marked in low-input systems). We note that organic certification makes it possible to improve the economic returns for crops produced in diversified systems.

Furthermore, the **relationship between plant diversification in agricultural areas and climate change** is often mentioned in the discussion points of the articles analysed. Some works collected in the corpus report on the positive effects of cover crops, intercropping, agroforestry, diversified rotations and linear elements planted and/or managed by farmers (such as grassy strips and hedgerows) on **carbon storage**, **water regulation** and **resilience to climate disturbances**. Varietal mixtures, intercropping and the presence of semi-natural elements in agricultural landscapes promote the **stabilisation of yields in the face of variations in annual climatic conditions**. Although an exhaustive bibliographical summary of this literature is to be undertaken, this information illustrates the interest of plant diversification in improving the resilience of agricultural systems and limiting the contribution of agriculture to climate change, given our understanding that agriculture is, according to the IPCC, the second largest sector contributing to climate change after transport.

Research

In addition to the knowledge gaps identified in Table 1, there is a lack of work on the effects of **combinations of diversification methods**, and/or **pest populations**. Anticipating these effects requires strengthening our understanding of the mechanisms underlying natural regulations. Designing **experiments at the scale of agro-ecological territories** is a way to achieve this, also making it possible to understand the dependence of natural regulations in local conditions. Such experiments are also necessary to assess the **sustainability** of regulation, as well as the **evolution of its efficacy** in the face of climate change and the erosion of biodiversity. The place of livestock in diversified cropping systems should also be considered, as a lever for diversification and as an outlet for crop production.

The **evaluation of the economic performance of diversified systems** is hindered by the lack of data obtained in real situations on emerging practices. **The study of the dynamics of the diffusion of innovations, such as plant diversification**, remains a major frontier in science, suffering from the lack of statistics on the development of these practices. The impacts of the adoption of these practices on farm management (in particular the work involved) and on pesticide use are insufficiently documented. The **collective organisation of plant protection at the territorial scale** has also received little attention. The large-scale experiments described above could be a means of developing new methods of coordination between actors.

The poor efficacy of public policies in promoting the adoption of plant diversification requires work on the **design of public agricultural policies** and on **their consistency with other sectoral policies**, in particular food policies, to bring together an offer of agricultural products which is more environmentally friendly and offers healthier and more sustainable diets. Work on **consumer behaviour** must be undertaken (willingness to pay for environmental attributes beyond just pesticide reductions and the acceptability of products that do not meet conventional standards).

Some **facilities** seem conducive to such integrated and territorial research, but they must be increased and made permanent. INRAE experimental platforms and long-term observatories in agricultural environments are suitable for such long-term studies. Participatory innovation approaches such as living labs seem to respond to the required systemic approach and allow for the comparison of wide ranges of diversified systems. In addition, spatial monitoring of the adoption of diversification practices can be based on remote sensing. Finally, **modelling** represents a complementary research path that should be utilised.

How much diversification? Some recommendations from the scientific literature

A few scientific articles[6] provide quantitative recommendations on the deployment of certain methods of plant diversification, though they do not target the objective of crop protection:

- **Varietal mixtures composed of 4 to 5 varieties** to effectively regulate diseases. By way of comparison, varietal mixtures of wheat (which represent more than 15% of France's wheat area) are composed of a maximum of 2 to 3 varieties.
- **Intercropping of 2 species not sensitive to the same pests and complementary in their resource use** (for example cereal or cruciferous plants with grain legumes) to regulate diseases, weeds and insect pests. Mixtures of cash crops now represent 0.1 to 3% of the agricultural area depending on the region and are mainly combinations of cereals and protein crops.
- **Rotations of longer than 3 years for arable crops, including winter and spring crops and, if possible, Brassicaceae** (to regulate weeds in particular) and **legumes** (for the fixation of atmospheric nitrogen). Currently, the majority of arable crop areas have rotations of a maximum of 3 crops (with a predominance of crop triplets including oilseed rape, wheat and barley).
- An **optimal arable field size of approximately 2.8 ha** to promote regulation and biodiversity. While the French average is around 3.1 ha, 50% of the UAA is occupied by fields of more than 6.8 ha.
- **20% of semi-natural elements in the landscape** to ensure the regulation of arthropod pests, the conservation of biodiversity and the provision of various ecosystem services; **linear hedges of around 300m per ha** to reconcile yields and biodiversity. Due to the lack of national statistics, it is currently difficult to estimate the share occupied by semi-natural elements in French agricultural landscapes. However, the share is often less than 5% on France's cereal plains and the dynamics of reducing semi-natural elements initiated after the war still continues for hedges and rows of trees, with an average loss of 7,000km per year. **Agroforestry** occupied only 100,000 to 170,000ha in the mid-2010s according to estimates, and is growing only slowly.

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For more information

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This document is the 2nd version of the summary (correction of Table 1).

[6] Scientific references are cited in the ESCo condensed report.

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