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Protecting crops through plant diversity

Anaïs Tibi, Vincent Martinet, Aude Vialatte, eds

éditions Quæ

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The documents pertaining to this assessment are available on the INRAE websites (https://www.inrae.fr/).

The authors of the scientific report, which is the basis of this work, are all the members of the CSA workgroup listed at the end of the book. Unless otherwise specified, the figures and tables were produced by the authors. The websites mentioned in this book were accessed in June and July 2023.

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Summary

Introduction

In the post-WWII context, the advent of synthetic fertilisers and pesticides prompted farmers to specialise their farms in the most profitable crops, thus freeing them from environmental constraints (presence of crop pests, availability of nutrients in the soil, climate variability, etc.). While this agricultural transformation boosted production levels, it also resulted in the gradual loss of plant diversity, both cultivated (with shorter crop rotations and increasingly standardised fields) and semi-natural (removal of hedgerows in favour of larger fields). The environmental and health impacts of this dominant model and its interrelationship with global changes (climate change, biodiversity loss, changes in land use) are now well documented by the scientific community.[1] Facing such challenges, France and Europe are witnessing a strong public demand for agriculture that is more respectful of the environment and human health and less dependent on synthetic inputs.

The demand for alternative production methods to so-called 'conventional' systems is reflected in some European public policies (European Green Deal, Common Agricultural Policy) and national policies (see box 1). These policies set targets for reducing pesticide use, and, more generally, they promote a shift towards more diversified farming systems that place biodiversity and ecological processes at the forefront of production factors. However, despite the growing recognition of environmental issues in public policies, it should be mentioned that the shift towards low-pesticide cropping systems is far from being sufficiently advanced to meet the targets set (Guyomard *et al.*, 2020). Furthermore, while political and scientific circles view plant diversification as a significant lever for this transition, there is still a lack of critical perspective and overall vision regarding its effectiveness 'in the field', particularly concerning crop protection. Finally, plant diversification covers a broad range of situations and practices. While some are well-known and used by some farmers (i.e., varietal mixtures), others are little known (i.e., agroforestry in temperate environments), and many are—rightly or wrongly—perceived by certain operators as relatively ineffective or too restrictive.

Purpose and scope of the Collective scientific assessment

In this context, the French Ministries of Agriculture, Environment and Research commissioned the INRAE in late 2019 to carry out two collective scientific assessments (CSA) in parallel, one on the impact of plant protection products on biodiversity and ecosystem

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

Box 1. European and French public policies on the use of pesticides and changes in agricultural production methods

At the European level, Directive 2009/128/EC, known as the SUD (Sustainable Use of Pesticides Directive), requires all Member States to draw up a general framework for action to limit the use of pesticides in the EU while encouraging farmers to use 'integrated pest management and alternative methods and techniques'. The recent European Green Deal, launched in December 2019, sets quantitative targets for 2030 through its strategic applications for agriculture (the 'from farm to fork' strategy) and biodiversity (European strategy for biodiversity). These targets include a 50% reduction in the use of pesticides,* an increase to 25% in the proportion of agricultural area used for organic farming, and a rise to 10% in the proportion of agricultural area used for 'high diversity landscape features' (buffer strips, fallow land, hedgerows, non-productive trees, etc.), which serve as a refuge for the natural enemies of crop pests. The main European policy that must be leveraged to this end is the Common Agricultural Policy (CAP) through its three environmental tools (cross-compliance, eco-schemes and agri-environmental and climate measures). While the CAP does not include an explicit target for reducing the use of pesticides, the re-diversification of farming systems has emerged as a challenge since the 2014 reform (one of the three greening measures) and is reinforced in the current programming.

In France, targets for reducing the use of pesticides are set out in a specific policy plan for pesticide use reduction, called the Ecophyto plan, launched at the Grenelle de l'Environnement in 2007. The Ecophyto plan is the French version of the SUD. Because the initial objective of cutting pesticide use by half between 2008 and 2018 ('Ecophyto 2018') was not achieved, French public authorities reviewed the Plan ('Ecophyto 2' then '2+') and pushed back the deadline to 2025. As a complement to the Plan, a Law on the Future of Agriculture, Food and Forestry (LAAAF for Loi d'Avenir pour l'Agriculture, l'Alimentation et la Forêt) passed in 2014.** As well as introducing the concept of 'agroecological' production systems into the legislation (without, however, defining their characteristics), it sets a target of 50% of French farms with agroecological practices by 2025. Parallel to agricultural policies, France's National Strategy for Biodiversity (which reflects the State's commitment under the Convention on Biological Diversity) includes in its 2022-2030 programme a commitment to promote the agroecological transition of agricultural production and food systems and to facilitate the implementation of agroecological infrastructures (to integrate ecological grids into land-use planning).

Finally, policies that target other issues may impact crop and landscape diversification. Examples include Directive 91/676/EEC on nitrates, which requires planting grassed strips along waterways; Directives 92/43/EEC on habitats and 2009/147/EC on birds, which aim to maintain the biological diversity of environments, particularly the (semi-)natural fraction of landscapes, and the national strategy on plant proteins, which encourages the introduction of legumes in crop rotations.

* The SUD Directive was due to be revised in the summer of 2022. Target that the EU has suggested including in the future Sustainable Use of Pesticides European Directive, thereby making it legally binding at the EU level. This project, however, failed at the end of 2023.

** It embodies the Projet Agroécologique pour la France (Agroecological Project for France), launched in 2012.

services (which conclusions were delivered in May 2022 - Leenhardt *et al.*, 2022), and one on the use of plant cover diversity to regulate pests and protect crops. The latter CSA, which is the subject of this book, responds to the need to assess the effectiveness of crop protection strategies based on plant diversification in agricultural fields and landscapes in light of published scientific results. It also aims to analyse the obstacles and levers to implementing such strategies by bringing together different disciplinary perspectives from the life sciences to economics and the social sciences. Finally, there is a need to clarify the role of plant diversity in providing other ecosystem services in synergy with the natural regulation of pests. This request is part of the Écophyto 2+ Plan.[2]

Since the mid-2000s, academic research has been increasingly active in analysing low-input production methods. Building in particular on the conceptual framework of ecosystem services popularised by the *Millennium Ecosystem Assessment* (2005), a body of evidence has highlighted the strength of the interactions between agricultural practices, biodiversity and the services provided by the latter to human societies (see, for example, Le Roux *et al.*, 2008). The 'EFESE-écosystème agricoles' survey carried out by the INRA has specifically highlighted the critical role of the nature and spatial organisation of plants in supplying all the services supporting agricultural production, including natural regulation of crop pests (Tibi and Therond, 2017). More recently, a growing number of studies have focused on the analysis of the benefits of plant diversification in agricultural fields and landscapes (such as the European projects under the aegis of the *Crop Diversification Cluster*). Similarly, several research endeavours are exploring avenues for eliminating the use of pesticides. The 'Écophyto R&D' survey carried out by the INRA (Butault *et al.*, 2010) showed that a target of reducing the use of pesticides by half could not be reached without the in-depth and sustainable redesign of production systems. The purpose of the CAS was to revisit and update this work by specifically reviewing the literature at the crossroads between plant diversification in agricultural systems and crop protection.

The CAS literature review is part of an ever-expanding scientific landscape. A European research alliance called *Towards a Chemical Pesticide-Free Agriculture* was created in 2020 at the initiative of the INRAE. Today, it brings together 34 research bodies from 20 European countries to foster transdisciplinary research and innovations. In France, the 'Cultiver et Protéger autrement' (alternative cultivation and protection methods) Priority Research Programme (PPR) was launched in 2018 to encourage research to design cropping systems free of synthetic pesticides. As the lead partner for this PPR, and in parallel to this CAS, the INRAE also carried out a foresight study proposing scenarios for the European Union's transition to pesticide-free farming methods by 2050 (Mora *et al.*, 2023).

The scope of the CAS encompasses all the spatial and temporal scales at which plant diversity can be rolled out or managed. Thus, at the field level, the focus is on the farmer's choice and method of planting species and varieties (varietal or species mixtures, grass

2. The CAS project received financial support from the Écophyto 2+ plan (*via* the Office Français de la Biodiversité—French Biodiversity Agency—which oversees the plan's funding) as part of its second area of focus on research and innovation.

strips, service plants, etc.) and the temporal dynamics of these plant cover crops (rotations). At the supra-field level (farm, landscape), the focus is on the effects of the composition and configuration of the vegetation as a whole, whether this concerns the farmed portion (cropping pattern, shape and size of land parcels) or semi-natural portion (nature and connectivity of agroecological infrastructures around the fields—hedges or borders—or which form islands in the landscape—woodland, permanent grassland, etc.).

The CAS scope includes all types of plant productions in France, whether field crops (for human or animal consumption, industrial use), perennial crops (arboriculture, vineyards) or horticulture. While the request addressed to the INRAE primarily aimed to gain a better understanding of the potential offered by plant diversification for the protection of cropping systems in mainland France, the systems in the French overseas territories have specific characteristics (in particular biogeographical, agronomic and socio-economic) that warrant a detailed analysis in the CAS. This analysis is presented in box 2.3.

The Collective Scientific Assessment (CSA) approach

The INRAE (formerly INRA) has carried out collective scientific assessment (CAS) activities since 2002. The CAS's institutional activity is covered by a national charter signed in 2011. The CAS involves analysing and collating scientific to inform public action. It aims to spotlight the scientific achievements, uncertainties, and areas of scientific controversy. The CAS does not provide advice or recommendations. Similarly, it does not provide practical answers to issues raised by managers. Instead, it provides as comprehensive a review of scientific knowledge as possible, using a multidisciplinary approach that combines the life sciences, economics and social sciences. It also identifies poorly documented issues that should be researched as a priority.

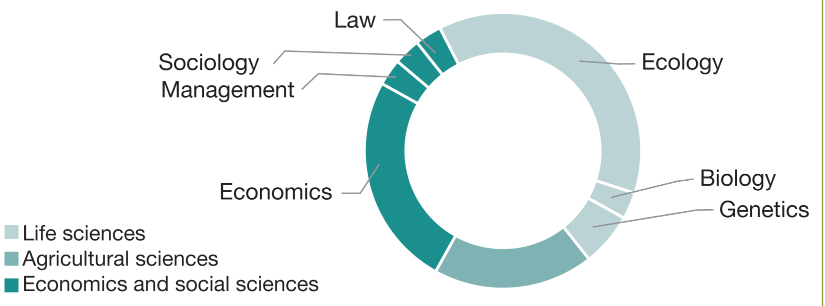
CAS operations are coordinated by the INRAE's DEPE (Directorate for Collective Scientific Assessment, Foresight and Advanced Studies) in compliance with an Institutional charter. The principles set out by the DEPE to guarantee the reliability of the findings of the work are described in a public booklet.[3] They include the competence of the experts (selected for their scientific publications), their plurality (they come from various public research institutes), the impartiality of the experts' committee (which relies on the examination of the experts' declarations of interest by the INRAE's ethics committee), the transparency of the methodology followed and the traceability of the actions and resources implemented during the operation.

INRAE brought together a committee of some thirty experts and scientific contributors with complementary disciplinary skills (figure I.1) to carry out this CAS. The members' list of the expert committee is included at the end of this document. Supported by two librarians, the experts compiled the scientific knowledge published to date on the various

3. https://www.inrae.fr/en/news/guidelines-collective-scientific-assessments-and-advenced-studies

issues addressed to INRAE, and extracted the relevant information to inform public decision-making. Two project managers were also recruited during the CAS to carry out complementary analyses to those produced by the scientific experts.

Figure I.1. Disciplines represented in the experts' committee



The figures show the number of experts in each discipline. Some experts are qualified in several disciplines.

Two librairians helped the experts' committee and project managers to identify and collect the scientific and technical references useful for the assessment (box 2). They conducted a bibliometric analysis of the final corpus supporting the scientific report.

The experts' committee was chaired by two scientific leads who set the CAS's scientific directions, oversaw the collective and multidisciplinary production, and checked the scientific robustness and integrity of the experts' conclusions. A team from the DEPE oversaw the general coordination of the CAS, the project's logistical and financial management, and the feedback symposium's organisation.

The CAS produced three deliverables. The analyses produced by the experts were initially compiled in a extended scientific report of some 1,000 pages, which includes the exhaustive list of references supporting the conclusions (cf. *infra*). Intended for a non-scientific but informed readership, the condensed report (presented in this document) compiles the main findings of the CAS report and provides a key to its interpretation. It should be noted that the 94 references quoted in this document are only a fraction of the bibliographical corpus of the CAS (only the references of figures, examples and data taken from publications are mentioned), as the extended report is based on 2,078 references. Finally, the CAS's main conclusions are presented in a twelve-page summary report in the most concise terms possible for a broad audience.

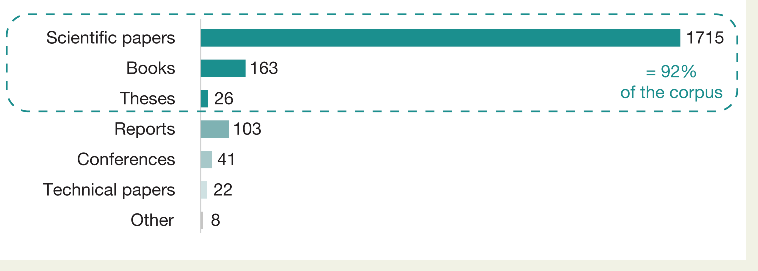
Box 2. The CAS bibliographic corpus

The expert's report is supported by a body of literature comprising 2,078 references, 94 of which are cited in this book. The librarians and the project leader have developed queries specific to each CAS topic in collaboration with the experts. These queries were used to search bibliographic databases (mainly the Web of Science, supplemented by Scopus for the economic and social sciences).*

The experts sorted the thousands of references from these queries and only selected those that could inform the questions in the request submitted to INRAE. The experts also enriched the corpus with references not captured by systematic searches of these databases (i), either because they are not referenced there (for example, academic references from journals not referenced in these databases and non-academic documents useful to the CAS, such as legal texts, specific reports, etc.), (ii) or because they are generic references, with research objects that are beyond the typical questions of the referral, but which enrich the CAS by providing structuring or discussion elements.

The final corpus comprises mainly scientific articles (83%)—the vast majority of which were published in peer-reviewed journals (78%)—supplemented by scientific books and theses, as well as reports (i.e. scientific reports or European Commission reports), information from scientific conferences, technical literature (mainly publications which include analyses of agricultural statistics) and other types of so-called 'grey' references complementing academic literature on aspects not covered by the latter.

Figure I.2. Nature of the references quoted in the CAS report



* These databases were last queried in late 2021.

A monitoring committee led by the DEPE met three times to liaise between the working group and the ministries and ensure that the work proceeded smoothly. It included representatives from the French Ministries of Agriculture, the Environment and Research, the INRAE's 'Agriculture' Scientific Division, the French Biodiversity Agency (OFB) and the Ecophyto Plan's Scientific Committee for Research and Innovation (CSO RI).

A Stakeholder Advisory Committee, facilitated by the DEPE, also met at the outset and conclusion of the CAS to inform stakeholders of the scientific directions and findings of the work and to collect the stakeholders' concerns, interests and questions regarding the operation. In addition to the members of the Monitoring Committee, several other stakeholders likely to be affected by the findings of the exercise and to use the results were invited to attend: stakeholders in the agricultural and food sectors,[4] environmental organisations,[5] consultancy firms,[6] local players,[7] etc.

4. Association de coordination technique agricole (ACTA-Agricultural technical coordination association), Réseau des Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural (CIVAM-network of centres for initiatives to promote agriculture and the rural environment), Fédération nationale des coopératives d'utilisation de matériel agricole (FNCUMA-National federation of cooperatives for the use of agricultural equipment), La Coopérative agricole, Fédération nationale du négoce agricole (National federation of agricultural trade), Union des industriels de l'agroéquipement (Axema-Union of agricultural equipment manufacturers), Association nationale des Industries alimentaires (ANIA-National association of food industries).

5. Ligue pour la protection des oiseaux (LPO-Bird protection league), Office Pour les Insectes et leur Environnement (OPIE-French office for insects and their environment).

6. Solagro (a non-profit promoting practices and techniques to save natural resources in energy, agriculture and forestry), Flor'insectes (a consultancy specialising in the management of plant cover to encourage biodiversity).

7. Water agencies, National Forest Office (ONF).

PART 1

A few definitions

This part presents the objects and concepts studied in the CAS. First, the concept of pests and their impact on crops. Second, the natural regulation of pests, with a paradigmatic shift away from chemical control strategies.[8] Finally, the different ways of diversifying farmland vegetation; these differ according to the type of vegetation in question (cultivated or semi-natural), the temporal dimension of the diversification (crop season only or multi-annual) and the spatial scale of the roll-out (field, farm, landscape).

8. Used here to refer to pesticide use.

1. Pest, crop protection and natural regulation

Pest: from injuries to economic losses

Pests are living organisms whose actions on cultivated plants cause physiological or mechanical injuries. Such injuries may be characterised by an alteration in the growth or vigour of the plant, its morphology or that of its organs (lesions, changes in colour, deformations, necrosis, galls, etc.), or even its chemical composition (nutrient content, presence of toxins, etc.). The injuries may result in quantitative or qualitative crop losses[9] (damages) and ultimately in economic losses.

Various organisms can harm cultivated plants: phytophagous arthropods (insects, acarids, etc.), weeds (crop volunteers and spontaneous vegetation) or parasitic plants, pathogenic microorganisms (fungi, bacteria, viruses, phytoplasmas, etc.) that cause plant diseases, gastropods, nematodes, birds, mammals (rodents, moles, etc.). Some pathogens are transmitted to plants by carrier organisms (usually insects, but also acarids, nematodes, mammals, etc.). Although it does not always harm the plant, the vector is generally targeted by crop protection methods and is therefore viewed as a pest. Given the concerns that motivated this CAS, the analysis focuses mainly on the categories of pests that are chemically controlled: weeds and parasitic plants, pathogenic microorganisms, and micro-meso-macrofauna invertebrates (arthropods, nematodes, molluscs). Table 1.1 summarises the types of injuries caused by these different pests.

The CAS takes a two-pronged approach to weeds. They are qualified as pests when they cause yield losses (due to the competition they exert on crops) and a deterioration in the quality of harvested products (unwanted seeds present in the harvest). The weed flora is, however, part of the plant component of agricultural areas and contributes to plant diversity, which this CAS analyses regarding its potential to regulate pests.

Determining the entire chain of causality between the presence (abundance) of pests, the occurrence of injuries, the level of damages and associated economic losses is no easy task (figure 1.1). The relationship between the abundance of pests and the occurrence of injuries is not proportional, mainly because there are threshold effects for some pests. In addition, the relationship between occurrence of injuries and level of damages

9. It should be noted that losses can occur after harvest, during storage, even if the pest attack happened in the field (for example, the development of late blight on potatoes or certain fruit diseases).

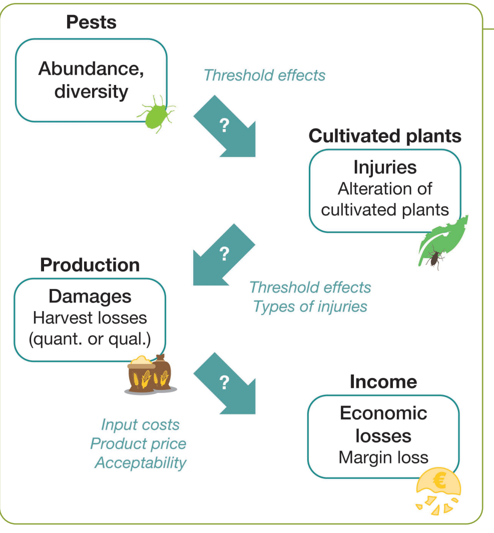
is typically not unequivocal. On the one hand, not all injuries leads to damage (i.e. when the injury does not target a harvested organ). On the other hand, crop yield and quality are composite variables resulting from various factors that interact, including meeting the crop's nutritional and water needs, making it challenging to identify and quantify losses caused by pests alone.

Table 1.1. Nature of injuries and potential damages caused by different types of pests on crops

Pest type	Injuries (observable symptoms)	Potential damages (crop losses)
Pathogens and phytophagous pests	Metabolic or mechanical alterations: – limiting plant rooting, germination and first stage of growth; – Interrupting (partially or totally) the absorption or translocation of water and nutrients (from roots or leaves to storage organs, fruit or seeds); – damaging the vital parts of the plant: storage organs, photosynthetic surfaces, reproductive organs, and support structures. → Alterations in the growth/vigour of the cultivated plant, its morphology (lesions, colour changes, deformation, necroses, galls, etc.), chemical composition (protein and sugar content, presence of toxins, etc.) or organs.	Failure of the cultivated plant to grow and/or deterioration of its organs, making it more challenging to harvest. → Yield loss. Downgrading of crop products due to non-compliance with organoleptic or health criteria. → Quality loss.
Weeds [1]	Competition with cultivated plants for resources (sunlight, water, nutrients). → Alteration in the growth of cultivated plants.	Hampered crop growth → Yield loss. Contamination of the harvest due to the weed seeds harvested at the same time as the cultivated plant. → Quality loss.
Parasitic plants [2]	Partial or total diversion of water and/or nutrients cultivated plants absorb. → Alteration in the growth or vigour of cultivated plants.	Hampered crop growth → Yield loss.

1 Crop volunteers and spontaneous plants.
2 Plants that live and develop at the expense of a host plant (e.g. sunflower broomrape).

Figure 1.1. The cascading effects of pests on crops

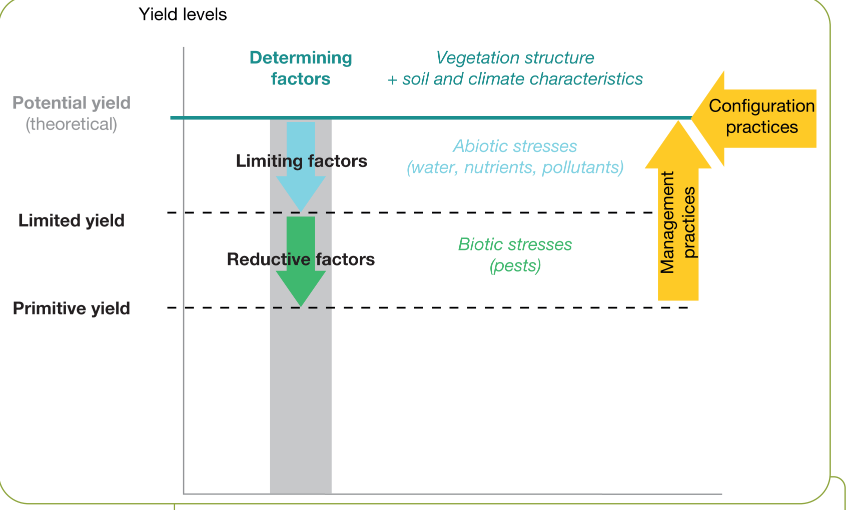


Estimates of damage caused by pests are fragmentary and only concern quantitative losses. This data comes primarily from technical institutes, which carry out yield measurements as part of controlled trials designed to assess the effectiveness of pesticides against certain types of pests. Data also comes from a few scientific papers, which provide estimates most often obtained through modelling. Such losses are evaluated in relation to potential (or achievable) yield, the maximum yield level that can theoretically be achieved when plants are not subjected to any biotic[10] or abiotic[11] stresses (figure 1.2).

Two types of yield loss estimates are available. Potential loss is the loss that could affect the crop in the absence of any protection against pests. It is typically measured by comparing plots that have been chemically treated/untreated for a given pest (or category thereof), other things being equal, and in both cases under optimised conditions regarding fertilisation and treatments against other pests. Hence, potential yield losses are overestimated by design and should be regarded as theoretical maximum values since they are obtained in a hypothetical situation of pesticide withdrawal, ceteris paribus (without implementing alternative management methods).

10. All interactions between living organisms: predation, cooperation, competition, parasitism, etc.
11. Physico-chemical factors in the ecosystem: soil characteristics, climatic, chemical and topographical factors.

Figure 1.2. Factors that determine, limit and reduce crop yield



Configuration practices define the ecosystem's structure: choice of plant genotypes (species, varieties), sowing dates and densities, and cropping sequences. Management practices aim to limit abiotic stresses (i.e., irrigation, fertilisation) and biotic stresses (such as pesticide treatments). Adapted from van Ittersum and Rabbinge (1997).

Actual loss corresponds to loss incurred despite implementing a protection strategy, often chemical, since the estimates available focus on conventional systems built around synthetic inputs. Compared with potential losses, estimates of actual losses indicate the effectiveness of current biocontrol methods. However, these estimates are fraught with uncertainty insofar as the yield also depends on the nutrient and water status of the crop, which may not be optimal (unlike the trials described above).

Table 1.2 summarises potential and actual loss estimates collected under the CAS.

Finally, the link between damage and economic loss is not a systematic one: damage only leads to financial loss if it results in a margin loss for the farmer. Yet this level of loss depends on a range of socio-economic factors such as the characteristics of the cropping system, the cost of inputs, the outlets for harvested products, and their price (which can increase when the damage affects a significant part of the sector, compensating in part for the loss of income in terms of quantity). The level of loss acceptable to the farmer is also influenced by psychological and economic factors (mainly financial or insurance-related).

Table 1.2. Orders of magnitude of average annual losses linked to pests reported in the literature

Crop	Ref.	Potential yield losses (in the absence of any protection against pests)	Actual yield losses (despite the implementation of a crop protection strategy)
Wheat	1	**Weeds**: 2.6 t/ha/year on average over 1993-2015	No data
	2	**Fungal diseases:** 1.6 t/ha/year on average over 2002-2020	No data
	3	**All pests:** 2 to 2.3 t/ha/year compared with actual yield over 1995-2012 (= 24.3 to 33% of actual yield)	No data
	4	**All pests:** 44% over 2001-2003 *including* ***weeds****: 18 to 29%, depending on the region* *including* ***diseases****: 12 to 20% depending on the region*	**All pests**: 14% over 2001-2003 *including* ***weeds****: 3% (or approximately 0.25 to 0.3 t/ha/year)*
	5	No data	**All pests except weeds:** 0.5 t/ha/year over 2009-2019 (or 5 to 10%, depending on the department) *including* ***septoria****: 0.2 t/ha/year*
	6	No data	**All pests except weeds:** 24.9% over 2010-2014 *including:* ***septoria*** *5.5%;* ***yellow rust*** *5.8%;* ***dwarf yellows*** *3.2%;* ***brown rust*** *2.5%;* ***powdery mildew*** *2.2%;* ***tan spot*** *1.9%;* ***fusariosis*** *1.8%*
	7	No data	**Fungal diseases**: 0.8 t/ha/year over 2004-2008 period including ***septoria****: 0.66 t/ha/year (the rest being rusts, fusariosis, powdery mildew)*
Barley	2	**Fungal diseases:** 1.51 t/ha/year on average over 2002-2020	No data
	8	**Diseases:** 12% over 1996-1998	**Diseases:** 5% over 1996-1998
	5	No data	**Fungal diseases**: non-significant over 2009-2016
Maize	9	**Helminthosporium:** 0.6 to 0.8 t/ha/year **Fusarium head blight:** 1 to 1.4 t/ha/year	No data

Table 1.2. Continuation

Crop	Ref.	Potential yield losses (in the absence of any protection against pests)	Actual yield losses (despite the implementation of a crop protection strategy)
Potato	9	**Downy mildew**: 25 t/ha/year	The actual damage (mainly associated with downy mildew) is difficult to estimate because of post-harvest losses (tuber rot).
	6	No data	**All pests except weeds**: 9.8% over 2010-2014 *including*: ***downy mildew*** *3.2%;* ***cyst nematodes*** *3.1%;* ***alternaria*** *1.3%*
	4	**All pests**: above 73% over 2001-2003	**All pests**: 24% over 2001-2003 period
	10	**Downy mildew**: 50 to 80% over 2006-2009 period for very weakly to moderately resistant varieties	No data
Rapeseed	1	**Weeds**: 0.35 t/ha/year on average	No data
	5	No data	**Diseases and insects**: 0.2 t/ha/year
Sunflower	1	**Weeds**: 0.41 t/ha/year on average	No data

Depending on the source, losses are expressed in absolute terms or as a percentage of potential yield (unless explicitly stated). Estimates are not comparable due to the diversity of pests (categories thereof) considered in each review. References: 1. Cordeau *et al.*, 2016 (France – Arvalis network); 2. Arvalis, 2021a (France – Arvalis network) ; 3. Hossard *et al.*, 2015 (France); 4. Oerke, 2006 (north-western Europe); 5. Devaud and Barbu, 2019 (France); 6. Savary *et al.*, 2019 (north-western Europe); 7. Willocquet *et al.*, 2018 (France); 8. Oerke and Dehne, 2004 (north-western Europe); 9. Verjux *et al.*, 2017 (France – Arvalis network); 10. Rakotonindraina *et al.*, 2012 (France).

Natural regulation in crop protection strategies

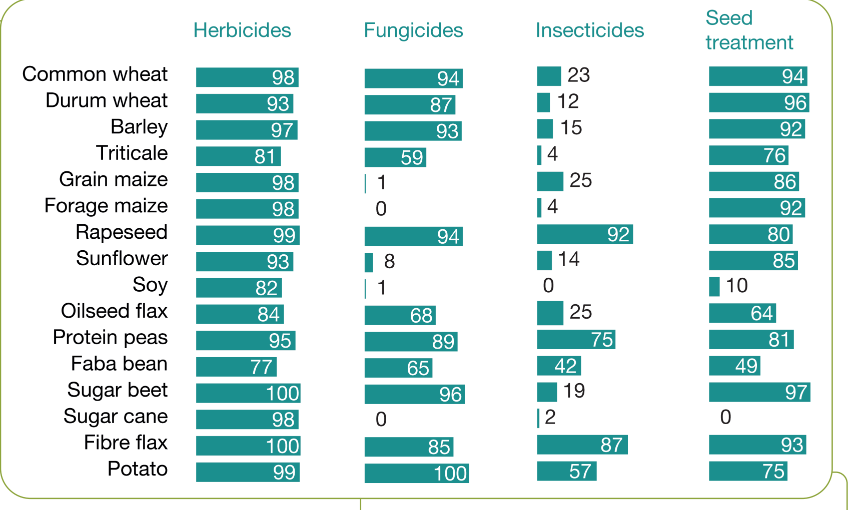
Crop protection refers to the strategies implemented to prevent or reduce harvest losses caused by pests. These strategies encompass both 'curative' and 'preventive' (prophylactic[12]) approaches, and are based on various types of practices and approaches.

Today's most frequently used strategy is controlling pest populations by employing chemical methods (pesticides). This strategy is applied to almost all arable land (figure 1.3 and box 1.1). In addition to synthetic pesticides, chemical control includes using certain biocontrol substances,[13] which are currently in the minority, although their use has increased

12. https://dicoagroecologie.fr/en/dictionnaire/prophylaxis/
13. The French Rural and Maritime Fishing Code (CRPM art. L.253-6) defines biocontrol products as 'agents and products using natural mechanisms as part of integrated pest management. They include, in particular, (i) macro-organisms and (ii) plant protection products containing microorganisms, chemical mediators such as pheromones and kairomones, and natural substances of plant, animal or mineral origin.'

in recent years. Most of the time, chemical control is combined with a choice of varieties that are not very susceptible or even resistant to pests (to combat diseases in particular), as well as cultural control methods such as crop rotation[14] (to manage weeds, fungal and bacterial diseases, insect pests and nematodes), sowing date and density (to manage insect pests and fungal diseases) and tillage (to control weeds).

Figure 1.3. Share (in %) of arable acreage treated with pesticides in 2017



Source: based on Agreste (2021), using data from the 2017 'Pratiques culturales' survey (French Ministry of Agriculture).

In contrast to the paradigm of eradicating pests, agroecological crop protection prioritises preventive measures to regulate their populations. To this end, it relies on biodiversity (plant and animal)[15] and all the processes naturally at work within the agricultural ecosystem.[16] In principle, such natural regulation of pests is based on the fact that a single

14. To a lesser degree than in the past, however.
15. Biological control through the introduction/release of auxiliary organisms, whether exotic (acclimatisation of auxiliary agents introduced) or not (artificial increase in endemic populations through external inputs), is not considered by the CAS as part of so-called 'natural' control. It is equivalent to the use of an input.
16. The agricultural ecosystem refers to the biophysical part of the agroecosystem. It corresponds to the soil-plant-animal system, including planned biodiversity (crops, livestock) and associated biodiversity (semi-natural vegetation including weeds, wildlife) present or circulating in this three-dimensional space.

pest cannot consume/colonise all cultivated plants due to its more or less marked specialisation concerning them. As a result, an increase in plant diversity 'dilutes' the pest's host plant in a plant cover or landscape of non-host plants, making it more difficult for phytophagous pests to find their host plant (bottom-up regulation). For weeds, a diversified plant cover provides a more competitive environment. In addition, natural enemies of pests are involved (top-down regulation), whose presence depends on the resources and habitats that intra- and extra-field vegetation can supply during their life cycle.

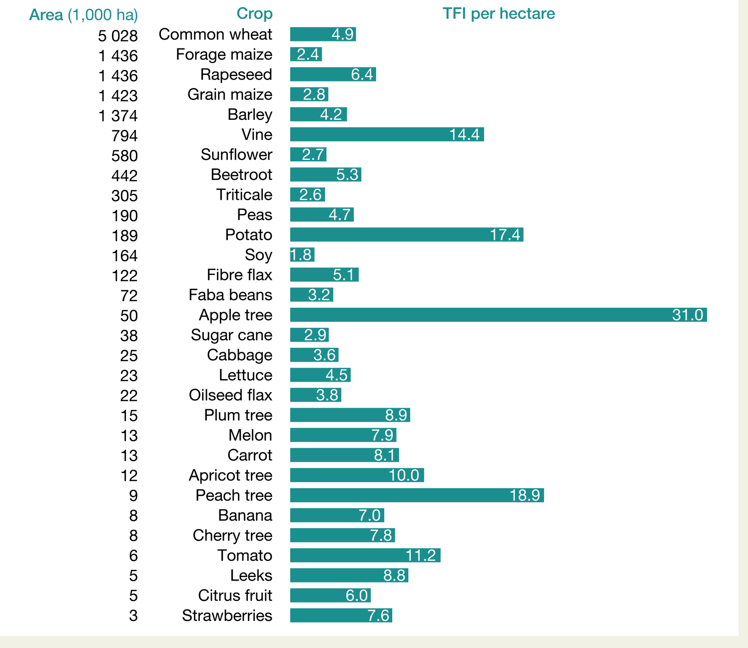
Pest regulation is an ecosystem service that benefits farmers by preserving yields and reducing the need for (and cost of) pest control practices.[17] By design, these processes depend on the structure of the agricultural ecosystem and nearby landscape matrix (particularly the composition[18] and configuration[19] of the vegetation). By helping to define the ecosystem's structure, practices such as the choice of plant species and varieties, sowing dates and densities, and cropping sequences are likely to affect the processes involved in the natural regulation of pests.

17. Society benefits indirectly from this service if its use by farmers reduces pesticide use and, consequently, associated pollution (Tibi and Therond, 2017).
18. Nature of living organisms (biocenosis) and their non-living environment (biotope).
19. Spatial organisation of ecosystem components.

Box 1.1. Use of chemical control in France

Figure 1.4 categorises the main crops grown in France according to their pesticide Treatment Frequency Index (TFI), which reflects the number of reference doses used per hectare over a crop year. The crops that consume the most pesticides per hectare are arboriculture, market gardening, vines, and potatoes. Although arable crops use fewer pesticides per hectare overall, they occupy the most extensive areas, in particular common wheat (5 million hectares, i.e., almost 1/4 of the utilised agricultural area, excluding permanent grassland), oilseed rape, barley, grain maize and forage maize (around 1.4 million hectares each), and to a lesser extent sunflower, industrial beet and triticale (0.6, 0.4 and 0.3 million hectares respectively).

Figure 1.4. Treatment frequency index (TFI) for the 30 most common crops in France (mainland and overseas) and their cultivated area

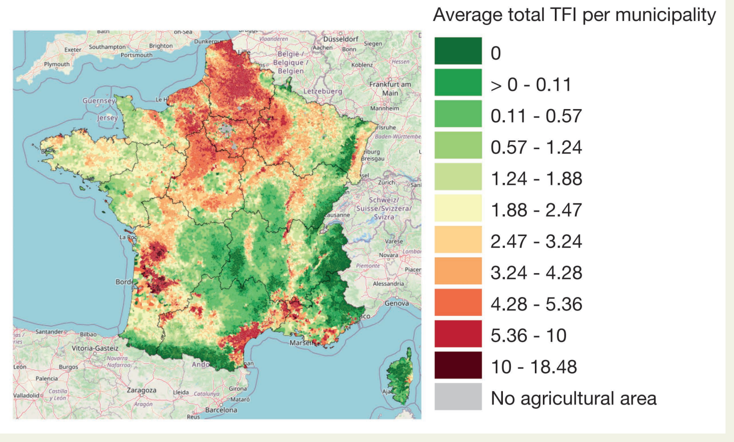


Source: data from the French Ministry of Agriculture's 'Pratiques culturales' (cultivation practices) surveys (field crops: 2017 season; vegetables and arboriculture: 2018 season; viticulture: 2019 season).

Box 1.1. Continuation

Note that this index reflects the frequency at which pesticides are used but does not consider their relative toxicity (a product may have a low TFI but high toxicity). Furthermore, these average TFI values at the national level conceal a broad spatial variability in use (figure 1.5). It should be noted that the calculation of the total TFI includes the use of biocontrol products (excluding macroorganisms). Natural substances (primarily sulphur) are estimated to account for 2/3 of sales of biocontrol products in 2019-2020; however, the use of biocontrol (surface area) is problematic to quantify (Mamy *et al.*, 2022).

Figure 1.5. Crop Treatment frequency index (TFI) for agricultural land by municipality in mainland France



Author: Solagro, June 2022

Sources: RPG 2020 (IGN)/ 'organic' surfaces 2020 (Agence bio, Certification bodies)/Computerised vineyard register (Customs)/RA 2010 (Agreste)/Agricultural practices surveys (Agreste)/Admin express 2022.*
* https://solagro.org/nos-domaines-d-intervention/agroecologie/carte-pesticides-adonis

2. Plant diversification in agricultural areas

The entire plant component of agricultural areas is accounted for in the CAS. This component encompasses both farmer-grown vegetation (annual or perennial plants grown to produce biomass or ecosystem services) and semi-natural vegetation (spontaneous vegetation present into fields (including weeds) or in the agricultural landscape).

The term 'plant diversity' is used in the CAS to refer to the level of diversity of the plant component without looking at the origins of this diversity (e.g., who establishes it, for what reasons and at what cost) or its feasibility context (e.g., the need for a compatible range of varieties or regulatory constraints). The term '(plant) diversification' refers to the (voluntary) action of increasing the level of plant diversity in the field and/or landscape (in other words, diversifying, for example, by replacing a monovarietal/monospecific crop stand with a mixture of species/varieties, increasing the number of crops in the rotation, or increasing the amount of semi-natural vegetation in the landscape). Consequently, the CAS reviews the ecological and epidemiological impacts of plant biodiversity on pests and analyses the necessary conditions for diversification.

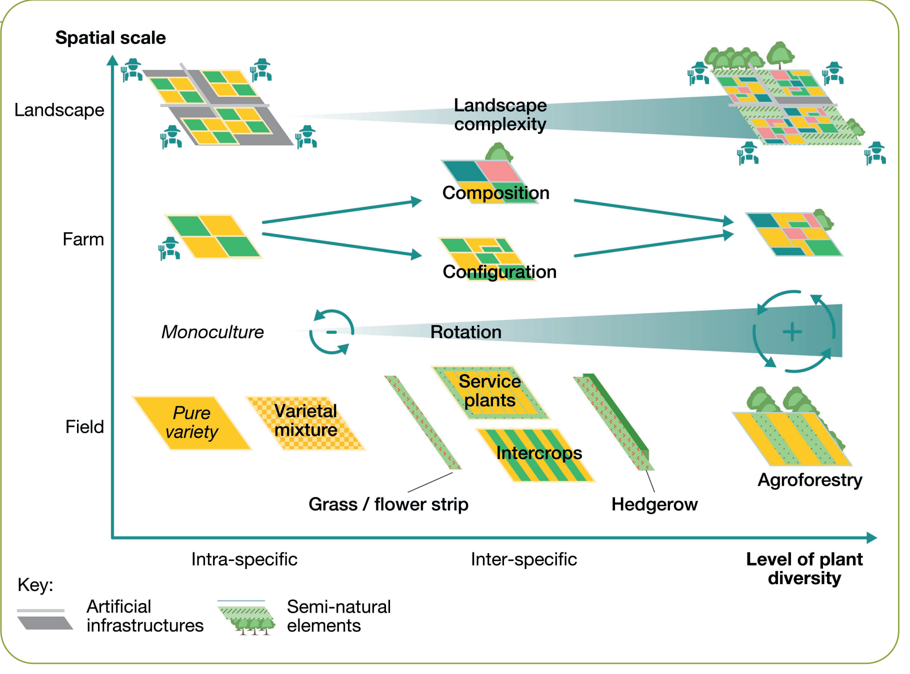
Given the scope of the CAS, which focuses on the spatial and temporal diversification of all plant components in agricultural areas, a broad range of diversification practices are covered in the literature review. These practices are laid out in figure 1.6 according to the degree of plant diversity they involve and the spatial scale of their application. They are presented below with, where available, information on the current status of their implementation in France. However, statistical data is lacking to provide a comprehensive and accurate review of the current implementation level of these various practices.

Increasing crop intraspecific diversity: varietal mixtures, use of heterogeneous varieties (farmer, traditional), etc.

Increasing intraspecific diversity means increasing the genetic variability of the cultivated population of a given species, either by simultaneously sowing several varieties (varietal mixture) or using heterogeneous varieties.

Traditionally, a variety is defined as a plant population obtained from a species through selection and possessing a set of common characteristics. In France (as in Europe), except for unregulated minor species (e.g. einkorn wheat), only seeds of varieties certified by registration in the Official Catalogue of Agricultural Plant Species and Varieties may be marketed to farmers. To this end, a variety must have phenotypic characteristics that (i)

Figure 1.6. Diagram showing the modalities of plant diversification reviewed in the CAS



set it apart from other varieties, (ii) are uniform between the individuals of which it is composed, and (iii) are stable from generation to generation (DUS criteria for distinctness, uniformity and stability). As a result of these criteria, certified varieties are, therefore, populations of plants with identical or very similar genotypes.

Generally, varieties not included in the Catalogue, either because they belong to an unregulated species or do not meet DUS criteria, cannot be marketed.

Varietal mixtures consist in simultaneous sowing of several commercial varieties selected for their complementary agronomic traits. Farmers mainly use them to control diseases by combining varieties with complementary resistance and/or tolerance to pests, thus creating a cover with an 'average' level of resistance adapted to the local pathogen complex. Farmers also use varietal mixtures for their robustness and more stable yields against interannual climate variations.

According to FranceAgriMer's national varietal deployment statistics, wheat varietal mixtures (figure 1.7) covered 12.2% of wheat acreage in 2020 (i.e., the equivalent of the most commonly grown variety)[20] and 17% in 2021, according to Arvalis.[21] These mixtures usually include 2 to 3 varieties, chosen from the most commonly pure-grown varieties in the regions. In practical terms, farmers make their own farm mixtures from pure varieties. However, the marketing of ready-to-sow mixtures is now authorised in France (the Mélanges Moulins Soufflet on offer since 2018 is one example).

Figure 1.7. Durum wheat varietal mixture

Another form of intraspecific diversification involves using traditional or peasant' seeds, which, by definition, offer a higher level of genetic heterogeneity than commercial varieties. Traditional (or landrace) varieties are typically 'population' varieties, comprising a set of individuals with varied genotypes, generally selected in the field by farmers and propagated by open pollination. As a result, their characteristics change according to

20. https://www.franceagrimer.fr/fam/content/download/65100/document/ENQ-CER-repvar-A20.pdf?version=1
21. Managed by FranceAgriMer until 2020, these statistics are now produced by Arvalis. The value given for 2021 comes from a survey of 7,000 farmers carried out by Arvalis for the 2021 harvest. Depending on the region, it varies from 6% to 32% of the area planted with common wheat. https://platform.api-agro.eu/members/s/5826ccef385c432c9266cc68ed82c76e

variations in local environmental conditions. Peasant' varieties are usually the result of a more recent selection process carried out by farmers based on traditional varieties, ancient local varieties or even varieties previously marketed, recovered and acclimatised to specific conditions, or recombined with other varieties.

For organic farming in particular, the new European Regulation (2018/848) incorporates two types of genetic material characterised by a high degree of heterogeneity to meet the needs of organic farming: Organic Heterogeneous Material (OHM) and Organic Varieties Suitable for Organic Production (OVSOP). These regulations, which were only recently enforced, should help promote the spread of traditional or peasant' varieties, often used by organic farmers. Practically speaking, OHM seeds can now be marketed on condition that they meet specific requirements in terms of seed quality, batch traceability and labelling (system currently being rolled out since January 2022). The possibility of registering OVSOP in the Catalogue reflects the gradual opening of the Catalogue since 2010[22] to varieties with characteristics in demand by farmers, processors and consumers of organic produce.

Increasing the interspecific diversity of the cultivated cover: mixed cropping, service plants, agroforestry, etc.

As opposed to pure crops, interspecific diversification of the cultivated cover entails the simultaneous farming of at least two different plant species within the field during all or part of their growth cycle, known as intercropping.

Annual cash crop mixtures

When all the species grown simultaneously are intended to produce biomass or grain (cash crops), they are known as cash crop mixtures. Crops may be sown freely mixed in the field (known as mixed intercropping or maslin) or sown in alternate rows (known as row crops). This is the case, for example, with fodder meshes, which mixes one or more cereal plants (wheat, triticale, oats, rye, barley) with one or more annual legumes (vetch, field beans, fodder peas). When the crops share only a small part of their cycle (with one being sown at the end of the previous crop cycle), they are known as relay crops. One of the main reasons farmers use crop mixtures is to produce more than their purely cultivated components by achieving a higher overall yield from the same cultivated area.

According to the abovementioned Arvalis survey,[23] in 2021, cash crop mixtures accounted for 0.1% to 3% of the land area, depending on the region, and mainly consist of cereal and protein crop mixtures (figure 1.8).

22. Creation of a specific system to evaluate wheat varieties for organic farming.
23. https://platform.api-agro.eu/members/s/5826ccef385c432c9266cc68ed82c76e

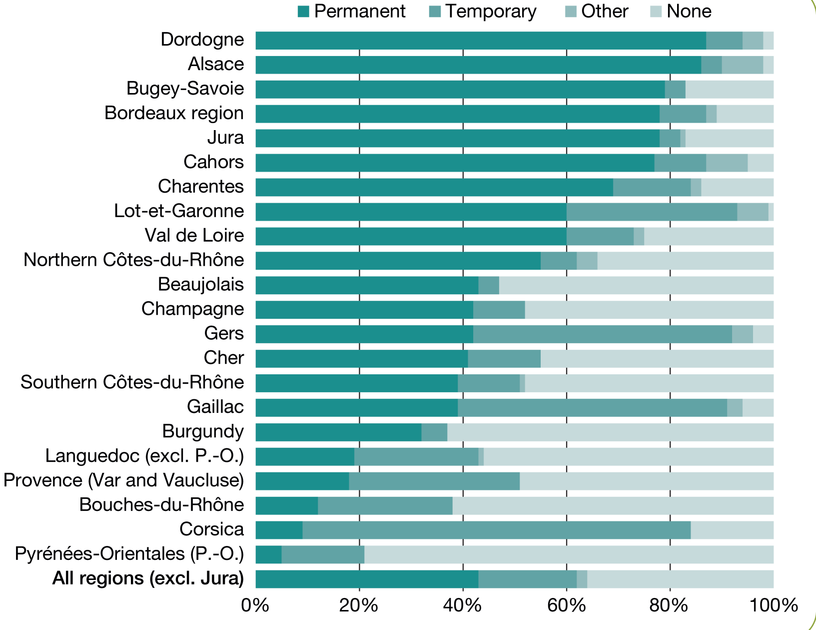
Figure 1.8. Wheat-pea mixture

Installing service plants during the life cycle of the crop

It is also possible to combine one or more cash crops with plants (or service plants) whose purpose is not to produce agricultural goods but to contribute to them by providing ecosystem services such pest regulation.[24] Such plants are sown freely mixed, in rows alternating with the cash crop or in strips (e.g. flower strips or grass strips). They are known as service, ecosystemic or sanitizing plants and can fulfil different roles through a variety of mechanisms. They can compete with weeds (as in the case of planting of grass between the rows in vineyards, see figure 1. 9), repel certain pests by secreting volatile odorous compounds (pest repelling or *'push'* plants), act as a barrier (to curb the access of pests to the cash crop through extensive development), attract pests away from the cash crop (trap cropping or *'pull'* plants), or provide ressources for natural enemies of pests (beetle bank).

24. Other benefits farmers seek include fixing nitrogen from the soil and returning it to the next crop (catch crop), increasing associated biodiversity (particularly pollinators), fighting soil erosion and preserving soil fertility.

Figure 1.9. Percentage of wine-growing areas covered by different types of inter-row grass cover in 2019



'Permanent' grass cover includes permanent, sown or spontaneous cover. 'Temporary' grass cover includes temporary, spontaneous or sown cover (green manure, etc.). The temporary grass cover may be simple (one type of cover) or combined. Other grass cover types include combinations of 'permanent' and 'sown temporary' grass cover.
Sources: based on Agreste (2021) using data from the 'Pratiques phytosanitaires en viticulture' (Phytosanitary practices in viticulture) 2019 survey (French Ministry of Agriculture).

Agroforestry

Finally, in the CAS, agroforestry refers to systems where one or several cultivated species (annual or perennial) are intercropped with ligneous perennial plants on the same field.[25] Agroforestry systems cover an extensive range of tree/crop associations.

In mainland France (figure 1.10), the traditional agroforestry system usually involves incorporating fruit trees into pastureland (sylvopasture) or cultivated fields (sylvoarable system), with the trees being exploited for both their fruit and their wood. Introduced

25. In the CAS, 'bocage' agroforestry, which considers the association of trees and crops on the scale of the landscape, is akin to semi-natural vegetation diversity.

in France in the seventeenth century, these systems have survived in Normandy (known as *pré-vergers* or *vergers hautes-tiges*, i.e., meadows planted with a low density of fruit trees, in particular apple or pear trees, developed on land unsuitable for wine-growing) or in the Dauphiné (walnut or chestnut groves associated with field crops such as barley and sunflower).[26] Modern systems were developed more recently (as innovation niches) in which any type of tree (fruit, forest, or even other woody species) can be integrated according to the farmer's objective. In these systems known as alley (or strip) cropping, the trees are planted in rows separated by arable crops or market crops (e.g. peach trees and vegetables, black locust trees and cereals), and their density varies between 30 and 200 trees per hectare. In the overseas territories, agroforestry involves growing crops under shade (such as vanilla, cocoa or coffee – shaded perennial-crop systems), Creole and Mahoran gardens, and other multistrata systems (see box 2.3).

Figure 1.10. Examples of agroforestry systems found in France: *pré-vergers* (a); barley-walnut (b); vegetable-fruit (c); Creole garden (d)

Few quantitative data are available to estimate the current state of agroforestry development in France. However, the areas concerned are still the minority despite a National Agroforestry Development Plan launched in 2015 (in line with the Agroecological Project for France). Monitoring is challenged by the diversity of agroforestry systems, which are not

26. Agroforestry systems also exist in forest environments and usually integrate livestock farming (meadow-forest association in mountain areas, extensive truffle pasture). They are not included in the CAS, which focuses on systems developed on agricultural land.

recognised as such in agriculture statistics, and by the variable definition of agroforestry depending on the source of information, most of which is not limited to intra-field agroforestry and includes the bocage (hedgerows, see *infra*). Estimates for traditional agroforestry systems vary from one source to another, but in the mid-2010s, they were estimated at between 100,000 and 170,000 ha (Actéon-Environnement, 2021; Dubois, 2016; CGAAER, 2015),[27] compared with several hundred thousand ha in the first half of the 20th century.[28] The spread of modern agroforestry systems is even more limited. The various sources available point to an approximate surface area of 3,000 ha, most of which has been implemented since 2010 (Dubois, 2016; CGAAER, 2015) and half of which is farmed organically.

A project dedicated to market-garden agroforestry systems,[29] launched in 2013, listed more than 130 agroforestry sites (planted or planned) throughout France, most dating from after 2010. A scientific and technical partnership (players in research, development and training) dedicated to agroforestry[30] was also launched in 2014. One of the actions scheduled for the RMT was to set up a national agroforestry observatory, but it was not yet available at the time of writing this book.

Increasing the temporal diversity of cultivated plants: diversified rotations

Growing different crops sequentially over several seasons or years is a fundamental component of agronomic activity, which farmers have used in some form or another for at least 6,000 years. In fact, the use of a combination of tillage and crop rotations is the definition of arable farming (Eurostat Glossary[31]), which is applied worldwide. A rotation is a fixed, specific sequence of crops of a certain duration designed to achieve a particular set of agronomic, economic and environmental objectives. The agronomic performance of rotations rests on soil fertility and structure management, water management and the control of weeds, diseases and other pests, to which all successive crops contribute (see, for example, the review by Struik and Bonciarelli, 1997). Agronomic, economic and environmental opportunities and constraints thus condition the types of rotation that may be implemented in a given production context. On the other hand, a rationale based solely on the world price of agricultural raw materials without strict agronomic and environmental objectives results in implementing simple sequences (short rotations), which can only be maintained by using pesticides and fertilisers.

The rotation principles we know today were developed during the 20th century. The adoption of rotations was considerably accelerated by the Green Revolution, which began in

27. These estimates are much higher than those produced by Solagro (2009) based on national land use statistics, which counted 54,300 ha of *pré-verger* (or 0.2% of the utilised agricultural area in France) in the early 2000s.
28. https://osez-agroecologie.org/contexte
29. https://www.agroforesterie.fr/smart-casdar-maraichage-et-agroforesterie/
30. https://rmt-agroforesteries.fr/
31. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Arable_land

the 1950s (crop selection, development of mechanisation, adoption of new agronomic practices and development of pesticides and synthetic fertilisers to boost crop performance). The latest structural change in rotation management was the widespread adoption of winter crops in the 1960s and 1970s. In recent decades, innovation in rotation and its treatment as a research subject has declined, mainly due to price support for some cash crops and the development of pesticides that achieve the same objectives as rotations but more efficiently. Since the 1980s, a few key crops eventually came to dominate, resulting in increasingly similar cropping patterns worldwide (Martin *et al.*, 2019a).

Table 1.3. The 34 main rotation groups applied to 10 million hectares of field crops in France between 2001 and 2005

Geographic areas	Crop rotation groups (percentage of crops in the rotation over 2001 to 2005)	Area covered in 2006	
		hectares	% of the area
North Champagne-Ardenne, Haute-Normandie, Nord-Pas-de-Calais, Picardie 2,608,000 ha	Beetroot (18%), common wheat (50%), potatoes (8%)	719,000	28%
	Fodder maize (24%), artificial grassland (10%), common wheat (39%), barley (13%)	561,000	22%
	Rapeseed (23%), common wheat (44%), barley (23%)	551,000	21%
	Common wheat (43%), barley (13%), protein crops (11%)	254,000	10%
	Grain maize (42%), common wheat (36%)	200,000	8%
	Protein crops (21%), common wheat (46%), barley (16%)	158,000	6%
	Beetroot (22%), common wheat (39%), barley (30%)	145,000	6%
	Fodder maize (100%)	21,000	1%
West Basse-Normandie, Britanny, Pays de la Loire, Poitou-Charentes 2,661,000 ha	Fodder maize (48%), common wheat (31%), temporary grassland (9%)	1,016,000	38 %
	Common wheat (46%), oilseed rape (13%), barley (13%), sunflower (21%)	621,000	23%
	Common wheat (40%), grain maize (40%)	369,000	14%
	Temporary grassland (79%)	214,000	8%
	Grain maize (88%)	189,000	7%
	Vegetable crops (13%), durum wheat (12%), common wheat (16%)	132,000	5%
	Common wheat (41%), protein crops (15%)	120,000	5%

Table 1.3. Continuation

East Alsace, Burgundy, Franche-Comté, Lorraine, Rhône-Alpes 1,612,000 ha	Rapeseed (18%), common wheat (40%), barley (23%)	578,000	36%
	Rapeseed (18%), common wheat (40%), barley (33%)	383,000	24%
	Grain maize (46%), common wheat (28%)	273,000	17%
	Fodder maize (36%), temporary grassland (16%), soft wheat (20%)	267,000	17%
	Grain maize (100%)	111,000	7%
Center Auvergne, Centre, Île-de-France 2,011,000 ha	Rapeseed (26%), common wheat (50%), barley (17%)	712,000	35%
	Common wheat (47%), barley (9%), grain maize (23%), sunflower (10%)	505,000	25%
	Common wheat (32%), fodder maize (12%), barley (5%)	239,000	12%
	Sugar beet (23%), common wheat (47%), barley (20%)	200,000	10%
	Common wheat (49%), barley (13%), protein crops (19%)	193,000	10%
	Durum wheat (37%)	118,000	6%
	Grain maize (95%)	45,000	2%
South Aquitaine, Languedoc-Roussillon, Midi-Pyrénées, Provence-Alpes-Côte d'Azur 1,118,000 ha	Common wheat (39%), sunflower (31%)	307,000	27%
	Grain maize (100%)	298,000	27%
	Grain maize (54%), common wheat (22%)	161,000	14%
	Durum wheat (64%)	138,000	12%
	Durum wheat (51%), sunflower (49%)	95,000	8%
	Grasslands (50% temporary, 18% artificial)	69,000	6%
	Fodder maize (64%)	51,000	5%
All of France 10,010,000 ha	Monoculture (all crops)	1,185,000	12%
	including maize monoculture (grain and fodder)	715,000	7%
	including durum wheat monoculture	256,000	3%
	including temporary grassland monoculture	214,000	2%
	2 crops	1,564,000	16%
	3 crops	5,547,000	55%
	4 crops	1,687,000	17%

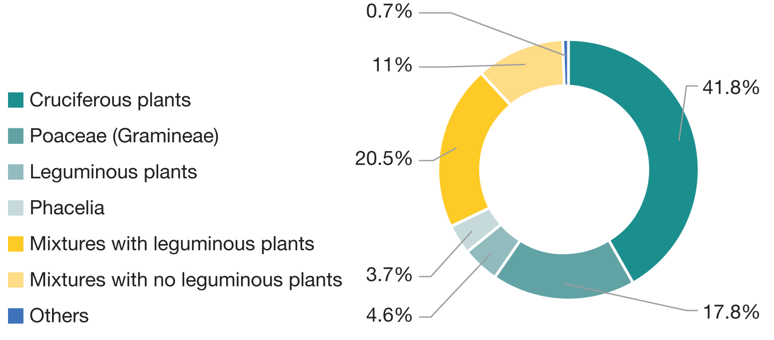
The groups are identified through the most present crops proportionally.
Source: Based on Jouy and Wissocq (2011), who analysed the 2001-2005 crop successions based on the 2006 'Pratiques culturales' survey (French Ministry of Agriculture).

Arvalis (Jouy and Wissocq, 2011) analysed the results of the French Ministry of Agriculture's 2006 'Pratiques culturales' (cropping practices) survey. They found that 34 major rotation groups were practised in France from 2001 to 2005 on the 14,000 fields surveyed (i.e., around 85% of field crop areas). According to this analysis (table 1.3), three crop rotations dominated during this period (55% of the field crop area considered in the study). Monocultures (mainly maize or wheat) alone account for 12% of the field crop area. Rotations involving more than four crops (five or more) are not sufficiently represented to appear in the analysis.

Diversifying rotations involves increasing the number of cultivated species in the sequence of crops (changing the nature and order of cash crops) and/or introducing additional crops between cropping periods (intermediate cover crops).

According to the 2017 'Pratiques culturales' survey, 14% of the arable land was preceded by bare soil during the winter of 2017 (down 6 points from 2011). This average hides a variety of situations depending on the species grown: two-thirds of soy acreage and just over half of grain maize acreage remain bare in the winter. When an intermediate cover crop is planted, it is a cruciferous crop in 42% of cases and a legume alone or in a mixture in 26% of cases (figure 1.11).

Figure 1.11. Nature of winter cover planted as arable crops in 2017



Breakdown of winter cover (excluding catch crops) as a % of field crop area under winter cover in mainland France
Source: based on Agreste (2021) using data from the 2017 'Pratiques culturales' survey (French Ministry of Agriculture).

Diversity of semi-natural vegetation in the landscape: hedgerows, permanent grasslands, groves, etc.

Semi-natural vegetation, hereinafter referred to as 'semi-natural features', is usually composed of biennial, multi-annual or perennial species. Semi-natural features include all spontaneous plants (or plants initially sowed but that developed freely subsequently) located within the field, on its perimeter and outside the farm that contribute to the diversity of the uncultivated part of the landscape. Most do not receive any plant protection treatment or fertilisation (chemical or organic). Some are isolated plant features (isolated trees, linear features), while others have a larger surface area (permanent grassland, for example). Semi-natural features, therefore, encompass a very wide range of vegetation types, most of which are referred to as 'agroecological infrastructure' (AEI[32]) by public policies (figure 1.12):

- All forms of more or less spontaneous vegetation located around the edges of fields: hedgerows (semi-natural features that are the most emblematic of bocage agricultural landscapes and which include a diversity of linear ligneous plants),[33] but also non-productive wooded or herbaceous borders that are distinct from the adjacent field[34] (for example, buffer strips) and ditches;
- Every other element inside or outside the farm composed mainly of spontaneous vegetation (herbaceous or ligneous): isolated trees[35] (specifically, those found on fields), fallow land,[36] tree groves, forest edges and permanently grassed surfaces.

Areas qualified as 'permanent grassland' deserve particular attention. In France, from a statistical point of view and under the Common Agricultural Policy, this notion is assimilated to areas under grass for at least five years (as opposed to 'temporary' grassland).[37] Hence, these surfaces are not included in crop rotation and are characterised by the limited (but not excluded) use of pesticides. As a result, plant communities in permanent grasslands can vary significantly in their specific diversity depending on the nature of the environment and associated farming practices, ranging from a high level of spontaneous plant species to a much lower level of specific diversity in grasslands that are managed more intensively and receive high mineral fertilisation. The scientific literature covers

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32. In the political sense, AEIs include non-plant features (ponds, traditional walls) not covered in this review, which focuses on plant diversification. They also include nitrogen-fixing crops and catch crops. The former are included in the CAS as part of the diversification of rotations, as they are mainly planted during the intercrop period. The latter refers to sowing a second cash crop when the first is harvested, but during the same cropping season: depending on how long the two crops coexist, the CAS considers catch crops either as a way of diversifying the interspecific cover of the field (a so-called 'relay' crop) or as a way of diversifying the rotation (an intermediate cover crop).
33. A hedgerow is defined in the Common Agricultural Policy as a linear unit of ligneous vegetation no more than twenty metres wide, including shrubs and/or trees and other ligneous plants (brambles, broom, gorse, etc.).
34. Grass or flower strips planted by the farmer inside the fields, partly composed of spontaneous vegetation, are considered in the CAS as service plants that contribute to the interspecific diversity of the cover of the field (cf. *supra*).
35. Forest species alone, scattered or grouped in clumps of less than 5 acres. Lines of trees on fields of land are essentially part of agroforestry systems, assimilated by the Common Agricultural Policy to AEIs, but considered in the CAS as a form of interspecific diversification of the vegetation of the field (cf. *supra*).
36. Under the Common Agricultural Policy, fallow land is defined as agricultural land that is not used or developed for a period of six months.
37. The notion of 'natural grassland', which is sometimes used (in particular by some farmers), has not been included in the CAS as it is difficult to characterise scientifically. Indeed, according to researchers, natural grassland does not exist in temperate latitudes.

Figure 1.12. Examples of semi-natural features: bocage (a), flower-filled fallow land (b); grazed moors with peat bogs (c)

a wide range of cover types called 'grassland'. However, it is impossible to restrict the analysis solely to unfertilised grassland, as the management methods used are rarely specified. In addition to these permanent grasslands, which are managed (to a greater or lesser extent) by farmers, other unmanaged grassland areas are used to a greater or lesser degree for livestock (grazing): moorland and summer pastures. In most cases, it is difficult to establish a specific distinction between the latter and permanent grassland in the scientific literature.

Moreover, as spontaneous vegetation that forms part of the field cover, weed flora contributes to the diversity of semi-natural vegetation in agricultural areas.

Semi-natural features can also be categorised according to (i) the extent to which humans manage them, (ii) their productive nature and (iii) their share in the agricultural area. These three dimensions (management, productivity and land use) are at the heart of farmers' decisions to include semi-natural vegetation in their production systems.

Not all semi-natural features are voluntarily added or managed by farmers. For example, the presence of certain groves, forest edges or summer pastures is independent of the farmer's actions. However, some of these semi-natural features may be managed by other territory managers (i.e., public players—local authorities, public establishments such as the French Coastal protection agency—or private players with no agricultural status, such as nature protection associations). This distinction impacts how farmers consider these vegetation features when managing their farms. For the semi-natural features that farmers can manage, diversifying means planting new ones[38] to restore an ecological network or increase the proportion of non-cultivated vegetation on their farms, to benefit from the services provided by these semi-natural features (e.g. erosion control, regulation of pollutant flows, biodiversity refuge, etc.). For semi-natural features over which the farmer has no control, 'diversification' is more indirect and involves the farmer using the presence of these semi-natural features to manage their cropping system (for example, choosing crops located near a particular semi-natural feature based on its presumed benefits regarding the pests associated with those crops).

In addition, certain semi-natural features can be used by farmers to produce biomass (whilst benefiting from the ecosystem services provided). This is the case for grazed or mown grassland or certain hedgerows that supply wood, for example. Lastly, it is worth noting that some semi-natural features can be partly implemented on the productive agricultural surface (where cash crops are grown), potentially resulting in loss of production.

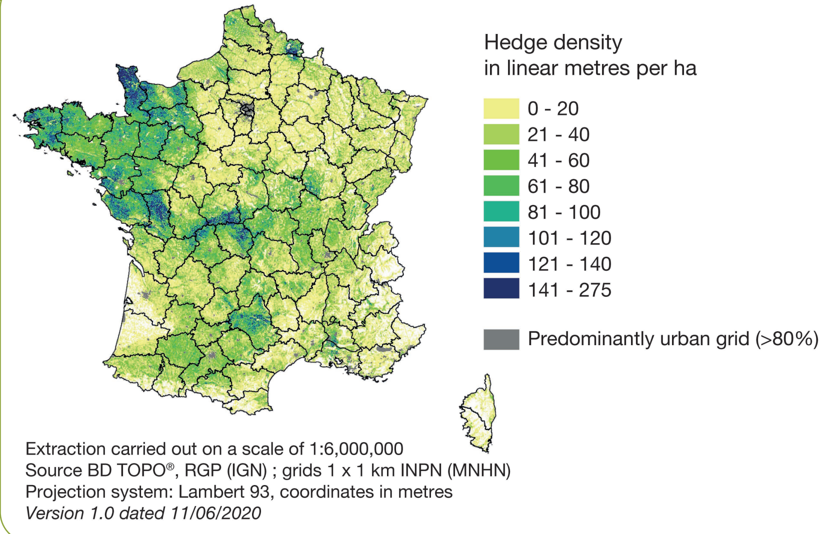
There is no systematic, up-to-date inventory of semi-natural features, a category that includes a wide variety of features for which no specific statistics exist.

However, with regard to hedgerows, the French National Agroforestry Development Plan (cf. *supra*) has initiated the creation of a national system for monitoring hedgerows, combining the skills of the French Biodiversity Agency (OFB) and the National Institute of Geographic and Forest Information (IGN – figure 1.13). Pending the finalisation of this system (not available at the time of writing this book), the available data on hedges is inconsistent. An overall view is all the more difficult because two metrics are used to quantify these infrastructures—the linear metre and the spatial footprint (hectares) — without any apparent, universal equivalence that would make switching from one to the other possible.

The annual Teruti-Lucas[39] survey, carried out by the statistical services of the French Ministry of Agriculture, tracks changes in land use and occupation across the country. Drawing on this survey, sources report a surface area of hedgerows and tree lines of around 1 million ha in 2006, 960,000 ha in 2012 and 930,000 ha in 2015 (CGAAER, 2015; OFB, 2022). Other sources report a loss of 1.4 million km of hedgerows out of more than 2 million from the end of the 19th to the beginning of the 20th century, with the loss rate falling from 45,000 km/year from 1975 to 1987 to 15,000 km/year from 1990 to 2007, settling in the last decade at around 7,000 km/year (Dubois, 2016). It should be noted that the 2021-2022 France Relance plan has set an ambition to plant 7,000 kilometres of hedgerows and tree lines between fields from 2021 to 2022. Since then, a new 'pact' was launched in September 2023 to obtain a net gain in the length of hedges of 50,000 km by 2030.[40]

38. Or not to remove existing ones.
39. https://artificialisation.developpement-durable.gouv.fr/bases-donnees/teruti-lucas
40. https://agriculture.gouv.fr/pacte-en-faveur-de-la-haie

Figure 1.13. Map of hedgerow density in mainland France



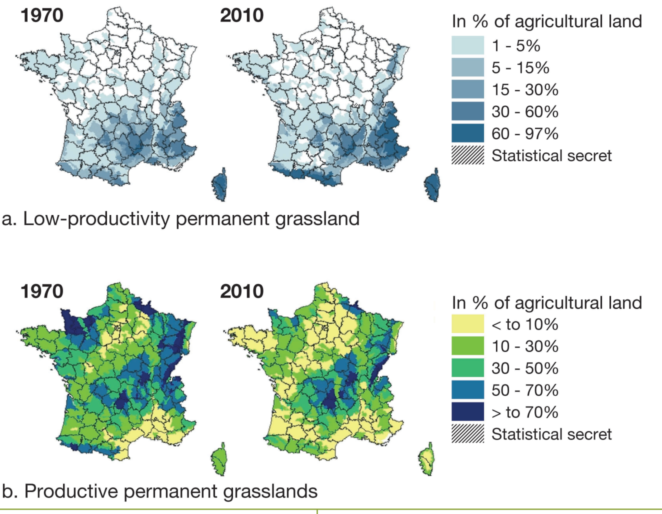
Source: National hedgerow monitoring system IGN/OFB*

* https://www.ofb.gouv.fr/haies-et-bocages-des-reservoirs-de-biodiversite

Grassland areas (meadows, heathland, etc.) diminished simultaneously as hedgerows due to land consolidation (15 million hectares of grouped farmland since 1945, according to Dubois, 2016). According to an analysis of agricultural censuses and annual agrarian statistics, they fell from 41% of the utilised agricultural area (UAA) in 1970 to 28% in 2010, while the proportion of arable land rose from 56% to 68% (Therond *et al.*, 2017). However, these national percentages hide significant regional disparities due to the specialisation of areas and cropping patterns, with grassland accounting for less than 10% of UAA in arable areas (figure 1.14).

Finally, as far as we are aware, the inventory published by Solagro based on national statistics from the early 2000s (2000 agricultural census, Teruti 2003 survey, 1998 grassland survey) is the only one to separately consider other types of semi-natural features (Solagro, 2009). According to this inventory, groves accounted for around 530,00 ha (less than 2% of UAA) some twenty years ago, grass strips 390,000 ha, isolated trees or lines of trees for 225,000 ha and grassy forest hedges for 85,000 ha.

Figure 1.14. Trends in the share of low-productivity permanent grassland (a) and productive permanent grassland (b) in utilised agricultural areas by agricultural region between 1970 and 2010



Source: Therond *et al.* (2017) based on agrarian censuses.

Managing the level of diversity in the landscape

Although this is seldom the case currently, the diversity of the landscape's composition and configuration (figure 1.15) can be managed through the coordination of the stakeholders in the landscape. For these reasons, the CAS considers it a diversification option in its own right.

At the landscape level, plant diversity results from individual choices, both in its composition (nature of crops grown in cropping pattern) and in its configuration (size and shape of land parcels, distribution of crop species in the landscape).

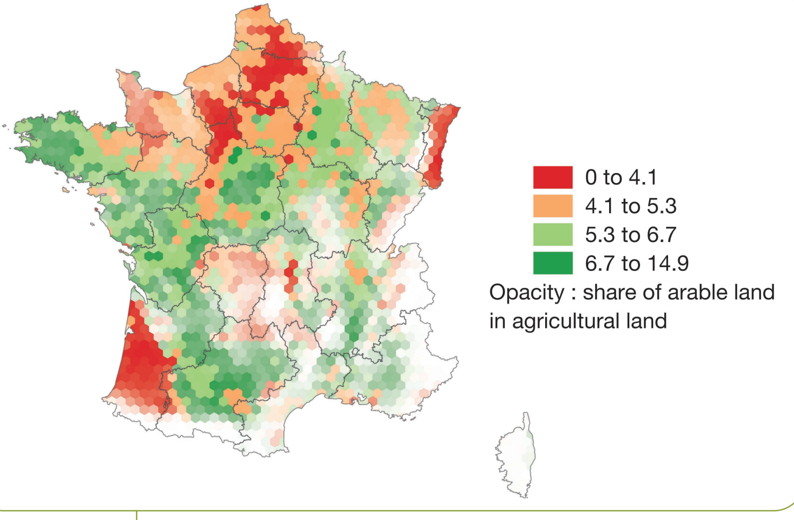
Firstly, the nature and distribution of crops in the cropping pattern (at the farm level and globally in the agricultural landscape) are the mechanical results of the rotation choices implemented on each land parcel. Cropping pattern diversity can be assessed using the Simpson index, which looks at the number of crops and their relative proportions in the cropping pattern[41]. The average Simpson index per arable farm in France is 2.47 (figure 1.16 - Sirami and Midler, 2021). For more than 85% of the farms, less than four crops cover more than 80% of the cultivated area. In 2018, the ten most common cropping patterns accounted for

41. This index shows the theoretical minimum number of species that should be grown in a balanced way on the farm to achieve the same cropping pattern diversity.

78% of the total UAA. Winter common wheat alone accounts for 18% of the UAA. Cropping pattern diversity may also be characterised by the spatial distribution of crops in the landscape (distance separating two land parcels bearing the same cultivated species).

Figure 1.15. Diversified agricultural landscape with grassland, hedges and woods

Figure 1.16. Diversity of arable crops in France, measured using the Simpson index



The hexagonal cells cover an area of around 350 km². Their colour indicates the diversity level of arable crops measured using the Simpson index, similar to the average number of crops per farm, weighted by surface area. The index is at its highest when each crop occupies the same surface for a given number of crops. The opacity of the cells reflects the proportion of arable land in the UAA. Source: Sirami and Midler, 2021.

Secondly, the length of the interfaces between fields and its immediate environment (other agricultural fields or areas dedicated to a different use) is, by design, linked to the size of the fields. A landscape comprising small fields will mathematically see the proportion of these interfaces increase and, consequently, those of their associated semi-natural features. Similarly, a change in field size leads to a shift in cropping pattern diversity, as it very often involves a change in plant cover.

PART 2

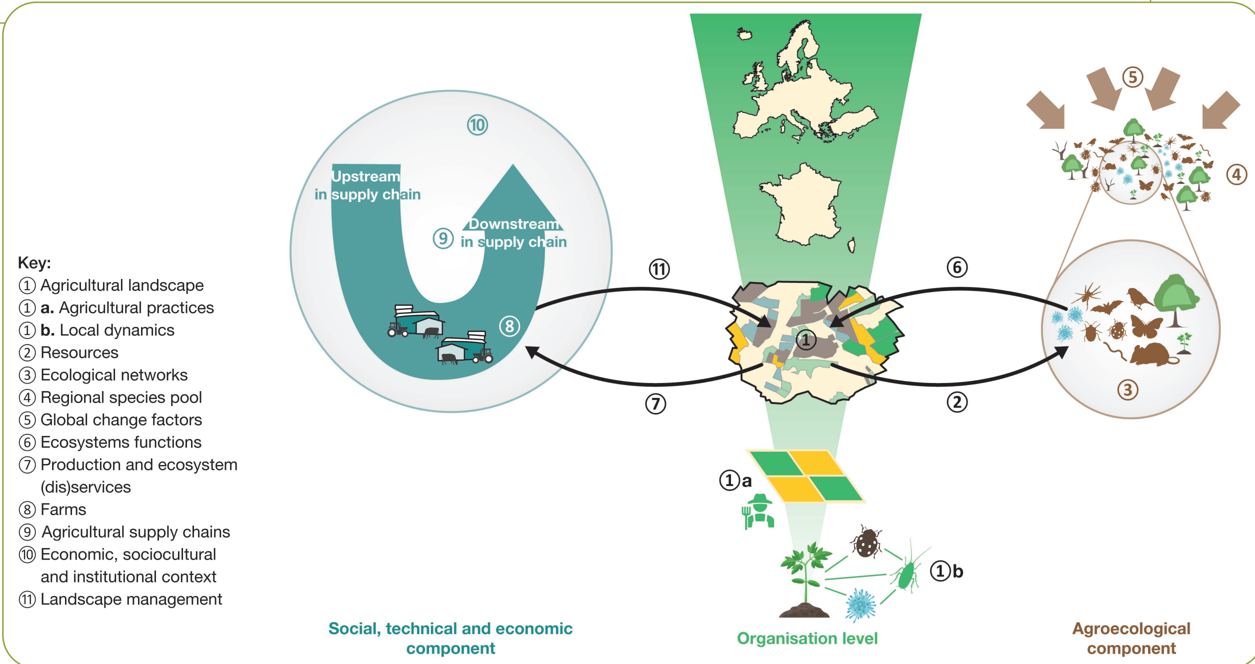
Lessons learned from the collective scientific assessment

To meet the request made to the INRAE by the French Ministries of Agriculture, the Environment and Research, the CAS adopted a multi-scale conceptual framework representing a farming socio-ecological system, combining a socio-technical-economic component (in blue) in interaction with an agroecological component (in orange) (figure 2.1 - Vialatte *et al.*, 2022). The socio-technical-economic component includes the fine scale of the agricultural field and the farm, where the farmer's decisions are implemented. This component also concerns the territorial level, where the stakeholder networks that influence farming practices and individual decisions are developed. Thus, it includes all related sectors (upstream and downstream of agricultural production), as well as the institutional (regulatory and political framework), economic (markets) and social landscape. The agroecological component spans from the level of organisms mobilised to regulate crop pests (plants, pests, natural enemies) to the biogeographical area of the agricultural landscape (the biocenosis[42] of which depends on the filters exerted by the resources provided by the mosaic of habitats and the agricultural practices implemented). The functioning of the system thus constituted can be influenced in the more or less long term by major levers of change such as climate change and biological invasions.

This framework describes the fact that the actions implemented by farmers on their farms result from (i) the technical and economic possibilities and constraints linked to the characteristics of the farms and their soil and climate environment, their integration into supply chains and the economic, socio-cultural and institutional context on the one hand, and (ii) the agroecological context linked to the ecological dynamics within environing ecosystems (mainly agricultural) on the other. Farmers' actions shape the landscape and ecosystems and, in turn, influence ecological dynamics, which can modify the functions performed by these ecosystems and, therefore, the context of the farmers' decisions, generating feedback loops that should be taken into account when considering the role that diversification can play in crop protection.

42. All the living beings that coexist in a given ecological space.

Figure 2.1. The CAS's conceptual framework to analyse the impacts of and conditions for implementing plant diversification in agricultural areas to regulate crop pests. Based on Vialatte *et al.* (2022)



The numbered dots are an interpretation key to the diagram; they illustrate the feedback loops between the various aspects of the agro-ecological component and those of the socio-technical-economic component (see the text for a description of each numbered element).

The agricultural landscape is at the heart of the conceptual framework ①. From a socio-economic standpoint, this results from a series of land use choices that assign a role to different areas (agricultural, forestry, natural) with a marked predominance of the agrarian role. Ecologically, it is defined as a mosaic of interacting habitats.

Each agricultural land parcel in such a landscape corresponds to the management unit wherein farmers implement practices (1a). On this scale, plant diversification involves varietal mixtures, intercropping and the introduction of semi-natural features such as hedgerows, grass strips, flower strips, etc., as well as diversified rotations. Field vegetation is colonised by various organisms interacting with one another and crops (1b). Among these organisms, those that use cultivated plants as hosts and cause potential damages to agricultural production are known as pests. As for their predators, they are referred to as natural enemies. Agricultural practices within the field affect these organisms' population and community dynamics. Still, they are also adjusted over time, specifically to account for such dynamics (i.e., pullulation).

Together, these fields and habitats supply several resources to the agroecological component of the landscape ②, supporting networks of variably diversified ecological interactions ③. These networks depend on the species pool in the biogeographical zone in question ④ which is itself influenced by major global change factors such as climate change or biological invasions ⑤. These networks perform ecological functions ⑥ which may provide ecosystem services (such as the regulation of pests, pollination, water regulation, etc.) for the socio-economic component of the landscape and are likely to support agricultural production or result in disservices which may, on the contrary, curb production ⑦. The spatial movements of these organisms and the material flows mean that farms are interdependent for some of these services and disservices ⑧. Farmers implement field management methods in response to the levels of services and disservices observed, but which are driven mainly by economic and non-economic motivations that may be linked to the upstream and downstream value chains ⑨ in which their production activity fits, to public policies initiated by institutions, market dynamics (local and global) and the social expectations of peers and fellow citizens ⑩.

All these organisation levels condition the choices of farmers in space and time, specifically in terms of species (and varieties) planted in the field and crop protection strategies ⑪. Diversifying cropping pattern, in turn, influences the ecological component of the landscape and, therefore, its functioning and associated ecosystem services, which have a cascading effect on the performances of the production system. Consequently, the agroecological and socio-technical-economic components are closely linked and dynamically influence one another through feedback loops.

3. Agroecological impacts of plant diversification

Diversifying the vegetation on agricultural fields and landscapes is a crop protection lever

Introduction

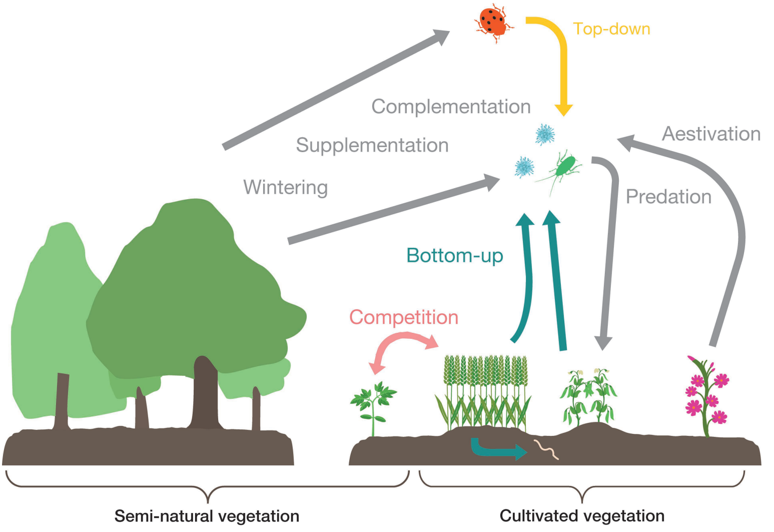
The natural regulation of pests is achieved through three types of interactions between living organisms (figure 2.2): bottom-up interactions between the cultivated plant and its pests (phytophagous, parasitic or pathogenic), top-down interactions between pests and their natural enemies[43] and the competition between the cultivated plant and surrounding vegetation (cultivated or weeds).

In principle, pest regulation through plant diversification relies essentially on the fact that the same pest cannot consume or colonise all cultivated plants: pests specialise in cultivated species to a greater or lesser extent. In other words, the 'difference' between one plant and its neighbour is one of the main determinants of the biological and ecological mechanisms that can help regulate pests. Therefore, from a theoretical point of view, an increase in plant diversity induces the dilution of the pest's host plant in a plant cover or landscape of non-host plants (see, for example, Halliday and Rohr, 2019): faced with a plant resource thus diluted, phytophagous pests take longer to find their host plant and colonise it. In addition, the action of the pest's natural enemies is highly dependent on the supply of various resources for these auxiliary organisms (floral resources, alternative prey, wintering sites, etc.), which also relies on plant diversity at different spatial and temporal scales.

In this review, the difference between plants within a stand is considered from the point of view of its agronomic management—according to intraspecific and interspecific diversity levels—and temporal and spatial deployment characteristics: from field to landscape. However, other differences between plants may also play a role in the effects of plant diversity on regulation, such as functional plant traits (e.g., leaf surface/dry mass ratio, plant architecture or type of mycorrhizal association).

43. Natural enemies are organisms that antagonise pests: predators of pests, parasitoids (whose larvae develop at the expense of another organism) and parasitic micro-organisms. Natural enemies of pests may be microorganisms (viruses, bacteria, fungi, nematodes), invertebrates (predatory or parasitoid arthropods) or vertebrates (mammals, birds). Along with pollinators, natural enemies count as crop auxiliaries.

Figure 2.2. Ecological interactions involved in the natural regulation of pests



Top-down: Biotic interaction between a pest (represented here by an aphid, pathogens and a nematode) and its natural enemies (here, a ladybird); Bottom-up: biotic interaction between the cultivated plant and its pests. Competition: Interaction between the cultivated plant and another (cultivated or weeds). The grey arrows illustrate a few examples of the ecological processes involved in the natural regulation of pests: these processes are said to be 'direct' when they involve the cultivated plant and its pests (i.e., predation) and 'indirect' when they affect third-party organisms/habitats (i.e., food supplementation). The spatial and temporal scales in question are not represented (see figure 2.1).

Approach to organising the knowledge review

As indicated in section 1.2, the diversification of agricultural fields and landscapes may be achieved using a wide range of practices, including the spatial and temporal diversification of cultivated vegetation on the field, the introduction of semi-natural features on the farm, or the coordinated management of cropping pattern and semi-natural features on a territory-wide scale. To assess the potential of plant diversification for crop protection, the various forms of diversification were considered individually:

• At the field level: intraspecific diversification (mixtures of varieties, farmers' or traditional varieties), interspecific diversification (cash crops mixtures, agroforestry, service plants...) and temporal diversification (crop rotations);

• At the landscape level: diversification of cultivated vegetation (cropping pattern and field configuration) and semi-natural features.[44]

44. In fact, the studies deal mainly with semi-natural features located outside fields.

By design, the CAS's field of study encompasses various pest categories (plants, animals, microorganisms) and crop types (field crops, market gardening, perennial crops). The scientific literature reviewed (not exclusive to France - see box 2.1) is abundant, as shown by the size of the bibliographic corpus used in the analysis (almost 1,000 references, including around sixty review articles - narratives or quantitative meta-analyses). To organise the knowledge review and move beyond the presentation of a collection of specific cases (for example, the effects of a particular crop association on a specific pest taxon), the literature review focused on identifying the ecological mechanisms underlying natural regulation, as well as the ecological traits of the pests affected by these regulation mechanisms. The literature review, therefore, provides results that are both general in understanding how the system works and adaptable (because the system's workings are understood) to local crop protection issues.

Box 2.1. Geographical contexts and topics studied in the corpus to analyse the effects of plant diversity on crop pests

Varietal mixtures

The literature focuses essentially on the regulation of airborne pathogens and insects. Most studies concern large cropping systems. Regarding airborne pathogens, the literature mainly deals with fungal diseases in field crops, specifically straw cereals (wheat, barley, oats, rice) and other arable crops (rapeseed) in temperate zones. A few studies focus on arboriculture (apple trees) and market gardening (lettuce), as well as on tropical or subtropical systems (soy, sorghum, cotton, maize, coffee, and banana). Concerning airborne insects, few studies focus directly on the regulating effect of varietal mixtures, and the interpretation of the mechanisms at play is based on regulations observed in natural systems. Most crop systems studies were carried out in the northern hemisphere's temperate zones.

Intercropping

The effects of regulating pests through cash crop mixtures are among the best documented, as shown by the numerous reviews available. They mainly concern the regulation of weeds, airborne insects and pathogens. This research covers almost the entire planet but focuses specifically on cereal-legume mixtures in Europe and Africa. In contrast, it covers a broader range of crops in the case of field vegetable and fruit-growing systems.

Agroforestry

Natural regulation in agroforestry systems is also well documented, but mainly in tropical environments (South America, Africa, and South-East Asia - around 75% of the corpus analysed). Temperate milieus (Europe, United States and China) represent 20% of the studies in the corpus. Semi-arid environments (Africa, North India) are the least represented, with only 5% of the studies in the corpus. The main pests studied are insects (around 50% of the corpus), followed by pathogens (fungi and bacteria) and weeds.

Box 2.1. Continuation

Crop rotation diversification

Crop rotation treatment as an object of scientific study declined from the 1970s onwards, concomitantly to innovation in rotation, thereby making it difficult to carry out an up-to-date literature review on this subject (not least because academic works published before the 1990s are less well-referenced in bibliographic databases such as the Web of Science). In the CAS corpus, research on crop rotations focuses mainly on their effects on weeds and, to a lesser extent, on nematodes and soil-borne pathogens. These studies are mostly conducted on field crops in North America and Europe.

Diversification of cultivated vegetation in the landscape

Methods used to diversify the cultivated part of the landscape (in terms of composition and configuration) are relatively less well-documented than the others. These studies focus mainly on European and North American field crop landscapes (straw cereals, maize, soy and rapeseed). More than half the studies focus on the regulation of insect pests, and around 20% on the regulation of weeds. Pathogen regulation has been studied very little and is essentially covered by theoretical studies that propound hypotheses that have not been empirically tested.

Diversification based on semi-natural vegetation in the landscape

The literature considers semi-natural vegetation primarily from the point of view of conserving biodiversity as a whole. It is rarely studied from the perspective of its interactions with agricultural production. Hence, the research reviewed in the CAS corpus focuses mainly on the natural enemies of pests associated with semi-natural features. The pests studied are mainly insect pests and rarely pathogens and weeds. Most of the papers in the corpus concern cereal (wheat, maize) and fruit crops (apple, pear, cherry trees) in temperate environments in Europe and, to a lesser extent, in North America. Various studies have also been conducted regarding vineyards in the Mediterranean, South Africa and the United States.

It is vital to remember that the quantification of the effects of plant diversification on reducing populations of crop pests is challenging, if not impossible, to determine generically because of the diversity of situations studied, even for a given diversification modality. Indeed, the articles cover a wide range of pests, cultivated and non-cultivated plants, agricultural practices, biogeographical zones and climatic conditions. The reference systems to which the diversified systems are compared also differ from one study to another. From a methodological perspective, the diversity of metrics used to assess the natural regulation of pests makes it challenging to compare the estimated effects. Quantifying the relative effects of plant diversification would require a dedicated meta-analysis, which was not carried out as part of the CAS.

Plant diversity has a predominantly positive effect on pest regulation

The scientific literature focuses mainly on the relationships between the functioning of the ecosystem and the abundance of pests. Consequently, the work provides information on the ability of plant diversity to contribute to reducing the size of pest populations compared with control situations. It rarely analyses the causality link between the latter and the characterisation (nature, degree) of the injuries done to cultivated plants. As a result, the literature points to a potential for regulation through plant diversity.

Table 2.1 summarises the effects of the different plant diversification modalities on the various categories of pests. It is important to note that the positive effects by major pest category or diversification modality in no way prejudge their additivity. On the one hand, the positive effects of different diversification modalities on various categories of pests[45] are no guarantee of their ability to regulate a broad spectrum of pests if used together because they may activate opposing or incompatible ecological mechanisms.[46] On the other hand, the positive effects of a given diversification modality on different pest categories do not mean that it is effective in simultaneously controlling these different types of pests[47] because the effects reported in the literature depend on how the diversification modality tested is applied to each category of pest: a given diversification modality is not used in the same way (cash crop mixture, design, choice of service plants, rotation design, etc.) depending on the category (or even taxon) of pest targeted.

The literature review shows that each pest category can potentially be controlled through at least one diversification modality. In most cases (diversification modality—pest category pairing), there is consensus in the literature on the positive effect of plant diversity. However, the level of scientific consensus varies between diversification modalities (with, for example, a high level of consensus on the effect of varietal mixtures on airborne diseases and a lower level of consensus on the impact of agroforestry on airborne insects in temperate environments). Moreover, a positive effect that has been well documented in the literature does not necessarily predict the magnitude of said effect. The efficiency of a diversification modality on a pest depends on the ecological mechanisms involved, which are a function of the life traits of the pests and their natural enemies, if any (cf. *infra*).

There appears to be more literature, particularly reviews (marked ***), on plant diversification at the field level (varietal mixtures, intercropping, rotations), and most of it reports positive effects of plant diversity on pest regulation. It should be noted that the research

45. For example, cash crop mixtures against airborne insects and rotations against nematodes.
46. Chapter 3 of the CAS extended report describes these mechanisms for each diversification modality.
47. For example, reading the line 'intra-field temporal diversity (rotations)' is insufficient to conclude that a diversification of rotations simultaneously and positively affects the regulation of weeds, soil-borne insects, airborne and soil-borne diseases, nematodes and slugs. It only leads to the conclusion that (i) when rotations are designed to regulate weeds, their positive effect on the regulation of such pests tends to be demonstrated, or that (ii) when they are designed to regulate diseases of telluric origin, the (abundant) literature demonstrates a potentially powerful effect on the regulation of these pests.

focuses mainly on intra-field plant composition (variety and species choice). The spatial arrangement (configuration) of intra-field vegetation (random planting, parallel strips, sowing density, etc.) is widely acknowledged in the literature as an effective lever for achieving the positive effects of plant diversification. However, research that focuses on the impacts of the spatial configuration of intra-field vegetation on pests is scarce, and the underlying mechanisms of the effects observed are partly confused with those of the biological composition (intra- and inter-specific) of intra-field vegetation (see box 2.2).

The effects of the cultivated (cropping pattern diversity) and non-cultivated (semi-natural features diversity) landscape are essentially covered by theoretical expectations but have not been tested experimentally (blue boxes). This is because they are inferred from the comparison of a spectrum of existing situations: the literature adopts an observational stance on the effects of landscape gradients on biodiversity, most often crop auxiliaries and, more rarely, pests. Here again, the effects of landscape composition (whether cultivated or semi-natural) are better studied than those of landscape configuration. However, a few remarkable studies jointly analyse the heterogeneity in the composition and configuration of the landscape's cultivated mosaic. This research suggests that the strength of configuration effects is at least equal to that of composition effects. Thus, diversifying landscapes to regulate pests should involve both diversification of cropping pattern and field size reduction. For example, Alignier *et al.* (2020) showed that while the aim is to foster the diversity of weeds in fields, reducing field size is a more effective lever than the diversification of cropping pattern and is just as effective as increasing the proportion of semi-natural features. Semi-natural features are sources of diverse plant species, while a reduced field size facilitates plant dispersal (including over short distances). Because the diversity of weed communities favours their regulation in fields (specifically through competition), diversity in the composition and configuration of the landscape is a positive factor of their regulation.

Overall, weeds appear to be regulated mainly by intercropping at the field level and crop rotations. The main traits of weeds involved in the effects of plant diversification are demographic ones (i.e., frequency and reproduction method) and forms of resistance (in the form of seeds, for example). Species mixtures act through their spatial distribution, which fosters competition for various resources, particularly for light. Allelopathy, whereby plants communicate chemically, is increasingly invoked as another mechanism to explain this regulation (particularly in agroforestry systems), but this remains to be demonstrated. Rotations act by diversifying selection pressures over time. The regulating effects of the landscape's plant diversity (cultivated and/or semi-natural components) remain essentially theoretical and have been little studied.[48]. There is virtually

48. Nevertheless, some of the studies are remarkable for the sheer size of the datasets collected. This is particularly true of the multi-country study by Alignier *et al.* (2020) which looked at 1,451 fields in 432 landscapes in seven European regions (Germany, UK, France, Spain) and one Canadian region. This article discusses the effects of the landscape (in terms of configuration and composition) on intra-field plant diversity as a support for organisms that play a role in the regulation of a part of this diversity, weeds.

Table 2.1. Review of the effects of the different plant diversification modalities on the various categories of pests

	Pest categories							
Diversification modality	Weeds	Aerial insects	Soil insects	Vector-borne diseases	Airborne pathogens	Soil pathogens	Nematodes	Others
Varietal mixtures	* (+)	**	?	*	***	*	?	?
Cash crops mixtures	***	***	*	?	***	*	?	?
Agroforestry	**	***	?	?	**	?	*	* Striga; * Gasteropods
Increase in rotation diversity	***	*	*	?	*	*	**	?
Decrease in the proportion of a crop in the landscape	?	*	?	* (+)		?	?	* Voles
Increase in cropping pattern diversity	*	*	?	* (+)		?	?	?
Reduction in field size	*	*	?	* (+/–)			* (+/–)	?
Increased distance between crops	* (+/–)	*	* (+)	* (+)			* (+)	?
Presence of semi-natural features	* (+)	**	?	*			?	* (+) Acarids

Tableau 2.1. Continuation

Level of investigation of the effects in the literature
*: Scarce/very sparse literature (but sufficiently robust to conclude)
**: Relatively abundant literature but no (or few) review studies
***: Abundant literature, including review work

Nature of the impact of the diversification modality on the regulation of the pest in question:

Consensus(1) in the literature favouring a **positive effect** on pest regulation (= the plant diversification modality reduces the pest population)

Lack of consensus in the literature: **ambiguous effect**

Consensus(1) in the literature favouring a **negative effect** on pest regulation (= the plant diversification method favours the pullulation of the pest)

No significant effect on the pest

Theoretical hypothesis on the direction of the effect (without empirical evidence)
+: positive effect expected; –: negative effect expected; +/–: ambiguous effect expected

? Insufficient information to conclude (including theoretically)

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

The non-additivity of the effects summarised in this table precludes any cross-sectional reading between rows but also between columns. This rule is all the more fundamental given that the analysis of the multiple effects of each diversification modality on a series of pests and the combined effects of several diversification modalities is a field of research that needs to be developed.

Box 2.2. Combined effects of the spatial configuration and biological composition of intra-field vegetation

The architecture of the plant or cover is the main spatial characteristic of diversified stands, which has been put forward to explain the effect of plant diversification on pest regulation. The architecture of the plant or cover provides a barrier against the dispersal of weed seeds, air- or soil-borne pathogens (*via* the architecture of the root profiles) and passive-flying insects. It also limits access to resources for pests, access to light, for example, which slows the growth of weeds, or access to egg-laying sites that regulate the reproduction of herbivorous insects. Indirectly, it modifies the microclimate and the structural complexity of the habitat for both pests and their natural enemies. In addition to the architecture of the plant or cover, intra-field spatial configuration determines the zone of influence of the diversification feature (for example, the distance to the service plant harbouring natural enemies) and, therefore, the intensity of the ensuing regulation.

The authors sometimes point out the ambivalence of spatial arrangement strategies concerning their effects on regulating pests. Thus, species mixed with the main crop are likely to have undesirable effects, such as dirtying the field (by increasing the stock of weed seeds) and competing with the cash crop, hence reducing yields. Therefore, choosing the biological composition of the species mixture must include the beneficial effects of niche complementarity or facilitation between species, which can offset the harmful effects of competition for light and nutrients. Similarly, while the more complex structure of diversified habitats fosters the presence of natural enemies, it also favours the presence of herbivorous insects. Complex structures can also be detrimental to certain beneficial insects, increasing the time needed to locate their prey or host. Consequently, while structural complexity favours the abundance of natural enemies, it does not systematically increase their predation efficiency and pest regulation.

While the regulating effect of the spatial configuration of intra-field vegetation is acknowledged, it is closely linked to the composition of said vegetation. The mechanisms involved are often identified in the literature analysed, whether at the plant or stand level. However, this question appears to be a scientific front because the contribution of spatial arrangement to the mechanisms involved must henceforth be quantified to deduce general laws that can be extrapolated to conditions other than the very local and specific ones that have been explored up to now. Developing dedicated experiments, creating large databases, and modelling should help move in this direction.

no literature on the effect of varietal mixtures on regulating weeds (and the rare effects reported are insignificant).

This review clearly shows that the abundance (or density) of weed flora is not a sufficient indicator of the effectiveness of its regulation. In fact, the diversity of species composing this flora also determines its ability to compete with the crop. The literature concludes that a diversified and balanced weed flora has a limited competitive impact on cash crops. In addition, the diversity of weed flora benefits biodiversity (which includes the natural enemies of pests). Thus, the agroecological management of weed flora aims to foster their diversity while maintaining their abundance/density below certain thresholds to avoid overly affecting agricultural production. Identifying the optimum abundance/density and diversity thresholds in terms of the balance between the risks that weeds represent for cultivated plants and the benefits of supporting biodiversity is a major scientific challenge. In parallel to the issue of thresholds is the question of the farmers' acceptance of weeds in their fields.

Insect pests can be regulated at the field level through interspecific diversity (and, to a lesser extent, intraspecific diversity) and at the landscape level through crop diversity. Typically, semi-natural feature diversity favours natural enemies (both in abundance and diversity), although its role in pest regulation has not been demonstrated. The main insect traits that modulate diversification effects are the degree of specialisation of the pests concerning the host plants and their dispersal capacity. Many mechanisms are involved in their regulation, primarily associated with reducing the spatial and temporal availability of resources (particularly the abundance of the target crop) at the intra-field and landscape levels and with the presence and abundance of natural enemies.

Airborne pathogens have been extensively studied at the field level and much less at the landscape level (at least experimentally). A few crops dominate in the literature, in particular straw cereals. At the field level, some of their pathogens may be regulated essentially through intraspecific diversity and crop rotation and, to a lesser extent, through interspecific diversity. The effects of plant diversity at the landscape level are mostly theoretical and result from modelling work: landscape fragmentation and barriers to dispersal (such as hedges) are expected to have a positive effect. However, due to the presence of relay host plants, adverse effects of semi-natural habitats on the incidence of certain diseases in fields have been observed. The main pathogen traits involved in the effects of plant diversification are host specialisation, the polycyclic nature of the disease, the latency period (demographic characteristics), and dispersal capacity. The mechanisms involved in their regulation are mainly the dilution/concentration effects of the host, the barrier effect, and the microclimate's effect. Given their lower dispersal capacity, soil-borne pathogens show a less marked response to diversification (particularly intraspecific diversification) than airborne pathogens. However, their low dispersal capacity means they are more sensitive to the temporal diversification of crops (rotations).

Other pests, such as soil-borne insects, vector-borne diseases, nematodes, gastropods and acarids, have received little attention in the scientific literature. A notable exception is the study of the effects of crop rotations on nematodes, which are all the more likely to be regulated through this diversification modality because of their low mobility.

The review also shows that the effects of pest regulation through plant diversity are based primarily on the interactions between plants and pests (bottom-up mechanisms following the logic of vertical trophic interactions) and competition between plants. These mechanisms are either structural, such as the physical distance between two host plants, dilution or barrier effects, or biotic, i.e., natural defence mechanisms or competition for resources. Pest regulation also involves multiple trophic levels, mainly interactions with their natural enemies (top-down mechanisms), largely favoured by intra- and interspecific diversity in the field and, at the landscape level, cropping pattern diversity and the quantity and diversity of semi-natural features. Field interspecific diversity also has marginally positive effects on natural enemies. Bottom-up and top-down mechanisms and competition may also collaborate or act in opposition.

While the vast majority of the literature points to the capacity of plant diversity to regulate pest populations, it is important to stress that there is a real risk of inefficiency or even adverse effects of a plant diversification modality on regulating certain pests in a specific context. Apart from the single consensus in the literature showing increased gastropod outbreaks in agroforestry systems (red box), case studies report adverse effects for all diversification modalities. For specific 'diversification modality - pest category' combinations, the literature reports as many adverse effects as positive ones (for example, concerning the impact of semi-natural features on aerial insects), making it impossible to reach a clear consensus (yellow boxes). The ambiguity of these cases is most often explained by the dependence of the effects on the life traits of the organisms involved (such as dispersal capacity and mode, host specialisation or forms of resistance). The analysis of the underlying ecological mechanisms also helps to understand ambiguous effects. The literature sometimes highlights opposing effects between mechanisms—for example, direct effects resulting from pest and plant interactions and different indirect effects involving natural enemies—reflecting the complexity of the processes involved. This is particularly true of diversification modalities that rely on spatial and temporal vegetation composition (on all scales). However, the effects of plant configuration tend to be univocal.

Finally, some studies report a delay in the expression of ecological processes induced by plant diversification on large spatial scales (diversity of semi-natural features, management of cropping pattern in landscapes), and for certain forms of intra-field diversification. This applies in particular to agroforestry systems that include trees, which are slow-growing by nature, or to crop rotations, which have a gradual effect on the evolution of the biological characteristics of the ecosystem.

A positive overall appreciation, but some specific situations need clarifying

The review's findings clearly show that the results are specific to each case study (idiosyncrasy). Context dependency is, therefore, a significant result that applies to all diversification modalities. However, the determining factors of this phenomenon are clearly identified in the literature:

Characterising the life traits of pests (and their natural enemies, where applicable) is often decisive in identifying the diversification modality(ies) to be encouraged. Indeed, pest regulation results from the encounter/interaction between ecological mechanisms induced by plant diversity (i.e., the spatial heterogeneity of a cover comprising a mixture of species) and the pest's traits (such as its dispersal ability).

The farming practices used in the fields (and by extension at the landscape level) are the main determinants of the variation in effects observed between production situations (i.e., tillage). Although they depend on human decisions, they are a lever for encouraging the expression of natural regulations. However, the underlying agronomic constraints and the need for a coherent combination of practices within a production system narrow the window of possibilities.

Local climate and seasonal conditions are systematically mentioned in pluriannual surveys to explain the variability of the effects observed. Occasional climate events (particularly cold, hot, wet or dry seasons) can disrupt the expected expression of regulatory mechanisms, leading, for example, to an increased mortality of natural enemies.

In contrast, our review shows that when a diversification modality is designed and optimised to control a given pest (clearly identified in the articles), its effect on regulation is often favourable. When a different agronomic (e.g., soil fertility management, economic performance) or environmental (water quality, biodiversity) objective is being pursued, and regulation is simply an additional piece of data collected as part of the study, the effects in terms of regulation are less convincing. Such studies account for many cases demonstrating that diversification has little or no effect on regulating pests. Hence, the type of objective targeted when implementing plant diversification significantly determines its effect on regulating pests.

As a result, there is no possible generic prescription for diversification modalities to ensure the regulation of pests. This observation places these methods in stark contrast to chemical control strategies, the deployment conditions and effectiveness of which are largely unaffected by the pedoclimatic context. Therefore, expert and *ad hoc* assessments are needed to adapt diversification modalities to local production contexts, with priority given to regulating specific pests, promoting local biodiversity and providing the expected ecosystem services in the territory (cf. *infra*).

Experimental conditions liable to underestimate the regulating effects of plant diversity

The potential of plant diversification to support natural pest regulation is most often assessed in conventionally managed farming systems, i.e., those which rely on the use of pesticides and fertilisers and varieties adapted to this type of management. As a result, the literature tends to theorise that the amplitude of the regulation effects observed in the current context might be underestimated. Consequently, a broad spatial and temporal roll-out of crop protection strategies based on plant diversification could amplify natural regulation effects.

Additionally, the implementation of diversification practices may answer different needs (cf. Section 1.2). Yet crop protection is not always the initial objective of plant diversification.

In other words, the plant diversification modalities studied were not necessarily initially designed to regulate pests. This contributes to explaining the variability of regulation effects highlighted in the research. Crop rotations are an emblematic case in point. The choice of crops to rotate varies according to the farmer's objective. As a result, in the literature, the effect of crop rotations on pests is either an intended effect of the rotation (when crop protection is the objective that justified the design of the rotation studied) or an 'unintended' effect of the rotation investigated (designed for another purpose). How natural regulation is considered is rarely explained in the literature on crop rotations, making it difficult to interpret the results regarding the potential offered by crop rotation diversification for pest regulation. Therefore, there is a bias in the literature for such diversification modalities: we can assume that the regulatory effect reported in this review is likely to underestimate the pest regulation potential[49].

It should be noted, as a counterpoint to these possible underestimations of the positive effects of plant diversity, that a particular scientific bias relating to the preferred publication of effects that are both positive and most likely to be obtained (and which may therefore favour the proportion of positive results) has been observed for at least two modalities of diversification: varietal mixtures (literature primarily dominated by the study of straw cereal pathogens in temperate environments) and, to a lesser extent, cash crop mixtures (dominated by research on straw cereal-legume associations).

Knowledge gaps

Finally, the review has identified gaps in knowledge acquisition. Firstly, the literature gives unequal consideration to the variety of target crops and pests: straw cereals and the taxonomic group of aphids, for example, are amply studied, whereas market garden crops, soil-borne insects, vector-borne diseases, nematodes, gastropods, acarids and parasitic plants are studied only anecdotally. Regarding plant diversification modalities, there is a particular lack of knowledge about semi-natural features and cropping pattern diversity in landscapes. The analysis of their effects often aggregates a diversity of composition and configuration of these habitats (Bartual *et al.*, 2019). The research on these features focuses more on the abundance of natural enemies than on regulating any ensuing pests.

Moreover, only a small proportion of the possible variations in plant diversification are considered in scientific studies. For example, the proportion of rotations studied in relation to the total number of theoretically possible rotations, based on the number of crop types currently grown, is very small (see Bohan *et al.*, 2021). Given the abundant North American literature on the matter, most results relate to rather moderate rotation

49. The literature puts forth two hypotheses regarding the impact of the evaluation context on the intensity of the regulation effects observed. On the one hand, the disruption caused by the widespread use of pesticides on the organisms present in agricultural areas reduces the potential for regulation. On the other hand, the use of pesticides in the landscape would limit bioaggressor pressure for untreated fields (the so-called 'chemical umbrella' effect), leading to an overestimation of the regulatory effects of the diversification methods tested on a local scale. However, some scientific evidence tends to support the first hypothesis.

diversifications (rotations with 2 or 3 crops compared with monoculture situations, a model more widely used in the United States than in Europe). Ultimately, very little is known about the true potential of diversified rotations to manage pests apart from the fact that their adoption has revolutionised crop protection (as well as soil fertility management and yields). Moreover, the knowledge is produced in a context where varietal selection focuses on the most profitable cash crops and the goal of pure crop production with a high level of inputs. In such a context, the varieties used in diversified system studies are not always the best adapted to such systems.

Finally, given the diversity of pest traits and their natural enemies, it would appear illusory (if not impossible) for the roll-out of a single plant diversification modality to be effective in regulating all the pests (also known as a cortège) associated with a given cropping system. Yet, except for the few studies that examine the interactions between landscape composition and configuration (cf. *supra*), the potential for regulation provided by the combination of plant diversification modalities is a blind spot in the literature. Similarly, no empirical study in the corpus evaluates the regulation potential of a given diversification modality concerning several pests.

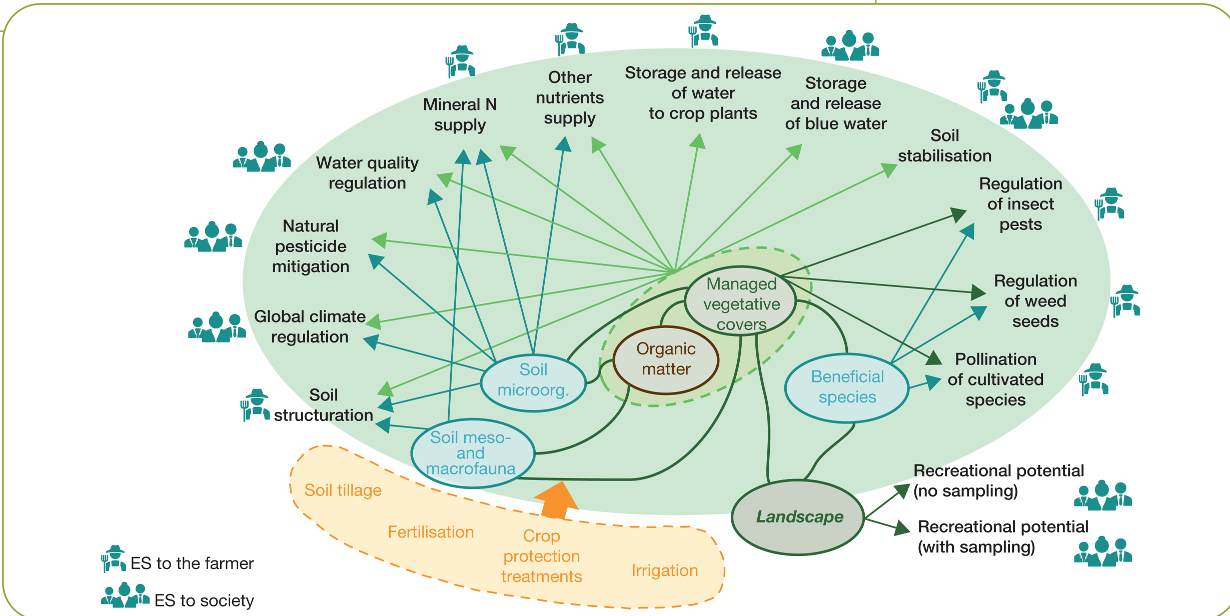
Plant diversification is good for the associated biodiversity and the ecosystem services provided to farmers and society

The 'EFESE-écosystèmes agricoles' study conducted by the INRA (Tibi and Therond, 2017) made it clear that managed plant cover and the structure of the surrounding landscape play a central role in providing a broad range of ecosystem services (figure 2.3).

Some ecosystem services directly benefit the farmer because they act as production factors (replaced, in so-called 'conventional' cropping systems, by using inputs). In addition to pest regulation, this is the case, for example, of the soil's nutrient supply to cultivated plants, storage and release of water to cultivated plants or the pollination thereof. Others are of more significant benefit to society as a whole, such as carbon storage, mitigation of greenhouse gas emissions, or cultural and recreational services. These different effects of plant diversity on agricultural ecosystem functioning contribute, in interaction with ecosystem management practices (fertilisation, irrigation, tillage, etc.), to shaping yield (quantity, quality) and stabilizing it.

The last decade has seen an exponential increase in primary studies comparing the provision of a given ecosystem service in different agro-pedoclimatic contexts. These individual assessments have been analysed statistically and published as meta-analyses. The work of Tamburini *et al.* (2020) and Beillouin *et al.* (2021), called meta-syntheses, are precisely meta-analyses of meta-analyses (second-order meta-analyses). As such, they provide an overview of the main trends from a large body of literature: Tamburini *et al.* (2020) have compiled the results of 98 meta-analyses, and Beillouin *et al.* (2021) those of 95 meta-analyses. Each of these two meta-syntheses alone covers more than 5,000 primary

Figure 2.3. Simplified diagram of the main components of biodiversity underlying the provision of various ecosystem services by agricultural ecosystems



The key components of biodiversity in agricultural areas that support these services are managed field vegetation (crops and weeds), organic matter, soil micro-organisms, soil meso- and macro-fauna, crop auxiliaries (natural enemies of pests and pollinators) and landscape composition and configuration. The primary farming practices impacting these components are shown in orange.
Only systems analysed in the EFESE-écosystèmes study are represented, hence the absence of other services such as crop disease regulation.
Source: based on the EFESE-écosystèmes agricoles study (INRA, 2017).

studies. These two reviews look at the links between different forms of plant diversification and (i) the associated biodiversity, (ii) a range of ecosystem services and (iii) crop yields (which, by definition, are the result of interactions between the functioning of the ecosystem—and therefore ecosystem services—and agricultural management practices).

Meta-analyses calculate effect sizes from empirically observed data provided by primary studies. An effect size measures the strength of the relationship between two variables, such as a plant diversity indicator and an indicator of a given ecosystem service. It provides information about a correlation rather than a possible causal link between the variables under consideration.

Plant diversification modalities explored in the meta-syntheses

Both meta-syntheses look at the effects of six categories of plant diversification whose correspondence with those studied in the CAS is presented in table 2.2. The primary studies investigated in the meta-analyses were carried out in various geographical settings, depending on the category of plant diversification under consideration.

Table 2.2. Plant diversification categories reviewed in Beillouin *et al.* (2021) and Tamburini *et al.* (2020) and the main geographical contexts in which these systems were studied

Plant diversification categories	Main geographical contexts in the primary studies
Use of varietal mixtures (Beillouin *et al.*, 2021)	United States, China, Europe
Agroforestry (Beillouin *et al.*, 2021): a category that covers a wide range of systems, combining at least one ligneous species and at least one cash or fodder crop (annual or perennial). This category includes systems with hedgefrows, which are covered in the CAS from the perspective of semi-natural plant diversity.	South-East Asia and some African countries
Implementing intermediate crops (Beillouin *et al.*, 2021): a practice covered in the CAS, either as interspecific diversification or temporal diversification of intra-field vegetation, depending on the planting date of the cover crops.	United States, China, Spain
Interspecific diversification of intra-field vegetation through cash crop mixtures, relay crops or service plants (Beillouin *et al.*, 2021)	China, United States, some African countries
Crop rotation diversification (Beillouin *et al.*, 2021)	North America, India, China, Australia
Introduction of non-cultivated vegetation on or around the field or environing landscape (Tamburini *et al.*, 2020)	Worldwide

Given the needs of the CAS, the meta-synthesis by Beillouin *et al.* (2021) was used to analyse the relationships between cultivated plant diversity, associated biodiversity and ecosystem services as it distinctly takes into account varietal mixtures, agroforestry (in a comprehensive sense, including the planting of hedgerowss), intercropping (cash crop mixtures, relay crops and service plants), intermediate cover crops and rotations.

The meta-synthesis carried out by Tamburini *et al. (2020)* completes the analysis of the relationships between plant diversity, biodiversity and ecosystem services supply regarding the diversification of the non-cultivated share of agricultural areas. It should be noted, however, that the authors' statistical analysis on the 'non-cultivated diversification' component is based on only two meta-analyses. In contrast, the corpus they analysed in their systematic review contains six meta-analyses (reporting 15 effect sizes). Therefore, the CAS chose to report the qualitative results of the systematic review (number of positive/negative effect sizes) rather than the quantitative results alone, which are too restrictive.

It is worth noting that the bibliography of the meta-syntheses analysed in this chapter is characterised by a high degree of asymmetry in the number of studies available on the different categories of plant diversification. While interspecific mixtures within fields are explored in several areas (intercropping, agroforestry), with an exceptionally high level of detail regarding agroforestry, inter-field crop diversity is not represented in the corpus analysed here. Meanwhile, varietal mixtures and the diversification of uncultivated vegetation have been comparatively under-researched regarding their links with biodiversity and ecosystem services.

Ecosystem services reviewed in the meta-syntheses

Both meta-syntheses analyse the relationship between plant diversification categories and the biodiversity associated with agrosystems (diversity of non-crop organisms). The main variables studied in the primary meta-analyses are abundance, taxonomic richness, biomass and diversity of organisms. It is worth noting that both meta-syntheses consider biodiversity as a whole, leaving no possibility of drawing more precise conclusions by organism type (e.g., macrofauna, pollinators, soil mesofauna, etc.) or of separating the effects on crop-dependent organisms from those on non-crop-dependent organisms.

Ecosystem services are not covered as precisely in these two meta-syntheses as they are in Tibi and Therond (2017), mostly due to the diversity of conceptual frameworks and services indicators used in the primary meta-analyses (which conceptual frameworks and indicator variables are not always explicit). In fact, both meta-syntheses group the variables used in the meta-analyses into the following categories:

- Pest regulation, mainly assessed through the abundance and/or diversity of insect pests, and, to a lesser extent, weeds and natural enemies in Tamburini *et al.* (2020) and pests overall (including diseases and weeds) in Beillouin *et al.* (2021);
- Pollination, studied only in Tamburini *et al.* (2020) through pollination abundance, diversity and activity indicators;

• Soil quality, from the perspective of its fertility, in Tamburini *et al.* (2020) and Beillouin *et al.* (2021) using a set of variables expressing soil fertility, carbon content and leaching;
• Water regulation, which, in Tamburini *et al.* (2020) confuses quantitative and qualitative aspects (concerning pesticide and nutrient pollution), while Beillouin *et al.* (2021) separates these two aspects;
• Contribution to climate change mitigation, viewed from the perspective of greenhouse gas emissions and, in the case of Tamburini *et al.* (2020) only, carbon sequestration (mostly in the soil).

These categories of ecosystem service indicator variables are not exclusive. They provide more of an analytical prism than an accurate classification of precisely defined ecosystem services. Thus, the two meta-syntheses do not use quite the same variables regarding the same services category. Moreover, the same variable may inform different categories in the same meta-synthesis. For example, in Tamburini *et al.* (2020), organic carbon concentration in the soil provides information about soil fertility and carbon sequestration both. Together, the two meta-syntheses provide an overview of the links between increased plant diversity and the functioning of the ecosystem.

Table 2.3 shows the relationships revealed by the two meta-syntheses between the plant diversification categories studied and biodiversity and various ecosystem services (including the natural regulation of pests). This synoptic table does not provide any information on the synergies/antagonisms between services or even on providing service packages by a given diversification category. It juxtaposes individual correlations, assessed in different research situations and contrasting agricultural and/or soil and climate contexts. In this sense, the juxtaposition of these correlations in no way implies their simultaneity. Therefore, this table should only be read 'column by column' and cannot be used to analyse the synergies or antagonisms between the service packages associated with each plant diversification category.

Relationships between plant diversity and associated biodiversity

Generally speaking, the various plant diversification categories explored have an overall positive relationship with biodiversity associated with agrosystems.

At the field level, the quantitative analyses show a clear separation between cultivated plants' intraspecific and interspecific diversity. While varietal mixtures do not seem significantly correlated with associated biodiversity, all forms of intercropping contribute to a substantially higher level of biodiversity than in less diversified systems. Agroforestry (all systems combined) is associated with the most significant increases in associated biodiversity (+61% on average). Including intermediate cover crops is associated with an average 21% increase in related biodiversity. Intercropping is positively correlated to more biodiversity, but only to a limited extent, since quantitative analyses report an average increase of 7% in biodiversity. Crop rotations are also associated with a 37% increase in associated biodiversity.

Finally, the diversification categories based on non-cultivated vegetation are positively associated with increased biodiversity.

Table 2.3. Synthesis of correlations evaluated by Beillouin *et al.* (2021) and Tamburini *et al.* (2020) between diversification categories, associated biodiversity and various ecosystem services

Diversification categories (1)	Associated biodiversity	Pollination	Soil quality	Water quality	Water regulation	GHG emissions	Carbon storage
Varietal mixtures	NS	NA	NS	NA	NA	NA	NS
Agroforestry	+61% [+26; +105]	NA	+19% [+16 ; +23]	+87% [+37 ; +156]	+45% [+13 ; +87]	NA	+19% [+14 ; +24]
Intermediate cover crops	+21% [+17 ; +25]	NA	NA	+61% [+12 ; +132]	NS	+29% [+1 ; +49]	+13% [+10 ; +15]
Intercropping	+7% [+3 ; +12]	NA	+11% [+5 ; +18]	+89% [+19 ; +198]	NA	NA	+13% [+6 ; +10]
Crop rotation	+37% [+16 ; +62]	NA	+5% [+2 ; +8]	NA	NS	NS	+3% [0; +4]
Non-cultivated vegetation	nES+ = 4	nES+ = 5	nES+ = 1	NA	NS	NA	NA

The green boxes show positive correlations, the orange box (intermediate cover crop - GHG emissions) shows negative correlations and the grey boxes show non-significant (NS) correlations. NA indicates that the meta-syntheses do not provide any information about the relationship between the plant diversity category and biodiversity or the ecosystem service under consideration.
The information gathered here comes from meta-analyses examining the relationships between various forms of diversification and associated biodiversity or certain ecosystem services. The table, therefore, does not provide a means of analysing the synergies or antagonisms between the packages of services associated with each plant diversification category.
(1) The values regarding crop diversification categories are sourced from Beillouin *et al.* (2021) and correspond to the average variation of effect sizes reported in the primary meta-analyses compared with the reference situation (in%). Where appropriate, 95% confidence intervals are given in square brackets. As there are few studies on sub-categories of agroforestry, only the effect is reported (in %), with no confidence interval. The data on non-cultivated vegetation diversification (last line of the table) comes from Tamburini *et al.* (2020) and corresponds to the number of effect sizes showing a positive (nES+), negative (nES-) or neutral (nESn) variation.
GHG: Greenhouse Gases

Relationships between plant diversity and ecosystem services supply

Firstly, the meta-syntheses confirm the strong positive link between interspecific plant diversity and the natural regulation of pests, as identified in the previous chapter. Semi-natural vegetation is also associated with a higher level of pest regulation. It should be noted that intra-specific diversification (in particular, varietal mixtures) and temporal diversification (rotations) do not feature in these two meta-syntheses.

Secondly, the meta-syntheses highlight an incomplete vision of the relationships between plant diversification and ecosystem services supply in the scientific literature. Some services (pollination, mitigation of greenhouse gas emissions, etc.) have hardly been investigated. Some forms of plant diversification seem to have been examined only rarely, if at all, from the point of view of their relationship with the provision of services, in particular varietal mixtures, certain agroforestry systems (multi-strata systems typical of Creole gardens, agroforestry in temperate regions, sequential agroforestry), as well as planting hedgerows. When studied, these relationships proved mostly positive, although their intensity varied depending on the category of plant diversification studied.

Pollination

Pollination is one of the least studied ecosystem service in relation to plant diversity. The corpus analysed does not allow for quantifying the link between these two variables. Still, the review literature points to a positive association between plant diversity and pollination in the case of agroforestry, intercropping and the presence of uncultivated vegetation. The other diversification categories are not documented in the review literature under consideration.

Processes linked to soil characteristics and the regulation of water quality and quantity

As previously mentioned, 'soil quality' is not strictly speaking an ecosystem service but instead reflects a set of variables describing the physicochemical characteristics of the soil, which are themselves involved in the provision of all the services rendered by soils (see Tibi and Therond, 2017): soil structuration and stabilisation (preventing soil erosion), nutrient supply to crops (replacing the use of fertilisers), storage and release of water to cultivated plants and of blue water (which can be used for other purposes), regulation of water quality and climate regulation through greenhouse gas mitigation and carbon storage (cf. *infra*).

These soil properties are among the variables most studied in the literature compiled in the two meta-syntheses. Beillouin *et al.* (2021) show an overwhelmingly positive link between the various forms of plant diversification and soil quality, albeit relatively weak: from an average of +5% for rotations to +20% for agroforestry, with intercropping in between. Conversely, varietal mixtures do not seem correlated to soil quality. Finally, the relationship between semi-natural vegetation and soil quality is poorly documented. However, the reviews identified it as systematically positive and quantified for hedgerows at +13% compared with the reference.

In terms of quality and quantity, water regulation services, on the other hand, feature very little in the meta-syntheses corpus. While water quality appears to be significantly higher in systems with higher interspecific diversity (ranging from +60% to +90% on average), these average estimates hide considerable variability between the primary meta-analyses considered. The relationship between the quantitative regulation of water and plant diversity is only assessed for agroforestry and is distinctly positive at +45%. Additionally, some reviews find a positive relationship between this ecosystem service and intercropping (Glaze-Corcoran *et al.*, 2020; Rosa-Schleich *et al.*, 2019).

Climate change mitigation

Among the variables selected in the meta-syntheses, greenhouse gas (GHG) emissions and soil carbon storage are indicators of the climate change mitigation service. Carbon storage is one of the more frequently measured variables, and its relationship with plant diversity is similar to the estimates made for soil quality (probably due to a certain redundancy between the metrics used): it is positively (but rather weakly) correlated with interspecific diversification and rotations, and not significant for varietal mixtures.

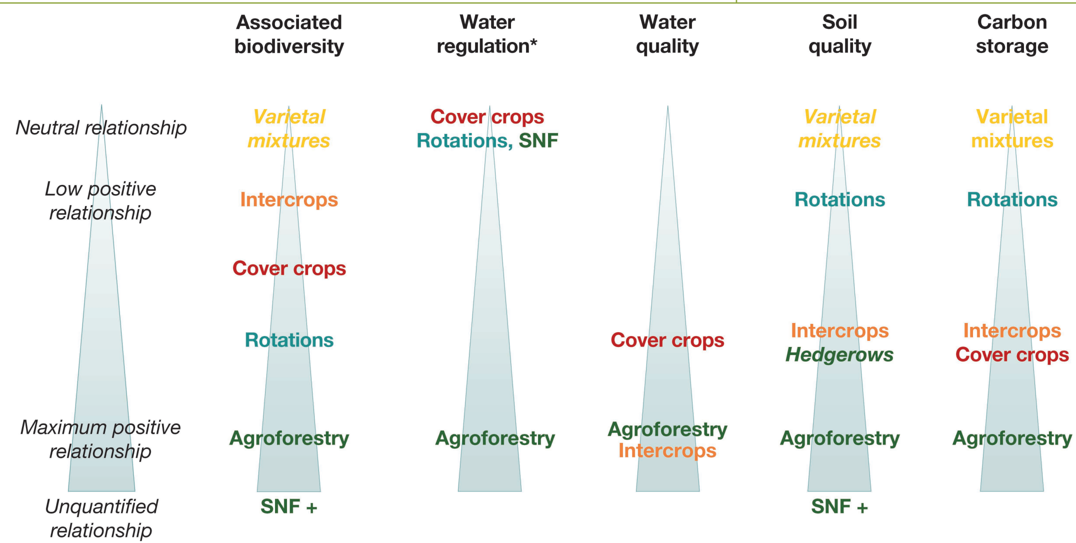
GHG emissions, on the other hand, are more rarely recorded, and statistical analysis only establishes a significant link with intermediate cover crops. Planting intermediate crops is associated with GHG emissions that are 29% higher on average than in the reference situation. This result can be explained by higher nitrous oxide emissions, linked to the introduction of legumes as intermediate crops, the incorporation of crop residues into the soil and a greater quantity of mineralisable carbon in the presence of plant cover. However, the multiple effects of the climate, farming practices or crop species on GHG emissions are still largely unknown.

Taking all the results together, the diversification categories appear to show varying degrees of interest in terms of associated biodiversity and the provision of other ecosystem services (figure 2.4). This hierarchy is based solely on comparisons between more or less diverse situations. The results show that varietal mixtures (intraspecific, intrafield diversification) have neutral or weak relationships with biodiversity and services supply. In contrast, agroforestry, at least as practised in Africa and Asia, is a diversification form with the most robust positive relationships with biodiversity and ecosystem services supply. Intermediate cover crops, rotations, hedgerows and intercropping are more or less 'in-between' in terms of associated benefits. Finally, the relative position of semi-natural vegetation diversification has yet to be studied due to the lack of relative quantitative assessment in the meta-syntheses. Still, the relationships with associated biodiversity and ecosystem service supply are positive in the literature.

Diversified systems often provide higher yields than poorly diversified systems

The yield of a crop, determined by the physiological performance of the plants that form a diversified or non-diversified cover, depends on a series of factors, including the effects of pests, but also other ecosystem services that are enhanced by diversification (soil fertility, pollination, etc.). According to the two meta-syntheses mentioned earlier, the link between plant diversity and yield is typically positive when diversification concerns cultivated vegetation (+2% to +47%) and neutral when it concerns semi-natural features, compared with pure crops (e.g., to assess the effects of mixtures of varieties or species) or monocultures (e.g., to evaluate the impact of rotations). It should be noted that these estimates do not factor in any products linked to semi-natural features (ligneous features)

Figure 2.4. Prioritisation of plant diversification categories according to their relationship with associated biodiversity and ecosystem services supply



SNF: semi-natural features diversity (unquantified relationships)

Only the categories of ecosystem services for which sufficient information is available concerning their relationship with plant diversity are included in this diagram (* quantitative regulation of water). Only the diversification categories for which relationships are mentioned in Tamburini *et al.* (2020) or Beillouin *et al.* (2021) are shown on the diagram. The positive relationships between semi-natural features (SNF), biodiversity and services are not quantified, which means that they cannot be positioned in relation to other diversification categories.

Source: Authors based on the results of Tamburini *et al.* (2020) and Beillouin *et al.* (2021).

or agroforestry (firewood, fruit, etc.). Additionally, the phytosanitary practices used in the low/non-diversified reference systems are not always explicit in the literature. The yields from variety or species mixtures are usually compared with untreated controls (experimental approach); conversely, in the case of other diversification categories (rotations, landscape diversification), the yield is mainly compared with conventional farming references (observational approach).

The trends mentioned by Beillouin *et al.* (2021) and Tamburini *et al.* (2020) are similar to those noted in the biotechnical literature which analyse the effects of each diversification modality on pest control. Thus, while small yield gains (around 3%, often insignificant) are observed with varietal mixtures, the literature highlights the inter-annual stabilisation of yields sought by farmers when they use these mixtures. This literature highlights significant yield gains with rotations (10 to 20%)[50] and above all, with crop mixtures, at least for one species in the mixture (a gain of around 20-40%), with yields for the other species remaining unchanged. Overall, yields are not affected by the presence of semi-natural features.

Although these orders of magnitude are based on research carried out worldwide, they can be transposed to France, particularly regarding intra-field diversification. In fact, they are largely confirmed by the few economic studies on diversification for crop protection purposes in agroecological and economic contexts comparable to the French context.[51] The studies on varietal mixtures (in field crops) suggest a significant, slightly positive effect on yield and a stabilising effect over several years. In the case of traditional and peasant' seeds, the literature documents lower yields, which is why these varieties have historically been abandoned.[52] A study into the use of service plants, specifically plant covers between the rows in vineyard to replace the use of glyphosate to control weeds, has shown that this practice is associated with lower yields. The literature concurs on yield gains for cash crop mixtures documented in field crops, whether for cereal-legume or cereal-oilseed mixtures. The economic literature on rotation diversification is more cautious than the life science literature on yields and reports cases of positive, negative and neutral effects thereon. The importance of the intention behind the design of the crop rotation is emphasised. An improvement in the yields of the subsequent crop is observed when the crop introduced breaks the cycle of a pest or through the use of biofumigation. It is worth noting that when introducing a new crop not previously sown by the farmer, yields from this crop may fluctuate due to a lack of expertise (which, for example, leads farmers to abandon legumes when they cannot master the associated cultivation techniques). The few studies analysing the effect of intermediate cover crops on yields document somewhat ambiguous effects (sometimes adverse, sometimes positive), which are

50. It should be noted that a very recent report found that diversifying rotations by adding a legume resulted in a yield gain of +20% on average worldwide for the crop following the legume crop and around +15% in Europe (Zhao *et al.*, 2022).

51. It should be noted that the mechanism behind the yield gain is not always linked to pest regulation.

52. The revived interest in these varieties is linked to niche development strategies.

highly dependent on the context. Introducing semi-natural features tends to induce production losses in the referenced economic studies, mainly due to the loss of cultivated area (cf. discussion below). This marks a difference with the biotechnical literature that studies yields, not production.

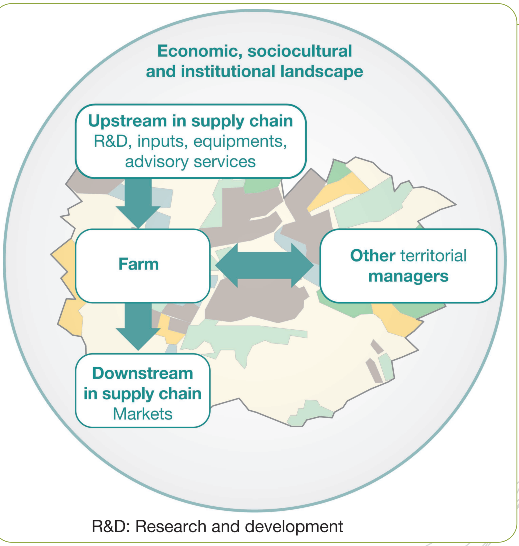
However, these estimates of yield gains per hectare must be weighed against the impact of diversification implementation on areas dedicated to agricultural production, a blind spot in the literature analysed in the CAS. In fact, implementing certain diversification modalities can reduce the area under cultivation—such as when introducing semi-natural features on the field—or, on the contrary, increase it—as is the case with certain crop mixtures. The most commonly used indicator to assess the global productivity of associated crops is the Land Equivalent Ratio (LER), defined as the sum of the relative yields of the species in the mixture. It quantifies the area that should be cultivated with pure crops to produce an equivalent amount (and in equal proportion) to what is produced by a hectare of crop mixture. A LER over 1 shows that the mixture is more productive per unit area than the corresponding pure crops. The CAS did not review studies estimating the LER of different types of crop mixtures. However, to illustrate this point, Dupraz *et al.* (2010) propose a measure of the LER of an agroforestry system associating durum wheat and poplar with a density of around 100 trees. Considering different poplar clones and tree line orientations, the authors report an average LER of 1.3 for a 13-year agroforestry rotation, with a relative crop yield of 0.50 and a relative tree yield (over the entire life cycle) of 0.83. This means that wheat production is halved but that the system's interest lies in the complementary production of wood, resulting in higher output than that obtained in two monospecific systems.

4. Implementing plant diversification to protect crops

Introduction

The farm is the central organisational level of the socio-economic system[53] at which the farmer makes decisions about crop choices and technical operations. Diagrammatically, it is situated on a vertical axis showing the players in the related sectors and on a horizontal axis showing the players managing the spatial entities that shape the agricultural landscape (figure 2.5). All these players interact in a general context ruled by economic, social and institutional standards.

Figure 2.5. The different levels of socio-economic organisation covered by the CAS



R&D: Research and development

53. The term socio-economic refers to the interactions between the social, economic and technical dimensions of agricultural and agrifood systems.

The primary determinant of production choices, cropping pattern and the use of variable inputs (e.g. pesticides, fertilisers, seeds, hired labour) and fixed inputs (e.g. machinery, buildings, land, family labour) is of an economic nature. The farmer seeks to ensure the profitability of the production activity by generating economic profits while limiting the random nature of such profits. This objective interacts with the farmer's non-economic motivations (such as environmental preferences, social norms or peer effects) and the specific biophysical and agronomic characteristics of the farm that limit the farmer's possibilities: topography, local soil and climate conditions, field structure, complementary activities (for example, feeding herds with fodder crops).

To a larger extent, a farmer's decisions depend on his interactions with the upstream and downstream players in the supply chains in which his productions take place. Upstream players determine the availability of and access to inputs (particularly seeds and seedlings, pesticides) and equipment and the range of advice available, particularly on crop management and protection. Downstream, the structure of agricultural sectors differs considerably depending on the market: selling fresh or selling fruit and vegetables to be processed; processing based on fractioning and blending for a large proportion of field crop production; and specific sectors with certifications and specifications. Depending on the case, expectations regarding the quantity and/or quality (visual, organoleptic, nutritional, etc.) of products can vary considerably, which may severely restrict farmers' production choices.

Public authorities also play an essential role in these choices by influencing the regulatory context and implementing restrictive or incentive policies. Such policies respond to various regulatory issues. The first reason for regulation is the desire to limit the negative externalities of agricultural activities (e.g., pollution linked to chemical inputs) or promote their positive externalities (e.g., the preservation of biodiversity). Regulation may also aim to improve a market's performance by encouraging innovation or interaction between players in the supply chain or coordinating the agents' actions in a given area to promote the collective production of public goods or the regulation of the use of common goods. Finally, the regulator may wish to support certain players or activities (such as agricultural production) for political reasons.

The conventional systems currently dominating agricultural production are the result of the co-evolution of knowledge, practices and organisations within the sectors. These systems have become specialised through self-reinforcing mechanisms between different levels of socio-economic organisation, resulting in barriers at all levels. Such barriers are inherited from the past evolution of farming systems and linked to the modernisation of agriculture.

Diversifying crops over time and space has long been the chief manner for farmers to manage soil fertility and regulate pest pressure. However, the advent of chemical inputs severed these links, making it possible to simplify and lighten the workload, remove agronomic constraints (limiting the allocation of land to certain crops rather than others) and manage production risks at low cost. Simultaneously, genetic progress focused on selecting varieties capable of achieving high yields by expressing their full potential in systems using such inputs. Specialisation then occurred at all levels, reinforced by an economic performance paradigm based on economies of scale at all levels:

- At the farm level, rotations specialised in the most profitable crops, thus generating economies of scale, which reduce unit production costs and the complexity of farm management when the volumes produced from the same crop increase. As well as impoverishing the farming community's expertise, this specialisation has reduced landscape diversity, on the one hand through the development of more homogenous cropping pattern and on the other through the removal of hedgerows and interstitial semi-natural features to enlarge fields.
- Because economies of scale also play a role in these supply chains, these have been organised to maximise the production of a small number of crop species by concentrating research efforts (variety selection), advice, the sale of seeds and inputs, harvesting and storage, while developing their market by producing large volumes of homogenous products, which are marketed by the agro-industry and distributed in large and medium-sized retail outlets thanks to the standardisation of food products. Agricultural cooperatives have played a pivotal role in these developments, positioning themselves at several industry activity levels (seed multiplication, input distribution—seeds, fertilisers, pesticides, etc.—collecting agricultural products and providing advice), enabling them to make adjustments upstream and downstream. Some activities were privatised; this is particularly true of genetic selection and advice activities, which have switched from public institutions to private operators. Within research institutions, the changes in how we think about and produce knowledge in agronomy have led to a disconnection between research and the complexity of the field and to a fragmentation of knowledge between disciplines that rarely interact.
- This specialisation occurred at the regional (and even national) level, with the geographical separation of crop and livestock production (except for mixed crop-livestock systems, which persist in areas with low cereal production potential) and, therefore, a specialisation of local players in the upstream and downstream supply chains.
- This specialisation was undertaken and backed by European and national public policies to support the main crops (cereals, oilseeds, milk, sugar beet) *via* guaranteed prices in the first versions of the Common Agricultural Policy, followed by farm income support linked to certain crops up to the late 20th century. In line with European policy, French regulations supported the modernisation of the agricultural sector towards professional enterprise farming by organising land rationalisation (land consolidation, removal of obstacles). With exports playing an essential role in French agricultural production, standards were developed to encourage the standardisation of products meant for increasingly international markets.

The current system is, therefore, characterised by specialisation at all levels of the supply chains and in the territories, resulting in a systemic lock-in that works against diversification. As a result, implementing crop protection strategies based on diversification calls for systemic changes at the scale of all food systems.

Nevertheless, alongside the dominant model, there are localised initiatives to build alternative supply chains, which have been maintained or developed in small areas or regions with low agronomic potential. They are based on agericultural systems that offer an alternative to the conventional model (organic farming, market gardening on living soil, etc.), reconnecting plant and animal production in an original fashion, or production and the supply of inputs, or production and consumption. Examples include (i) developing markets for legumes to encourage their reintroduction into arable farming systems, (ii) participatory selection of farmers' varieties to produce locally adapted seeds that are more resistant to pests, and (iii) developing materials and services (grazing) exchanges between farmers and livestock breeders. These initiatives often address a range of issues, including reducing pesticide use. Analysing how they fit into the upstream and downstream supply chains can provide keys to understanding the factors that drive the development and/or the best use of plant diversity to protect crops.

Approach employed for the knowledge review

Given this general framework for farmers' decision-making, the CAS set out to analyse the literature dealing more specifically with the conditions for adopting diversification practices to protect crops. Unlike the analysis of the effects of plant diversity on the natural regulation of pests, biodiversity and the provision of other ecosystem services, this literature review is limited to work carried out in a European or equivalent context (mainly North America). Indeed, diversified systems deployed in economic contexts (sector, market structuring, etc.) and institutional contexts (public policies, legal framework) that are too far removed from systems characteristic of Europe provide little information about the conditions under which such practices are introduced in France.

Two major socio-economic issues are typically addressed in this literature. The first is to assess the profitability of these practices, usually estimated at the field level and compared with less diversified systems. The second concerns adoption factors, which typically extend beyond the farm level to cover the entire value chain, from the supply of inputs and agri-equipment to outlet management. The results of this work are consistent with the conclusions of the INRA study of (Meynard *et al.*, 2013) on crop diversification, with no specific connection to the crop protection issue.

In addition, the literature describing the policy instruments (mainly Common Agricultural Policy measures) and regulatory framework in force was used to analyse how they influence the roll-out of plant diversification. It should be noted that public policies do not explicitly consider diversification with regard to crop protection issue. In addition, as there is very little academic literature on this topic, recent non-academic reports and grey literature were included in the corpus to document the possible effects of the provisions of the 2023 Common Agricultural Policy and the French National Strategic Plan (NSP) on the deployment of plant diversification. The French legal and regulatory aspects likely to impact the deployment of plant diversification were addressed using literature published mainly in French law journals and non-academic documents relating to the law of the Rural and Civil Codes.

Plant diversification has contrasting effects on short-term farm profitability

The profitability of diversified systems is one of the critical factors in the adoption thereof, with the economic dimension strongly influencing farmers' choices (cf. *supra*).

A farm is profitable when income from the sale of production exceeds production costs. The amount of revenue depends on the production volume (the yield of each crop and the surface area allocated to it) and the selling price of the products (which depends on the market)[54]. Production costs include all the costs specific to the different types of production (inputs) and those associated with operating the farm (equipment, overheads, employees).

This profitability will enable the farmer to generate income and/or invest in his farm. Yet adopting a diversification practice is likely to affect (positively or negatively) each of the components of profitability. It is worth noting that public aid (overall or associated with a crop) can increase revenue (and income) but is not explicitly represented in the figure, as this dimension is discussed below. Profitability excluding public subsidies indicates the influence of the dynamics of economics within the sectors on the farmers' behaviour.

Few studies have assessed the economic impact of crop diversification on farms, specifically concerning crop protection. The profitability of such systems is all the more challenging to evaluate because the diversification modalities studied affect many of the determinants of profitability in different ways (and magnitudes). In addition, crop diversification modalities are often combined with other practices based on agroecological principles (e.g., soil improvement practices), which impact profitability. As a result, it is difficult to identify the specific effects of crop diversification on profitability. The effects on yield were discussed in detail in Section 2.1.3. Still, diversification can also affect the area allocated to each crop, as well as the selling price of the product (positively or negatively), by altering its quality and, therefore, its potential markets. It can lead to savings in inputs (pesticides in particular) but can also result in additional expenditure on equipment (equipment hire, sub-contracting). It can affect insurance or advice requirements and their associated costs. The impact on work can be ambiguous, with an increase in the complexity of tasks (and knowledge requirements) and a possible capping of workload peaks. Ultimately, the combined effects on farm profitability will be contingent, and no generic result can be deduced *a priori*.

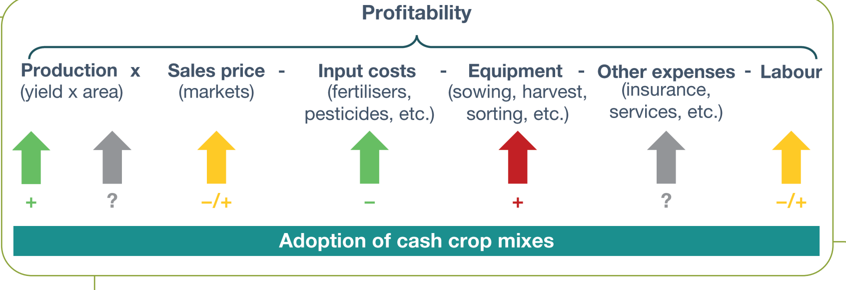
With this limitation in mind, it is still possible to give some indication of what the literature suggests on this topic. However, these results should be treated cautiously as they were not replicated.

At the intra-field level, articles studying the adoption of varietal mixtures of certified seeds conclude that this diversification modality does not seem to affect farm profitability significantly but that it can stabilise incomes. The case of peasant' seeds/traditional

54. Profitability here is defined as the gross operating profit. Income could include other sources, such as rental income for equipment or land, work for a third party, etc. Such elements are not considered here.

varieties is interesting because, although generally associated with lower yields and a lack of profitability, it can give rise to profitable production in niche strategies when the farmer enters a short distribution channel, either through a joint processing activity (for example milling and farm bakery), or through a partnership with users (restaurant owners, end consumers in an 'Association pour le maintien d'une agriculture paysanne' (AMAP), etc.) who value the products from these varieties for their specific qualities: organoleptic properties, local supply, seasonality, environmentally-friendly production method, etc. Diversification in market gardening can benefit from the same direct sales or short distribution channel strategies, where consumers are sometimes less demanding about the visual appearance of fruit and vegetables than large and medium-sized retailers. The few articles studying the profitability of service plants conclude that they are not very profitable. Lastly, the diversification option most studied is cash crop mixtures, which is proving profitable despite the additional costs associated with agricultural equipment (mainly for sowing, harvesting and sorting). The results in the literature are outlined in figure 2.6.

Figure 2.6. Main effects of the adoption of cash crop mixtures on profitability components



The symbols represent the effects of the adoption of a cash crop mixture on each component of profitability: increase (+), decrease (–), ambiguous effect (+/–), unknown effect (?). The colour of the arrows indicates the nature of the effect on profitability: positive effect (green), negative effect (red), ambiguous effect (yellow), insufficient data (grey). For example, diversification tends to foster yield (+), which increases profitability (green arrow), but it tends to increase costs associated with specific equipment (+), which reduces profitability (red arrow). Public aids (global or associated with a crop), discussed on page 90, are not explicitly represented in the figure.

At the farm level, diversifying rotations and cropping pattern by introducing a new crop (generally a minor crop) gives very variable results (some positive, some negative, often neutral), depending on the case study. Unprofitability generally stems from introducing new crops into production systems that are already specialised in the most profitable crops, which means that less profitable crops must be grown (notably because of limited markets and/or lack of research and development into their productivity). Lack of profitability can also be explained by the farmer's lack of expertise in growing these new crops. Similarly, introducing semi-natural features is not deemed cost-effective without subsidies, at least in the short term.

An analysis of this literature also offers several general lessons about some of the determinants of profitability. Overall, the plant diversification modalities studied performed better economically under high pest pressure. This result should be compared with previously discussed agroecological and yield stabilisation effects. Furthermore, the economic performance of many crop diversification modalities is also higher in low-input systems, particularly in organic farming. Economic profitability is also enhanced in conditions of low production prices or high input costs, which reduce the effects of any potential yield loss and reinforce the 'input savings' effect. Lastly, for certain diversification modalities and certain crops, profitability is achieved through niche strategies (marketing through short distribution channels, based on product quality features, etc.) (cf. *supra*), which may limit the prospects for large-scale deployment.

The literature also shows that, even for diversification modalities deemed profitable at the farm level, the studies emphasise that the potential gains concerning a conventional production system are generally insufficient to encourage the farmer to tackle the obstacles he may face in implementing this diversification. These barriers are linked to the socio-technical organisation of the sectors and the interactions between players within the regions. They are outlined in the following section.

Methodologically, assessing the profitability of diversified systems is hampered by the failure to consider various factors:

- The timeframe and/or multi-annual nature of the agroecological effects induced by plant diversification: the fact that natural pest regulation mechanisms are only fully effective in the medium/long term (particularly for semi-natural features) argues in favour of a long-term analysis of the profitability of diversification. In addition, some studies suggest that more diversified systems offer more stable performance over time. This is a clear advantage in current and future conditions of high meteorological variability and is particularly interesting to risk-averse farmers, who attach importance to such stability.
- The multiplicity of positive effects/externalities, expressed beyond the farm's boundaries and not limited to pest regulation. As well as affecting farm profitability, diversification on a given farm can have an economic impact on the profitability of neighbouring farms by controlling pests throughout the landscape. These effects are not factored into a farm-wide profitability calculation. In addition, diversification can increase the supply of certain ecosystem services (see Plant diversification is good for the associated biodiversity and the ecosystem services provided to farmers and society) which benefit society and whose value is not considered when calculating profitability. For example, while cost/benefit analyses of semi-natural features such as hedgerows tend to show that they are not profitable, no study (except for Morandin *et al.*, 2016) looks at the benefits of associated pesticide savings or the benefits of providing other ecosystem services (pollination, fertilisation) that may benefit other players in the territory. For example, some of the ecosystem services provided by semi-natural features do not generate income for the farmer

through agricultural production. Still, they could justify payments for environmental services, which, if included in profitability calculations, would significantly reduce the time to return on investment.[55] The literature mentions the value of financial incentives for diversification, which are justified, among other things, by the beneficial effects of diversification on the environment and biodiversity. Such incentives can be implemented by public policy (*via* the Common Agricultural Policy, in particular, see Public policies are a key factor in the deployment of plant diversification) or by market mechanisms. One relevant certification for semi-natural features is the one associated with carbon storage. The 'low carbon' certification label launched in 2018 certifies greenhouse gas emission savings and carbon storage achieved by farms. It values them through carbon credits paid for by private or public players or sold on carbon offsetting markets. However, this certification is still largely in its infancy. It needs to be appropriated by the players involved to foster genuine funding for the introduction of semi-natural features.

These factors argue in favour of changing our approach to the profitability of production practices and systems by including the multi-annual dimension of the benefits of plant diversification and the fact that some of these benefits extend beyond the farm's boundaries. There is still much to be done, particularly regarding diversified systems. Similarly, the question arises of integrating the adverse effects of crop protection strategies based on synthetic pesticides to calculate the 'social' profitability of the production methods that use them. These issues are linked to the role of public policies, discussed below.

To encourage plant diversification, several obstacles must be removed both within agricultural supply chains and at the territorial level

Although the literature focuses more on certain diversification modalities (varietal and species mixtures, rotations) to the detriment of others (semi-natural features, specifically), the barriers and levers to implementing crop protection strategies based on plant diversification are, by their very nature, rarely specific to one form of plant diversification in particular. However, there is insufficient literature to systematically rank the importance of each factor in adopting the different diversification practices.

55. Morandin *et al.* (2016) have used a cost-benefit analysis to calculate the economic profitability of hedgerows adjacent to tomato fields in California. Considering that hedgerows allow farmers to reduce the use of insecticides through their favourable effect on regulating pests, the authors estimated that the insect pest regulation service would offset the cost of planting a hedgerow and the land required for this after 16 years. When other ecosystem services are included, such as the pollination service provided by wild pollinators, the return on investment is reduced to 7 years.

Adoption factors upstream in the supply chain

Upstream of the farm, the availability of high-performance seeds and seedlings (in agronomic and economic terms)[56] in a diversified system and adapted to the farms' various soil-climate and agronomic conditions is one of the factors most frequently mentioned in the literature. It has a decisive influence on the implementation of most diversification practices.

First, the dynamics of varietal innovation depend on the level of investment in genetic selection, which in turn depends on the size of the markets for each species/product. This means that plant breeders tend to neglect a species or variety whose technological or organoleptic properties do not attract large markets. The limited range of varieties available for niche species (such as hemp and chikpea in arable farming) limits the scope for diversifying rotations through the introduction of a new crop. To illustrate, only six varieties of broad bean, one variety of lupin and one mustard variety were registered by the GEVES between 2009 and 2012 (and none of chickpea and hemp) compared with 139 varieties of wheat and 360 of maize (Magrini *et al.*, 2016). When varieties are available for niche species, they often perform poorly in terms of emergence rate, yield level and stability, and resistance to certain pests and lodging.

For the so-called 'majority' species, a wide choice of varieties does not guarantee their performance when used in a diversified system, particularly as a mixture (of varieties or species). On the one hand, the varieties available have been (and still are) selected for their value in pure crops and conventional growing methods. Their performance in mixtures is not one of the selection objectives. Yet the traits sought in mixtures differ from those pursued in pure crops. For example, pea resistance to lodging is essential in a pure crop but not in a mixture with barley, as the latter supports the pea; similarly, a grass used as a service plant must have limited rooting and summer dormancy to limit competition with the main crop, traits that are generally counter-selected in the case of grasses, so it is worth using older (and less selected) germplasm. The main crop should have specific characteristics for a good combination with the service plant (e.g., reaction to shading effects). On the other hand, a plethora of marketed varieties makes it more difficult to choose which ones to combine to obtain the desired effect. While farmers and research and development organisations can experiment to compare different mixtures, this can only be done on a pre-selection of combinations. Participatory ideotyping approaches were implemented in France to work on such preselection in cereal crops, and research is being carried out to develop rules for assembling varieties to meet farmers' production objectives. With a view to agroecological production, some authors recommend more generally that varietal selection should aim to restore greater diversity within the pool of cultivated varieties (Chacon-Labella *et al.*, 2019).

56. Performance is multidimensional; it covers yield potential, environmental adaptation, resistance to biotic stresses (pests), product quality characteristics, etc.

To counter these obstacles, in addition to the necessary investment in breeding, sharing experience and exchanging seeds between farmers (possibly combined with participative breeding or selection of population varieties) can play an essential role in specific supply chains or regions.

Agricultural equipment adapted to diversified crops is also lacking for deploying certain diversification modalities and/or adding value to the production from these systems. This is particularly the case for cash crop mixtures, where the need for specific equipment is the most commonly cited obstacle in the literature reviewed, and for diversifying rotations by introducing a niche crop and maintaining semi-natural features (although there is very little research on this subject).

Regarding crop mixtures, most of the sowing and harvesting equipment was developed to mechanise the production of pure crops, and it is not always adapted to mixed crop production. Therefore, specific equipment (or adaptations) may be required to sow different-sized seeds and plant them at different depths. This type of seed drill is available but is relatively expensive compared with conventional seed drills because it is complex and produced on a small scale. For harvesting, the combines available on the market are suited to a wide variety of combinations, but adjusting them to the optimum requires a certain amount of technical skill and must consider post-harvest sorting requirements (bearing in mind that mixtures that are 'easy' to harvest —i.e., two species with similar grain sizes—are usually the most difficult to sort, and vice versa). There is a similar issue when introducing a diversification crop, as illustrated by the cases of flax and hemp, two species for which the seeds and fibres are harvested simultaneously but which have different uses (industrial and textile).

Equipment sharing, whether as group purchases within CUMA (cooperatives for the use of agricultural equipment) or services provided by other farmers (agricultural works companies), is mentioned as a lever for pooling investments. However, equipment pooling means users must be coordinated to optimise operations planning, particularly sowing. Owning one's equipment is more practical for a farmer but also more expensive unless a minimum part of the farm's utilised agricultural area is allocated to each diversification crop for the investment to be profitable. The development of self-build equipment by farmers (to adapt existing equipment) is also a lever for reducing the cost of equipment.

The literature also often mentions inadequate expertise (on the part of both farmers and advisers), a lack of technical and economic references and a lack of advisory support (in all respects) on how to run diversified systems. This fuels farmers' uncertainty as to the benefits of diversification (particularly its effectiveness against pests), achievable yields and the value of production. These uncertainties prevent farmers from assessing the possible economic profitability of the system they use (cf. *supra*). This barrier applies to all forms of plant diversification. This is all the more problematic given that the long-term adoption of diversification modalities on the farm depends on the farmer's ability to manage the cultivated covers technically. In addition to this lack of expertise, the literature also points to the diversity of advisory sources in France (private advisers, cooperatives, technical institutes, chambers of agriculture) and their lack of coordination, sometimes leading to contradictory advice.

There are several reasons for this shortage of technical references. On the one hand, similarly to what has been observed previously in varietal improvement, the economic model of Technical Institutes (whose funding is correlated to the volumes harvested for each crop) encourages them to work primarily on majority crops and systems, which leads to knowledge gaps regarding niche crops and systems with a relatively high level of complexity (highly diversified rotations and cropping pattern, agroforestry). On the other hand, research into advisory services regarding crop rotations highlights the lack of benchmarking throughout the system: only the performance of a focal crop is assessed, without regard, for example, to its effects on the subsequent crop. The performance thus estimated neglects some of the effects linked to the practice of diversification (cf. Plant diversification has contrasting effects on the economic profitability of the farm in the short term.)

For diversification modalities based on semi-natural vegetation (planting hedgerows, implementing a permanent meadow, agroforestry), farmers may lack knowledge regarding the regulatory framework applicable to managing such, mostly perennial, vegetation, return on investment, and the ecosystem services it provides. This last point is all the more critical given that the introduction of 'non-productive' semi-natural features on the farm comes up against the high cost of installing these features and against the rural social norm, which is committed to the farmer's productive function and to 'clean' agricultural fields with a homogeneous composition.

In addition to increased investment in research & development and consultancy, several levers are mentioned to foster the acquisition and/or sharing of references. On-farm experimentation encourages the gradual learning of new practices and their step-by-step adaptation to the characteristics of the farms on which they are implemented. Still, it should be assisted to be more effective. Involving farmers in peer networks to share knowledge is one way of dealing with the lack of references from other players in agricultural development. Research also has a role in providing tools for assessing the effects of diversification practices to inform farmers about their benefits. Finally, decision-support tools for farmers are also an important lever. They can contribute to lightening the mental load associated with the complexity of designing and managing certain crop diversification modalities, such as rotation diversification. Deci-FlorSys is an example of a such tool (Colbach *et al.*, 2021). Coupled with the FlorSys model, it can be used to assess the effects of a selection of cropping systems on controlling weeds.

Adoption factors downstream in the supply chain

Downstream from the farm, another recurring barrier is the lack of markets for products from diversified systems.

For field crops, the processes used to transform plant raw materials in the standard supply chains require specific technological characteristics that cannot be obtained in diversified systems. The quality requirements and varietal purity imposed by the milling industry act as a barrier to adopting varietal mixtures, traditional or farmers' varieties and cash crop mixtures, especially as this outlet currently offers much higher added value than others. There are also few outlets for unsorted mixed crops (e.g., cereal-legume combinations), except for specific marketing channels such as organic shops. Similarly, a niche crop's relatively low commercial value may prompt agricultural cooperatives to exclude it from their marketing strategy (this is the case for legumes, for example). As mentioned above, the lack of technical and economic data on the performance of niche crops (nutritional qualities, environmental benefits, profitability) also affects market development by creating uncertainty for the manufacturers likely to market them.

In market gardening and arboriculture, produce must meet strict quality (particularly in size and appearance) and volume standards at specific ripening dates to enter the medium and large retail channels. However, diversification of market garden crops may lead to (i) the sub-optimal control of cultivation techniques during the first few years following the introduction of new crops, resulting in visual defects in the produce, (ii) a change in cultivation calendars, and ultimately discrepancies with the requirements of large retail stores.

These barriers may be removed by exploiting specific product characteristics achieved explicitly in diversified systems (e.g., particular organoleptic or nutritional qualities or the fact that they are obtained without using pesticides) in local and/or labelled production chains, with a higher selling price for the products. Short distribution channels are also a way, particularly in market gardening, to promote products from diversified systems to consumers sensitive to product diversity, seasonality and proximity to the production area (in addition to the environmental and quality criteria mentioned above). In this respect, the resurgence of collective action around responsible consumption since the early 1990s is an opportunity to promote products from systems that opt for crop protection strategies based on plant diversification rather than chemical control. As a result, direct sales and short distribution channels (both individual[57] and collective[58]) have developed significantly. These range from farm gate sales to AMAPs (Associations de Maintien de l'Agriculture Paysanne), in which the consumer pays in advance and commits to the producer over a given period. AMAPs foster solidarity by transferring part of the production risk to the consumer. The literature (meta-analyses) shows that consumers interested in products with environmental certification are, on average, 30% more willing to pay for such products than standard products. They also show a willingness to pay for local products.

The absence of a market can also be circumvented by a transition to an economic model in which the farmer processes his production on the farm (flour, bread, pasta). Such a model can, however, entail a higher workload. The presence of a local industrial project can act as a lever for species requiring more complex processing. For example, discussions between farmers and researchers on introducing camelina into cereal cropping systems in the Isère region were encouraged by a potential industrial partner interested in setting up an oil biorefinery in the area (Leclère, 2019).

57. Open air markets, retail outlets.
58. Group of consumers who enter into a contract with a producer, a platform that brings together consumers and local producers such as 'La Ruche Qui Dit Oui'.

In the case of plant diversification based on the introduction of semi-natural features on the farm, the challenge is to succeed in selling the wood produced by the hedgerows or tree lines in agroforestry systems. In addition to creating value-adding channels, if these don't already exist, farmers must learn how to integrate them with the required technical support.

Developing plant diversification requires territorial coordination

Finally, territorial coordination is vital to deploy plant diversification, whether to implement diversification modalities at the landscape scale (spatial organisation of crops, management of semi-natural vegetation) or to guarantee the sustainability of certain diversification modalities deployed at the field level. For example, the widespread introduction in an area of a crop variety carrying a resistance gene against a pest can induce selective pressure on the genetic evolution of pest populations and select variants capable of bypassing the resistance, rendering the variety ineffective in protecting the crop over time. Therefore, maintaining the sustainability of varietal resistance involves planning their deployment on the landscape scale.

Territory-wide solutions involving various stakeholders (farmers, agricultural advisors, agri-food manufacturers, cooperatives, water management organisations, associations and non-agricultural players, etc.) around plant diversification projects are emerging but are still rare. The literature highlights the methodological difficulties in studying and managing territories due to the multiplicity of spatial and temporal scales and the diversity of stakeholders involved. The deployment of plant diversification on a territorial scale thus runs up against the vicious circle of needing proof of concept to implement this territorial management and the need to implement collective strategies on a territorial scale to obtain proof of concept. To overcome these difficulties, cross-disciplinary approaches have been developed that foster participatory research with the stakeholders concerned and thus facilitate the emergence of solutions acceptable to all.

The literature points to three levers favouring territorial solutions: (i) the fact that collective action produces a collective gain, which may be, for example, eco-certification or payments for environmental services; (ii) the establishment of collective organisations to manage agricultural territories, such as polycentric governance mechanisms (i.e., stakeholder networks using shared communication and information systems or local collective institutions such as cooperatives) or centralised planning and incentives by the State; (iii) product, farm and landscape certification, and commercial outlets such as catering markets.

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

Since the post-war period, public policies have been a powerful driver for initiating and supporting the modernisation of agriculture. This has led to the current dominant position (spatial hold) of conventional agriculture and a loss in the plant diversity of agricultural fields and landscapes. Because the conventional system is very stable due to the many barriers operating at the different levels of socio-economic organisation of sectors and territories, the scientific literature highlights the critical role that public policies can play in redirecting production systems towards greater diversification. However, a large-scale transition requires ambitious public policies with the means to remove these systemic barriers. In addition, the legal context, which is not always consistent with the incentives provided by public policies, can also work against plant diversification, mainly regarding the conditions for planting and managing semi-natural features.

Ambitious policies to overcome the systemic barriers of conventional agriculture

Although the Common Agricultural Policy (CAP) has progressively introduced measures in successive programmes to reduce the environmental and health impacts of conventional farming (in particular *via* the agri-environmental measures under the 2nd pillar introduced in 1992, the fact that aid has been conditional since 2003, and the greening of its programming in 2014-2020, see Appendix), the assessments carried out in certain Member States and France all show that the actual effects remain disappointing. Thus, while greening has had a symbolic impact by strengthening the contract between farmers and society and explicitly linking a proportion of direct aid to environmental conditions, the actual impact on the environment and biodiversity in agricultural areas is not very visible (European Court of Auditors, 2017; 2020). This is mainly because the Member States and the European Parliament have unravelled the initial ambitions of the 2014 CAP under pressure from interest groups and the fear of losing competitiveness. The articles by Pe'er *et al.* (2019) and Pe'er and Lakner (2020), for example, provide a review of scientific work and expert advice highlighting the CAP's absence of environmental ambition.

Developing certain diversification modalities will only be possible with the support of public policies. The introduction of semi-natural features is a case in point. For a long time, the CAP directly or indirectly encouraged farmers to extend their utilised agricultural area at the expense of semi-natural features along the edges of fields and trees and thickets on fields of land, whose size and maintenance were seen as a hindrance to modernisation and increased agricultural productivity. Agroforestry systems were also excluded from CAP subsidies until 2001. However, since the early 2000s, environmental and agricultural policies, particularly at the European level (CAP, Nitrates Directive, Habitats and Birds Directives, etc.), have sought to encourage their conservation and restoration. As a result, semi-natural features are now central to many public support schemes (GAEC,[59] green payments, AECM,[60] aid for non-productive investments, and eco-schemes from 2023).

The measures adopted in the 2014-2020 programming period (green payment, AECM targeting the establishment or maintenance of semi-natural features) focused on maintaining

59. Good agricultural and environmental conditions.
60. Agro-environmental and climate measures.

existing semi-natural features to prevent their destruction or degradation. While they appear relatively efficient in this respect, they are not ambitious enough to encourage the establishment of new semi-natural features within farms or landscapes or the development of agroforestry (Appendix). On the one hand, the lack of a clear definition of these elements in the CAP has encouraged circumvention strategies by certain Member States who have opted for less restrictive farming practices, allowing farmers to comply with the thresholds imposed by making only few (if any) changes. On the other hand, genuinely protective measures are mostly rolled out in ecologically protected areas, where these features already exist in large numbers, leaving 'ordinary' territories by the wayside. In addition to European aid, several French schemes fund the planting of hedgerows and tree lines within fields (agroforestry): the 'France Relance' plan at the national level, financial programmes initiated by local authorities (regions), and the local and experimental introduction of payments for environmental services (in particular remuneration for carbon sequestration in the soil). In addition to the lack of any assessment of the impact of these schemes, the fact that aid is spread over a wide range of measures does not seem enough of an incentive. Existing subsidies are insufficient to act as a genuine driving force and compensate for the complexity of implementing certain practices, such as agroforestry or grassland management. The 2023 CAP now includes greening measures in the so-called 'reinforced' cross-compliance, creating a 'no turning back' ratchet effect. While leaving Member States a certain amount of freedom in the design of their eco-schemes, it does not impose any strong and specific conditions on improving the presence of semi-natural vegetation in agricultural areas. The French NSP is different, however, in that it introduces an access route to the eco-scheme dedicated to agro-ecological infrastructures (which include semi-natural features) and a 'hedgerow' bonus designed to encourage the protection and implementation of new hedgerows on agricultural land. It remains to be seen whether farmers will adopt this approach and what net impact it will have on the surface area of semi-natural features, particularly in 'ordinary' areas or those with very few of these features.

For other modalities of diversification, whose short-term economic benefits are currently insufficient to remove the barriers to adoption by the supply chains, the literature identifies several public policy levers to directly or indirectly support diversification rather than the use of pesticides to protect crops.

• Direct support is designed to assist the adoption of diversification practices through subsidies, thereby transferring to taxpayers (national and European) the economic burden of farmers accepting environmental responsibility. Public policies can also directly support the industry by targeting advice, research, investment aid and the creation of markets (particularly for the development of minor crops, such as the French Strategy for the development of plant protein, launched in 2021[61]). Such support may be targeted to encourage innovation and its dissemination, for example, by fostering the emergence of

61. https://agriculture.gouv.fr/batir-notre-souverainete-alimentaire-en-proteines-vegetales-o

a niche practice/crop, protecting its development and supporting its adoption.[62] It can also be backed by payment for environmental services, given the many beneficial effects of diversification on biodiversity and ecosystem services supply. This type of support is generally welcomed by industry and local stakeholders. Still, it is hampered by budgetary constraints and complex technical implementation (calculating and evaluating environmental benefits).

• Indirect support would involve correcting the market imperfections that currently favour conventional production systems that use synthetic inputs, particularly pesticides. This could involve banning the use of the most toxic pesticides or taxing them at a rate commensurate with the harmful externalities their use generates. Taxation offers interesting alternatives to regulation and bans on use. This type of environmental taxation is much favoured by environmental economists (see Berendse, 2017 and Finger *et al.*, 2017 for recent discussions), because it is an effective tool, on a theoretical level, which triggers both a reduction in uses (starting with the least profitable) and substitution mechanisms, i.e. the use of alternative crop protection strategies, which include plant diversification. Environmental taxation also generates revenue, which can be used to support the shift towards more virtuous practices, for example. However, It should be noted that the influence of lobbies (Swinnen *et al.*, 2015; Ansaloni, 2015), and the low acceptability of taxation in general and environmental taxation in particular hinders the implementation of such disincentive tools. Given the low elasticity of demand concerning the price of pesticides, high taxation (or taxation that increases rapidly over time) is necessary to produce an effect. The public perceives such taxes as coercive, and they are less effective than positive incentives (subsidies) in changing behaviour.[63] Environmental taxation of pesticides remains a potentially powerful tool for kick-starting the agroecological transition. Its implementation would require a prior analysis of the determinants of the social acceptability of such policies. One solution could be to earmark tax revenues for programmes that farmers are keen to support.

Be that as it may, the study of public policy instruments to support and accelerate the agroecological transition is an area of research set to expand. The National Strategic Plan (NSP) for the future CAP in France[64] aims to 'achieve a mosaic of crops throughout the year in landscapes, with a high potential for soil and biodiversity conservation, while at the same time enabling a reduction in field sizes where they have expanded, in particular by encouraging the re-creation of agroecological infrastructures, and hedgerows specifically, *via* the eco-scheme bonus that can be cumulated with practices'. (French NSP, p. 99). The objectives of the NSP include aspects relating to plant diversification on various levels, in particular by strengthening the cross-compliance of first pillar aid and introducing diver-

62. See, for example, the recommendations from the DiverIMPACT project (https://zenodo.org/record/6382721#.YoZ3NkzP2Ul).

63. This phenomenon has been observed in other issues, most famously the carbon tax and its effect on fuel prices, which led to its rejection in many countries (see review by Maestre-Andrés *et al.*, 2019).

64. https://agriculture.gouv.fr/telecharger/131861

sification conditions in the eco-scheme (cropping pattern diversification and increase in the share of semi-natural features in the landscape—Annex).

It is still too early to evaluate the impact of the future CAP on plant diversification, and more research is needed to assess the effects of such measures. However, it is likely that without strong political will to define binding targets, crop protection strategies that are alternatives to pesticide use will struggle to emerge independently, and that ambitious targets (such as the 50% reduction in pesticide use by 2030) will not be achieved (Guyomard *et al.*, 2020). A group of more than 300 scientific experts from 23 EU Member States has suggested that to build the future CAP in favour of biodiversity, the requirements of cross-compliance and eco-schemes should be raised, and, if possible, priority should be given to AECMs with a commitment to results rather than means, to improve their effectiveness and avoid windfall effects (Pe'er *et al.*, 2022). These experts also emphasised that attention should be paid to the coherence of the schemes, for example, by allowing the cumulation of eco-scheme and AECM payments in cases where they foster complementary actions in favour of biodiversity in the same area. In France, the position taken by the Environmental Authority[65] on the first version of the NSP, submitted in December 2021, highlights that the level of environmental ambition is insufficient to place France on a trajectory that will enable it to achieve the objectives it has set itself in the low-carbon strategy, the biodiversity plan and the Water Framework Directive. Following an equally critical opinion from the European Commission, the slightly revised version of the French NSP was finally approved by the European Commission in August 2022.

In addition to ambitious agricultural policies, a widespread transition in agrarian production methods in favour of agroecological systems calls for proactive food policies to ensure the supply of more environmentally friendly farming products and healthier, sustainable diets. Such policies cannot be designed independently (Guyomard *et al.*, 2020), whether at the European or national level.

As we saw earlier, one of the solutions to ensure the profitability of diversified systems is to promote the particular qualities of the products (health, environmental, etc.) in niche markets and/or *via* some form of certification. Although the literature does not give much detail on the topic, such strategies may be associated with an increase in the sale price of food products. While the literature shows that consumers are willing to pay more for environmentally friendly products, it also indicates that budgetary constraints (heightened by crises such as the health crisis and the war in Ukraine) are pushing them to react to inflation by turning to cheaper products, possibly of lower nutritional and environmental quality. Such a reaction may, on the one hand, lead to more or less profound changes in eating habits (not necessarily in favour of a more balanced and healthy diet[66]), and, on

65. https://www.igedd.developpement-durable.gouv.fr/IMG/pdf/211022_psn_pac_delibere_cle08263b.pdf
66. Recent studies document the link between consumers' environmental concerns and diet structure: organic farming product consumers buy higher quantities of fruit and vegetables, legumes, whole grain products, plant proteins and lower amounts of meat and alcoholic and sugary drinks (Baudry *et al.*, 2017).

the other, dissuade (not encourage) farmers from adopting more environmentally friendly practices such as plant diversification.

Added to this is the fact that the French's eating habits, characterised by an average diet that is relatively high in animal products and low in plant products (mainly fruit, vegetables and legumes), are not conducive to good health (as defined by recommendations such as those of the World Health Organisation - see Tibi *et al.*, 2020). However, it is now accepted that, for most consumers, dietary changes will not happen without political incentives. Moreover, not every health-promoting diet is more virtuous environmentally, and vice versa (see, for example, Vieux *et al.*, 2018; 2020).

Although the matter of coordinating agricultural and food policies has been raised for many years, at present, there is no consistent design in this direction (Galli *et al.*, 2020; Recanati *et al.*, 2019). However, the European Commission has launched an initiative to ensure the sustainability of the EU food system by integrating it into all food-related policies.[67] The Green Deal's Farm to Fork strategy is an important step taken in this direction. In France, the Egalim law of 30 October 2018[68] demonstrates, among other things, the commitment to improving the health and environmental quality of products and promoting healthy, safe and sustainable food for all, and creates a connection between consumption and production patterns. For example, as of 1 January 2022, the law requires public catering establishments to offer meals with at least 50% 'sustainable' or quality-certified products and a minimum of 20% organically farmed products.

Legal instruments that are not conducive to the increase of semi-natural features

While the French legislation of the late 20th century sought, above all, to protect the environment and biodiversity from farming activities that had become too intensive (defensive stance), recently, the tone shifted towards the will to promote diversity at the very heart of agricultural production. As one of the main challenges is to reduce the use of synthetic pesticides, the Ecophyto plan to reduce the use of pesticides (first drafted in 2008) is one of the main strategies implemented by France.

The French Law on the Future of Agriculture, Food and Forestry (loi d'avenir pour l'agriculture, l'alimentation et la forêt) of 13 October 2014 marks a political shift by promoting a new production model known as 'agroecology', characterised by a threefold economic, social and environmental performance. With this, the legislator wishes to put forth innovative production methods based on ecosystem services and collective initiatives carried out on a territorial and multi-annual scale (e.g., reforestation operations). While the ambitions are high, the technical resources introduced (including opening up rural leases to environmental obligations and creating groups of farmers and other partners around common production

67. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13174-Sustainable-EU-food-system-new-initiative_en

68. https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000037547946

projects, (known as GIEE for 'Groupement d'intérêt économique et environnemental') as a framework for agroecological initiatives) remain minimalist, purely on a voluntary basis and sector-based. Their actual impact on changes in farming practices is difficult to measure.

The 'Climat et Resilience' Law of 22 August 2021 reasserts the importance of plant diversification, setting the target of increasing the area of French farmland cultivated with legumes to 8% of the utilised agricultural area by 1 January 2030, the imperative of preserving and planting hedgerows and tree lines, and the maintenance and development of farmland with permanent grassland. Remarkably, the Law sets out a compatibility principle for the French version of the new Common Agricultural Policy (CAP) with several national roadmaps (national low-carbon strategy, national biodiversity strategy, national strategy to combat imported deforestation and national health risk prevention plan). For the first time, the national measures for the payment of CAP aid should be harmonised in compliance with national environmental objectives.

However, concerning the deployment of semi-natural features, many obstacles are due to inappropriate regulations or regulations that do not adequately recognise the importance of such features. Most of these landscape features are located on private land and are hampered by rigid rural land tenure laws. As it stands, the tenancy law governing landlord-tenant relations, which applies to 70% of French agricultural land, tends by default to allow the destruction of hedges, ditches and trees separating adjoining fields in the name of the farmer's freedom to farm, while discouraging planting operations.

The siting of semi-natural features at the edge of fields is also likely to generate recurring problems for neighbours in rural areas. In addition, the Civil Code (which governs neighbourly relations) restricts the planting of semi-natural features set back from the boundary that divides properties. As a result, these features have a more significant footprint on the area given over to cash crops. Finally, departmental council afforestation regulations may also prohibit planting in certain areas.

Some imperfect approaches to certain semi-natural features have also been observed in the legislation. Permanent grasslands, for example, are only defined in terms of their duration without consideration of their intrinsic qualities and the management methods applicable to them. This single criterion may have the perverse effect of encouraging farmers to remove a grassed area before it falls into the permanent grassland category.

It should be noted that agroforestry poses difficulties as a poorly identified legal object because it combines an agricultural production method with an activity classified as non-agricultural (forestry), two activities which fall under separate legal regimes. The land area taken up by trees may also reduce arable area and, consequently, the amount of aid farmers receive for their productive areas. In addition, most agricultural enterprises (in France: GAEC, EARL, GFA) are incompatible with forestry activities. Creating a proper regulatory framework for agroforestry would remove such obstacles.

Finally, tools, albeit dispersed, do exist to protect semi-natural features. Examples include rural leases, which, if the parties agree, can include a clause preserving a minimum level of agroecological infrastructure (AEI), and real environmental obligations (REO), which are voluntary commitments by landowners to protect biodiversity on their land. Urban planning documents (such as the local urban plan) also contain measures to classify semi-natural features and protect them against harm. However, there are no quantitative studies or surveys to measure the actual roll-out of this type of system or its true effectiveness.

Box 2.3. Plant diversification to protect overseas crops

The CAS's scope includes all French territories, including overseas. Overseas territories have specific historical, biogeographical, social, economic and political characteristics that are likely to condition the roll-out of crop protection strategies based on plant diversification in a different way from that observed in mainland France.

Because of the expert skills brought together in the CAS, the main focus here is on the five French Overseas Departments and Regions (DROM), all located in tropical environments: Guadeloupe, French Guiana, Martinique, Mayotte and Réunion. While each territory has a unique socio-economic profile, the DROMs share several socio-geographic characteristics: remoteness/isolation, narrow land area and insularity (except for French Guiana). However, these same geographical characteristics imply constraints that are seen as obstacles to their growth and development: political, economic and sectoral dependence on the outside world (mainly mainland France), limited integration into local economic areas, small market size, access difficulties, limited economic diversification and exposure to natural hazards (cyclones, for example).

From an economic point of view, agriculture in the French overseas departments and territories is characterised by dependence on uncompetitive external markets in increasingly globalised markets. In the so-called historic DROMs (Guadeloupe, Martinique and Réunion), as in mainland France, the agricultural landscape is dominated by cash crops grown using conventional production methods (these plantation crops occupy more than 40% of the utilised agricultural area (UAA), mainly sugar cane - Agreste, 2021). These systems are developed to exploit savings, even though their contribution to the creation of wealth beneficial to the economies of the DROMs is much debated.

Alongside conventional farms, several diversified production systems exist, some ultra-diversified, based on compliance with agroecological principles and partly on vernacular practices. Many of the diversified systems in the DROMs are family-run mixed farms with fruit and vegetable crops. These account for 70% of farms in the DROMs (but only 5.6% to 29.6% of the UAA depending on the DROM - Agreste, 2021). Species associations are common there, especially agroforestry. Field size is reduced to allow family-run management. Public support measures promote hedgerows. Some of these farms are moving towards organic farming (for example, in Réunion, the number of organic farms doubled between 2011 and 2018 - Agreste, 2019), directly mobilising plant diversification to control pests.

Box 2.3. Continuation

The agricultural and peri-urban area also includes the Creole gardens, a traditional and highly diversified subsistence mixed farming system. This ultra-diversified system is further being developed with the emergence of permaculture and urban gardens.

The DROMs thus offer local agricultural landscapes with nearly unequalled plant diversity. The different modalities of diversification considered in the CAS are implemented in these farming systems. Although Creole gardens have always been pesticide-free, this is not always true for family farms, where pesticides are often used out of habit or fear of risk. Yet, several scientific studies illustrate the effectiveness of plant diversification in conventional farming systems in regulating pest populations in tropical environments (trap plants for vegetable flies or cane borers on Réunion, plant cover in mango orchards on Réunion, maize borders for tomato moths in the West Indies, etc.). A comparison of diversified and monospecific systems in the French West Indies (Guadeloupe, Martinique) shows that the former have better biological soil quality and provide more ecosystem services, in line with the significant trends in the global literature. Lastly, diversified farming systems allow farmers to mitigate production risks, particularly concerning natural hazards, which are particularly recurrent and severe in these areas. They are also a source of satisfactory yields and income.

However, in keeping with the literature that studied the conditions for adopting diversification practices, the diversification of dominant systems (plantations), the protection of diversified systems found on family farms and the safeguarding of highly diversified Creole gardens are severely hampered by technical, social and economic barriers. Again, this is where agricultural equipment adapted to plant diversification comes up short. Technical references and agricultural advice for many endemic diversification crops (such as sweet potatoes) are also virtually non-existent, although there is dynamic research and transfer activity regarding diversified cropping systems in overseas France. Unusually, in these territories, as opposed to mainland France, systemic knowledge of diversified production exists; however, this knowledge is carried by individuals outside the dominant agricultural system through inter-individual and mainly oral transmission.

Alongside these obstacles, the general context seems to offer opportunities to increase agricultural diversification in the DROMs. The rise of responsible consumerism in support of environmentally friendly production methods, societal demands for transparency in production methods, and the disengagement of public institutions regarding tariff protection for cash crops are fundamentally challenging the robustness of conventional production systems. This observation regarding overseas territories is in similar to that made in mainland France. Politically, there are windows of opportunity to spotlight alternative systems, but they are still small.

Box 2.3. Continuation

They materialise at different levels: international (e.g. the FAO's Climate-Smart Agriculture 2010), supranational (e.g., the Common Agricultural Policy's green payments) and national (e.g., the 2014 French Loi d'Avenir). They advocate the recognition of diversified and even ultra-diversified cropping systems. These contextual factors, particularly political ones, are fostering a climate conducive to raising the profile of these systems and, more generally, developing agricultural models in overseas economies. Lastly, a lever for diversification is currently emerging in terms of outlets, with product chains based on a basket approach, which is an innovation compared with the dominant system and allows for economies of scope.

Given their historical structure and current dynamics, the diversified agricultural systems of the French overseas departments and territories (DROMs) have great potential as an open-air laboratory for developing viable farming systems in which plant diversity promotes the natural regulation of pests, the provision of other ecosystem services and the maintenance, or even increase, of yields in areas where the risks (environmental, economic, health and social) associated with global change are concentrated.

PART 3

Outlook and research needs

This third part follows from the literature reviews by putting the CAS's conclusions into perspective concerning two issues: (i) the place of diversified farming systems and landscapes in a large-scale transition of agriculture towards zero pesticides, and (ii) the contribution of plant diversification to climate change adaptation and mitigation. In addition, it sets out the quantitative recommendations made in the scientific literature concerning the deployment of certain plant diversification methods in response to a series of environmental issues (going beyond the sole objective of agroecological crop protection). Finally, it identifies the need for further research and work to fill the knowledge gaps identified in the literature.

5. Perspectives: plant diversification and environmental challenges

What role can plant diversification play in the transition to pesticide-free agriculture?

The CAS's remit did not include evaluating possible ways of reducing the use of pesticides, an objective that falls within the scope of a foresight exercise conducted by INRAE and is contemporary with the present analysis (Mora *et al.*, 2023). However, the lessons learnt from the CAS provide some initial insights into the role of diversified systems in a large-scale transition of agriculture towards 'zero pesticides'.

Crop protection strategies based on the diversification modalities examined in this CAS are typically accompanied by a reduction in pesticide use (an effect noted in articles analysing diversified systems) or implemented in low-input or organic farming systems (where they prove to be the most profitable). However, the literature rarely quantifies the reduction in pesticide use achieved by these strategies, and there is no guarantee that plant diversification, even on a large scale, will achieve a 'zero pesticide' target without these strategies being coupled with regulatory obligations in this area.[69]

Other scenarios are proposed in the literature or political circles to help agriculture phase out the use of pesticides. This is the case, for example, with the massive development of organic farming (AB). In fact, the European Green Deal sets a target of allocating at least 25% of agricultural land to organic farming by 2030. The French AB certification prohibits the use of synthetic chemical inputs, including pesticides. In this sense, it guarantees an effective reduction in the use of pesticides.

In fact, although organic farming can also harness plant diversity to regulate pests, the AB certification does not impose plant diversification as the main crop protection lever. Alternative agricultural practices can be used, some of which may raise environmental issues when used intensively (such as spraying pest control products like pyrethrins, clays, oils and copper). The strong development of organic farming in recent years has, in some regions (e.g., Spain),

69. Very few connections have been made in the literature between the natural regulation of pests in diversified systems and the abandonment of treatments, mainly due to the lack of socio-economic studies on how farmers take agroecological dynamics into account when making treatment decisions.

involved some form of intensification, with the implementation of practices whose value in terms of preserving biodiversity and providing ecosystem services is debatable (e.g., the conversion of semi-natural features into arable land, or intensive cultivation in heated greenhouses). Thus, while organic farming favours biodiversity on average, compared with conventional agriculture (see the review by Rosa-Schleich *et al.*, 2019), it fails to achieve levels of biodiversity conservation as high as those obtained in diversified landscapes (Tscharntke *et al.*, 2021). A greater diversity of habitats on agricultural land increased butterfly diversity on farms by around 50%, which is not the case when farming practices transition to organic farming (Weibull *et al.*, 2000). Increasing the length of hedgerows by 250 metres per field raised bird diversity from one to 12 species while converting from conventional to organic farming only increased species richness by 50% (Batary *et al.* 2010).

Furthermore, organic farming is sometimes criticised for its yield gap compared with conventional agriculture (Gabriel *et al*, 2013).[70] In contrast, the literature review carried out by the CAS shows that diversified systems are, on average, associated with yield gains.

To achieve ambitious targets for reducing pesticide use without compromising yields and while preserving biodiversity and the supply of ecosystem services, organic farming and plant diversification should be viewed as two tools that, while different in nature ('agroecological' in the case of diversification and 'regulatory' in the case of organic farming), are complementary and mutually supportive when combined. Diversification into organic farming is profitable and delivers good ecological performance. Given that the AB certification label is well-known and sought-after by consumers, it may enhance the value of agroecological production based on plant diversification. In return, increasing plant diversity in organic farming systems reduces the yield gap between such systems and conventional farming (Ponisio *et al.*, 2015).

Plant diversification of agricultural systems to meet the challenges of climate change

The relationships between plant diversification in agricultural areas and climate change was not studied in the CAS. The agroecological studies in the corpus analysed do not address this aspect, but it is often mentioned in the discussion or perspectives sections in recent articles. This section aims to provide non-exhaustive scientific information on the effects of plant diversification in terms of (i) resistance and resilience (ability to adapt to disturbances or to return to a routine regime) in the face of specific climate events (i.e., a severe summer drought, a harsh winter, flooding, a storm, a cyclone in the French overseas departments and territories, etc.) and global changes (such as rising temperatures),

70. According to Meemken and Qaim (2018), organic farming shows a yield loss of around 19 to 25% compared with conventional methods. This discrepancy is linked, in particular, to the absence of mineral fertilisers (Knapp *et al.*, 2018).

and (ii) contribution to mitigating climate change through levels of greenhouse gas emissions, carbon sequestration and water regulation. The Rosa-Schleich *et al.* (2019) review identifies the positive effects of intermediate cover crops, crop mixtures, agroforestry, diversified rotations and linear semi-natural features planted and/or managed by the farmer (such as grass strips and hedgerows) on carbon sequestration, water regulation and resilience to climate disturbances. Varietal mixtures, intercropping and semi-natural features in agricultural landscapes help stabilise yields against annual weather fluctuations (Raseduzzaman and Jensen, 2017; Reiss and Drinkwater, 2018; Redhead *et al.*, 2020). Semi-natural features help to maintain biodiversity in agro-ecosystems during adverse climate events (Duflot *et al.*, 2022). The literature review indicates that most diversification modalities store higher levels of carbon, particularly agroforestry, except for intermediate cover crops because they are destroyed. This scientific information illustrates the value of plant diversification in improving the resilience of agricultural systems and limiting agriculture's contribution to climate change, bearing in mind that, according to the IPCC, agriculture is the second most significant contributor to climate change after transport.

The literature on the relationship between plant diversification in agricultural areas and climate change exists, but it must be reviewed to assess such relationships accurately. Finally, it should be noted that no information is provided here on water use by diversified crops, which is another essential assessment to be carried out.

To what extent should we diversify? Some recommendations from the scientific literature

The scientific literature (meta-analyses or extensive monitoring of diversification on a national or even European scale) provides quantitative recommendations for the deployment of certain plant diversification modalities. It should be noted that these recommendations only concern some of the diversification modalitiesdiscussed in the CAS, and do not specifically address the deployment of plant diversification to protect crops. They take a more global (and indiscriminate) view of the various presumed benefits of diversification: promoting and preserving biodiversity as a whole and providing a range of ecosystem services to farmers (services which support agricultural production) and society. The recommendations set out below are compared with the figures showing the current level of deployment of these diversification practices in France (presented in Chapter 1) to indicate how far the current situation is from the targets to be achieved.

According to Borg *et al.* (2018), varietal mixtures must include 4 to 5 varieties to control diseases efficiently. By comparison, wheat varietal mixtures (around 15% of the national wheat acreage) include a maximum of 2 to 3 varieties.

Corre-Hellou *et al.* (2014) showed that associations of 2 crop species that are not vulnerable to the same pests and complement each other in their use of resources (for example, cereals or crucifers and grain legumes) often suffice to regulate diseases, weeds and insect pests effectively. Mixtures of cash crops now account for 0.1 to 3% of the land area, depending on the region. These are mainly cereal-protein crop mixtures.

Bohan *et al.* (2011, 2021) recommend arable crop rotations of more than 3 years, diversifying the cropping periods (winter and spring crops) and, if possible, including Brassicas to control weeds in particular and legumes for nitrogen fixation. Currently, most arable land is planted in rotations of up to 3 crops (with a predominance of sequences including rapeseed, wheat and barley), and monocultures covered 12% of arable land in 2006. In addition, the soil is left bare during the intercrop period on 14% of arable land, rising to two-thirds for soy and just over half for grain maize.

Drawing on a vast European study comparing 435 agricultural landscapes (1 km^2 portions) located in seven European regions and one North American region, Sirami *et al.* (2019) found that an average arable field size of around 2.8 ha is optimal for promoting regulation and biodiversity. The authors estimated that a reduction from 5 ha to 2.8 ha would increase biodiversity levels just as much as when the proportion of semi-natural features rises from 0.5% to 11% in the landscape. This recommendation should be compared with the French average of 3.1 ha (all types of cropping patterns combined), although this average hides a considerable disparity. While nearly 50% of fields are smaller than 2.1 ha, 50% of the utilised agricultural area is occupied by fields larger than 6.8 ha (Sirami and Midler, 2021[71]).

The consensus in the literature is that semi-natural features must occupy around 20% of the surface area of landscapes to regulate arthropod pests (by sustaining populations of natural enemies), conserve biodiversity in general and provide various ecosystem services (including crop pollination) (Tscharntke *et al.*, 2002; Thies *et al.*, 2005; Garibaldi *et al.*, 2021). In addition, one study estimated that hedgerows surrounding fields should reach 200 to 400 m per ha to achieve a balance between yield and biodiversity (Martin *et al.*, 2019b). However, there is no systematic, up-to-date inventory of semi-natural features, a category which includes a wide variety of features (see Chapter 1). Due to the lack of national statistics and the considerable variability of figures from one source to another, it is currently difficult to estimate the proportion of semi-natural features in French agricultural landscapes. However, this proportion varies considerably from one region to the other. Although very high in areas with extensive livestock farming (due to permanent grassland and other areas always under grass), it is often less than 5% in cereal-growing plains. While this trend has been more or less curbed over the last few decades, the decline in semi-natural features that began after WWII is still ongoing for some features, particularly hedgerows and tree lines, which are losing an average of 7,000 km a year. In fact, restoring hedgerows is one of the objectives of the French pact launched in September 2023, which aimed to restore 50,000 km of hedgerows by 2030.

The development of agroforestry is one way to increase intra-field tree lines. Although it was supported by a five-year plan launched in 2015,[72] its development in France is difficult

71. https://agreste.agriculture.gouv.fr/agreste-web/disaron/Ana163/detail/

72. It is worth noting that the plan's evaluation report, published in 2021, stressed that the plan—which did not receive dedicated funding or propose a quantified target for the development of agroforestry by 2020—was essentially 'a plea in favour of agroforestry', aiming above all to maintain areas dedicated to agroforestry.

to estimate because available statistics are scattered and often include hedgerows (see Chapter 1). The study carried out by the INRA on the contribution of French agriculture to reducing GHG emissions (Pellerin *et al.*, 2013) estimated that 3.9 Mha of crops and 2 Mha of grassland should be suitable for complanting with trees in 2030.[73] Assuming the slow uptake of these practices (whose adoption implies a profound change in production methods) over only 4 to 10% of this base, the authors estimated that between 230,000 and 590,000 ha of intra-field agroforestry could be achieved by 2030, compared with the 100,000 to 170,000 ha estimated in the mid-2010s. In fact, these systems were developing at a rate of around 1,000 to 5,000 ha per annum in the 2010s (CGAAER, 2015), which, if maintained, would, at best, reach the low range estimated by Pellerin *et al.*, (2013) in 2030.

73. Fields larger than 4 ha (to ensure compatibility with mechanised work between rows of trees) with sufficiently deep soil capable of storing water for plants (i.e., 38% of arable land and 31% of grassland).

6. Further research and studies needed

Gaining a better understanding of the natural regulation mechanisms of pests

The literature review whose results are discussed in Chapter 5, highlights several gaps in knowledge. While there is abundant literature on the regulatory effects of plant diversity, the research effort is not evenly distributed between (i) pest categories and (ii) diversification modalities. As a result, soil-borne insects, vector-borne diseases, nematodes, gastropods, mites and parasitic plants are insufficiently studied. The potential benefits of cropping pattern diversity and semi-natural features in the landscape should also be explored further. Furthermore, arable farming systems were much more extensively studied than market gardening, resulting in little knowledge for designing the deployment of plant diversification in these farming systems, which are currently among the highest consumers of pesticides per hectare. In addition to these knowledge gaps concerning 'diversification modality - pest category' pairs, research is lacking to estimate (i) the regulation effects of diversification modality combinations (ii) to control multiple pests. Anticipating such effects calls for a better understanding of the underlying mechanisms of natural regulations, as some are only studied theoretically in scientific studies without any functional demonstration.

Bridging these gaps would require a paradigm change to study the effects of plant diversity. Rather than an *ad hoc* comparison of different levels of landscape simplification on pest regulation, the effects of diversification should be explicitly assessed through large-scale experiments to restore landscape plant diversity; in other words, through the design of experiments at the scale of agroecological territories. Such experiments would help understand how natural regulations depend on local conditions and include damage measurements (in addition to simple measures of pest population variations). Such long-term mechanisms are also necessary to assess the sustainability of regulations and changes, and their effectiveness in light of global changes (climate change, biodiversity loss). These change factors affect the distribution areas of pest species and their natural enemies and act as a selection pressure driving evolutions in the species themselves (biological adaptation corresponding to the modification of life traits). In the collective interest, all modalities of plant diversification must be geared towards achieving a good balance between 'sustainability' and 'efficiency'. It should be noted that climate change also impacts plant distribution areas (whether cultivated or not), thus limiting plant diversification deployment.

Gaining a better understanding of socio-economic organisations

Firstly, more research needs to be carried out into the precise determinants of farmers' crop protection choices, at the farm level or collectively in local areas. No study has been carried out on how farmers (individually or collectively) understand agroecological dynamics and changes in pest populations or on the role that 'agroecological' consulting could have in this respect. Another area for study is how diversification practices link with biocontrol methods, particularly during the transition from conventional farming to agro-ecology. Such research would provide a better estimate of the impact of adopting plant diversification practices on farm management (in particular organisation and working time) and pesticide use. The impact of recent regulatory changes on the organisation of the industry and the development of alternative approaches to plant breeding must also be studied. Meanwhile, developing markets for products from diversified systems calls for research into value distribution within sectors and consumer behaviour towards particular production methods and/or products that do not meet conventional standards. The study of the dynamics of the spread of innovations, such as crop diversification, also remains a significant area of scientific research, requiring work on the role of networks, behavioural economics and the spread of these new practices throughout the region.

Secondly, assessing the economic performance of diversified systems is hampered by the lack of real-life situation data on emerging practices. On the one hand, the data traditionally available does not adequately identify emerging practices and cannot be analysed in detail. On the other hand, evaluating the economic performance of diversified systems calls for reassessing the concepts of nuisance thresholds (above which harm becomes damage), damage and economic profitability. These notions are currently defined regarding the standards associated with conventional systems and do not include the adverse externalities of pesticides or the positive externalities of plant diversification modalities.

Once again, the above-described large-scale experiments could help meet these research needs at all levels of socio-economic organisation. They would provide the opportunity to combine ecology research with that of the various disciplines studying farmers' behaviour and the determinants of their decisions (economics, management, systems agronomy, sociology, ergonomics, etc.) to study simultaneously (i) farmers' behaviour in response to pest pressure and (ii) the effects of the methods used on pest populations, biodiversity and ecosystem services supply. Finally, the role of livestock in diversified cropping systems should be examined as a lever for crop diversification and an outlet for crop production.

Building on long-term research and using digital tools...

Some interdisciplinary and transdisciplinary research programmes seem conducive to integrated and territorial research, but such endeavours should be multiplied and consolidated on a national and European scale. In agricultural environments, INRAE experimental platforms and workshop areas (inter-institute and inter-organisation) are adapted to long-term studies. Participatory innovation approaches such as living labs[74] seem to meet the systemic approach required and provide a means of comparing a broad spectrum of diversified systems. Rolled out in several different countries, such systems would offer the opportunity to compare different approaches on a European scale. In addition, remote sensing could be used for quantitative and spatial monitoring of the adoption of diversification practices, with some necessary technological developments for certain diversification modalities.

Modelling is a complementary avenue of research to (i) help optimise each diversification modality (e.g., varietal and specific composition and spatial arrangement) in terms of its effects on the pest regulation and the provision of other ecosystem services and (ii) explore the broad range of possible strategies for combining diversification modalities on large spatiotemporal scales, including to assess the sustainability of these production systems and the feedback loops at different time scales between the agroecological component and the socio-economic component of agricultural landscapes.

... to design public policies that foster diversification

The low efficacy of public policies in promoting the adoption of plant diversification and its spatial coordination in agricultural landscapes calls for further applied work on evaluating measures in place (*ex-post* evaluation) or planned (*ex-ante* evaluation). The goal would then be to measure the causal effect of policies, i.e., the effect attributable strictly to the measure and not to other determinants. This would require better collaboration with policymakers and professionals to establish experimental protocols such as randomised social experiments.

Research should also focus on the design of agricultural public policies. Such work must include a reflection on (i) the coherence of agricultural policies acting on different levels (local, national, European) and (ii) their coherence with other sectoral policies (e.g. agriculture, environment or biodiversity and food), involving the same players/territories. In addition, insufficient consideration is given to the consistency between public policy tools and regulatory tools.

74. The living lab is a participative innovation approach that includes users. It aims to address complex, multidisciplinary issues on a territorial scale. https://dicoagroecologie.fr/en/dictionnaire/living-lab-2/

Conclusion

The scope of the CAS covers all the spatial and temporal scales at which it is possible to envisage plant diversification, whether it concerns vegetation cultivated by the farmer or the semi-natural vegetation associated with farming areas. Thus, the analysis covers a wide range of diversification practices, which can be combined.

Plant diversification on agricultural fields and landscapes is a crop protection lever

In principle, the same pest cannot consume or colonise all cultivated plants because of its more or less marked specialisation concerning these plants. As a result, an increase in plant diversity is expected to 'dilute' the pest's host plant in a plant cover or landscape of non-host plants, hence making it more difficult for phytophagous pests to find their host plant (bottom-up regulation). For weeds, a diversified plant cover provides a more competitive environment. In addition, natural enemies of pests are involved (top-down regulation), whose presence depends on the resources and habitats that intra- and extra-field vegetation can supply during their life cycle.

The literature review carried out in the CAS shows that each pest category can be controlled through at least one diversification modality. In most cases, there is a consensus in the literature on the positive effect of plant diversity. However, the level of scientific consensus varies from one diversification modality to another. The literature is more extensive on plant diversification at the field level (varietal mixtures, intercropping, diversified rotations), for which it reports mostly positive effects on regulating pests. The effects of the cultivated (cropping pattern diversity) and non-cultivated (semi-natural features) landscape are essentially the focus of theoretical expectations which has not been tested experimentally. The literature suggests that the spatial organisation of the landscape (field size and crop distribution) has at least as significant an impact as its composition (diversity of cultivated and semi-natural species).

Weeds are primarily regulated through intercropping (associated crops, agroforestry) and diversified rotations. Insect pests can be controlled using all types of intra-field diversification methods (particularly intercropping) and by increasing the diversity of cultivated vegetation in the landscape. Regarding crop diseases, the literature focuses mainly on airborne pathogens targeting straw cereals (wheat, barley, oats, rice). The latter can be regulated mainly by using varietal mixtures, crop rotations and, to a lesser extent, cash crop mixtures. Other pests have been far less studied, with the notable exception of nematodes, which are controlled through certain types of rotations.

While the literature agrees on the regulating effect of plant diversity, this method has proved inefficient (sometimes with adverse effects) in some cases. In addition to the gastropods favoured by agroforestry systems, some research has reported adverse effects for all diversification modalities. For some 'diversification modality - pest category' pairs (e.g., diversification of semi-natural features - aerial insects), there are as many positive effects as negative ones, making it impossible to reach a clear consensus. These ambiguities are essentially explained by the context-dependence of the effects in the cases analysed:

- The results typically depend on the life traits of the organisms involved (dispersal capacity and mode, host specialisation, forms of resistance, etc.), preventing any generalisation of the effect observed on one taxon to an entire category of pests;
- Farming methods play a significant role in the variability of effects. In particular, the literature suggests that conventional practices (use of synthetic inputs and varieties adapted to this type of management) are likely to reduce the regulating effects provided by plant diversity. Positive effects are often more pronounced in low-input systems;
- Local climate and seasonal conditions are systematically mentioned as factors that can modify the expression of natural mechanisms.

As a result, it is impossible to lay down general rules as to which plant diversification modality should be used to control which pest. Unlike chemical control strategies, which are characterised by homogeneous implementation regardless of the agronomic and pedoclimatic context, expertise is required to adapt plant diversification modalities to local production contexts. Also stressed is the importance of the objective sought by the farmer, particularly regarding rotations, which can be designed to meet various goals. For example, a rotation designed to improve soil fertility is not necessarily efficient in controlling pests.

In addition to the natural regulation of pests, plant diversification fosters associated biodiversity and ecosystem services provided to society

The quantitative review of the literature highlights a positive relationship between plant diversity (both cultivated and semi-natural) and associated biodiversity. The strength of this relationship varies with the modality of diversification: the most robust relationships are observed in agroforestry systems, whereas they are insignificant for varietal mixtures.

Understanding of the relationship between crop diversity and ecosystem services is fragmentary: certain services are poorly assessed (pollination, greenhouse gas emission mitigation), and certain modalities of plant diversification are poorly studied as to the provision of services (varietal mixtures, agroforestry in temperate zones, hedgerows). When these relationships are studied, they are mostly found to be positive. Once again, however, their intensity varies greatly depending on the diversification modalities considered.

Overall, the various diversification modalities are of varying degrees of interest in terms of preserving biodiversity and providing ecosystem services. Varietal mixtures show neutral relationships with biodiversity and services. Conversely, agroforestry (applied in tropical environments) is the most relevant method concerning these aspects. Intermediate cover crops, diversified rotations, hedgerows and intercropping are more or less in an intermediate position. Finally, introducing semi-natural vegetation (excluding hedgerows) is associated with higher biodiversity levels and ecosystem services than low diversity systems. Still, quantitative assessments are missing to position this plant diversification modality in relation to the others.

Plant diversification often results in higher yields than systems with little diversification

Yield depends on several factors, including losses caused by pests, but also the genetic potential of the plants grown, meeting the crop's nutrient and water requirements, pollination efficiency, and so on.

According to the literature reviewed in the CAS, crop diversification is usually associated with an increase in yield (compared with less diversified systems[75]). This yield gain ranges from a few per cent for varietal mixtures and intermediate cover crops in temperate environments to several tens of per cent in tropical agroforestry. Rotations and cash crop mixtures offer intermediate yield gains. The presence of semi-natural vegetation does not appear to impact the yield of the adjacent field. It should be noted that varietal mixtures help stabilise yields from one year to the next.

These orders of magnitude, taken from studies carried out worldwide, are largely confirmed by work which specifically analyses diversified systems deployed in agroecological and economic contexts comparable to France. However, some case studies have reported reduced yields. Lower yields are associated with using traditional or farmers' varieties (which is why they were historically replaced by certified varieties from varietal selection). A farmer's lack of expertise in managing diversified systems (for example, when introducing a niche crop into the rotation: hemp, spelt, etc.) can also cause yield fluctuations. Finally, introducing semi-natural features in or around fields tends to cause production losses, mostly due to the reduction in farmed area (assuming, however, that the potential value of this vegetation is not taken into consideration: wood, fruit, etc.).

75. Unlike the other diversification modalities, the yields of varietal or species mixtures are predominantly compared to untreated controls (experimental approach), primarily compared to conventional farming references (observational approach).

Plant diversification has contrasting effects on short-term farm profitability

The profitability of diversified systems is one of the critical drivers of their adoption, given the weight of economic aspects in the farmers' choices. Few research has evaluated the economic impacts for the farm of adopting plant diversification practices to protect crops. Such an assessment is made all the more difficult because the diversification modalities analysed affect the determinants of profitability in different ways. Additionally, plant diversification is often associated with other agroecological practices, which also affect profitability.

Cash crop mixtures is the most studied diversification modality, and it usually proves profitable despite the additional costs associated with agricultural equipment (sowing, harvesting and sorting). Adopting varietal mixtures does not seem to affect farm profitability significantly but can stabilise income. Although associated with lower yields, traditional or farmers' varieties in field crops can prove profitable in niche strategies when the farmer controls the product distribution through short distribution channels. In contrast, diversifying rotations and cropping pattern by introducing a new crop yields very variable results (with some positive effects, occasionally negative, often neutral). In general, lack of profitability stems from the fact that the new crops introduced are often, by definition, less profitable than those initially chosen by the farmer. Similarly, introducing semi-natural features is not deemed cost-effective without subsidies, at least in the short term.

Overall, the plant diversification modalities studied perform better economically in high pest pressure and low-input systems, particularly in organic farming. Economic profitability is also boosted in economic contexts where production prices are low (which attenuates the effects of yield losses) or high input costs (reinforcing the impact of input savings). However, the potential gains over a conventional production system are generally insufficient to encourage farmers to face the obstacles linked to the socio-technical organisation of the sectors and the interactions between players in the territories.

Methodologically, assessing the profitability of diversified systems is hampered by the failure to consider various factors:

- The time it takes to implement ecological mechanisms (fully effective after a few years in the case of landscape diversification, rotations and semi-natural vegetation) and/or the durability of the agroecological effects induced by plant diversification (i.e., inter-annual stabilisation of yields);
- The many positive externalities of plant diversification extend beyond the boundaries of the farm (diversification implemented on a farm can help to regulate pests on the scale of the landscape) and are not limited to pest regulation (provision of certain ecosystem services that benefit society);
- The matter of the 'social' profitability of production methods, including calculating the environmental and health impacts of crop protection strategies based on chemical control.

There are barriers to plant diversification within agricultural supply chains and in the territories

Production methods that prevail in the dominant conventional farming systems (based on the use of synthetic inputs) are characterised by systemic barriers that prevent diversification. As a result, implementing crop protection strategies based on plant diversification calls for systemic changes both upstream and downstream of the agricultural supply chains and in the relationship between the farmer and other territorial stakeholders. The obstacles to and levers of such strategies are rarely specific to one diversification modality. However, the literature does not help rank the weight of each obstacle and lever in adopting various diversification modalities.

Upstream of the farm, the availability of seeds and seedlings adapted to diversified systems is one of the factors most frequently mentioned in the literature. Besides the necessary investment in the breeding effort, sharing experience and exchanging seeds between farmers (perhaps combined with participatory breeding involving researchers and farmers) could help to overcome this obstacle.

Agricultural equipment adapted to diversified crops is not always available. This is particularly true for sowing and harvesting crop mixtures or certain niche crops and for maintaining semi-natural features. Equipment sharing (grouped purchases, provision of services) is mentioned as a lever. However, it requires a certain amount of coordination between users. Self-built equipment (adaptation of equipment) is also a way for farmers to reduce equipment costs.

The literature also often mentions inadequate knowledge (on the part of both farmers and advisers), a lack of technical and economic references and a lack of advice on how to run diversified systems. In addition to increased investment in R&D and consultancy, several levers are mentioned for which research has a role to play: on-farm experimentation, integration into a farmers' network, and access to decision-making tools and tools assessing the effects of diversification modalities (particularly their effectiveness against pests).

Downstream from the farm, another recurring barrier is the lack of outlets for products from diversified systems. Standard outlets require certain specifications that are difficult to achieve in a diversified system (varietal purity, compliance with size and appearance criteria, etc.). These barriers can be overcome by leveraging other characteristics specific to the products obtained in diversified systems (organoleptic, nutritional or environmental qualities, proximity, seasonality, etc.) in local channels and through certification, thus enabling a higher selling price. The absence of outlets can also be circumvented by switching to an on-farm processing business model (e.g., flour for cereals, preserves for fruit and vegetables), albeit with a higher workload. When semi-natural features are introduced onto the farm, the challenge is exploiting the wood produced by the hedgerows and tree lines in agroforestry systems *via* sectors often unfamiliar to farmers.

Finally, territorial coordination is essential if diversification is to be deployed on a landscape scale (spatial organisation of crops, installation of a network of semi-natural features) or to guarantee the sustainability of certain diversification modalities implemented on a field scale (to ensure the long-term effectiveness of varietal mixes, they need to be deployed on a landscape scale).

Plant diversification projects involving various stakeholders (farmers, agricultural advisors, agri-food manufacturers, cooperatives, water managers, non-agricultural associations, local authorities, etc.) are emerging but are still rare. The literature highlights the methodological difficulties in studying and managing territories due to the diversity of spatial and temporal scales and stakeholders involved. To overcome these difficulties, cross-disciplinary approaches have been developed that foster participatory research with the stakeholders concerned and thus facilitate the emergence of solutions acceptable to all.

Three levers were identified to promote territorial solutions:

- The fact that collective action generates a collective gain (i.e., eco-certification or payments for environmental services);
- Setting up collective organisations to manage agricultural areas (i.e., local collective institutions such as cooperatives) or centralised planning and incentives by public authorities;
- Product, farm and landscape certification to open more markets (i.e., catering markets).

Large-scale plant diversification implementation calls for ambitious public policies

Public policies, notably the Common Agricultural Policy (CAP), have been a powerful lever for initiating and supporting the modernisation of agriculture since the post-war period. Therefore, removing the systemic barriers of this highly stable dominant model requires ambitious public policies and changes to the legal framework governing agricultural area management.

Although the CAP has gradually introduced measures to reduce the environmental and health impacts of conventional farming, the actual results on the environment and biodiversity of agricultural areas are not obvious. The introduction of semi-natural features is a point in case: while the measures adopted in the 2014-2020 CAP seem relatively effective in preventing the destruction or degradation of existing semi-natural features, they are insufficient to encourage their expansion and have not fostered the development of agroforestry. The effectiveness of the measures implemented in France has not been assessed, but the fact that aid is spread across multiple measures does not appear to be enough of an incentive. Moreover, the legal context is not always consistent with public policy incentives.

Several political levers exist to support plant diversification rather than chemical control to protect crops. Subsidies for adopting diversification practices transfer the economic burden of environmental responsibility from the farmer to the community. Public policies can directly support the industry by targeting advice, research, investment assistance and market implementation. Such support may also be backed by payment for environmental services, given the many beneficial effects of diversification on biodiversity and ecosystem services supply. This type of support is generally welcomed by industry and local players. Still, it is hampered by budgetary constraints and complex technical implementation (calculating and evaluating environmental benefits).

Indirect support would involve correcting the market imperfections that currently favour conventional production systems which use synthetic inputs, particularly pesticides. This could involve banning the use of the most toxic pesticides or taxing them at a rate commensurate with the harmful externalities their use generates. This type of environmental taxation would reduce both uses and substitution mechanisms while generating revenue that could be employed to drive the change towards more virtuous uses, for example. Given the low elasticity of demand concerning the price of pesticides, high taxation (or taxation that increases rapidly over time) would be necessary to produce an effect.

It is still too early to evaluate the impact of the future CAP on plant diversification, and more research is needed to assess the effects of such measures. However, it is likely that, without a solid political will to set binding targets, crop protection strategies that are alternatives to the use of pesticides, including plant diversification, will struggle to emerge on their own and that the ambitious targets set by the European Green Deal will not be met.

By cross-referencing all the findings summarised in the CAS, plant diversification modalities can be placed according to the gradient of transformation of the cropping system that their adoption requires, in relation to their expected benefits.

• Varietal mixtures face several barriers at the industry level (supply of appropriate seed for the mixture, production outlets) but seem feasible in conventional systems without significant changes to management methods or equipment at the farm level. Nevertheless, their associated benefits regarding pest regulation and ecosystem services supply are also the lowest compared to other diversification modalities.

• Diversifying rotations by introducing a new crop into the farm's cropping pattern offers interesting potential for providing ecosystem services (including natural regulation of pests). Still, it comes up against obstacles both at the farm level (the challenges of managing a new crop and the need for new equipment) and at the industry level (lack of variety selection, advice and research for minor crops, limited outlets).

• Cash crop mixtures involve technical challenges (for sowing, harvesting and sorting) but they seem to be among the most profitable. This diversification modality uses a combination of mechanisms (dispersal barriers, allelopathy, etc.) to manage several pest types (weeds, insects, soil-borne pathogens).

• At the other end of the gradient are agroforestry systems (mostly studied in tropical contexts), which require the most significant transformations: fundamental redesign of the system, use of specific agricultural equipment, integration into forestry outlets, and complexity of the legal status. There is still much to be done in temperate environments to assess pest regulation through agroforestry. Still, the many studies of (sub)tropical agroforestry demonstrate the benefits of these complex covers in preserving biodiversity and providing a wide range of ecosystem services.

Introducing semi-natural features, particularly beneficial to biodiversity and the provision of ecosystem services, raises specific issues at the landscape level. In particular, it calls for coordination between different categories of territorial stakeholders and calls for public policies that provide incentives for spatial planning (e.g., to set up green corridors) that are challenging to design and implement.

Beyond the transition to synthetic input-free production methods that are more respectful of the environment, the development of agricultural systems must address the challenges of food security: ensuring sufficient food production in quantity and quality for the world's human population in the future, equitable access to food and food autonomy, within complex frameworks such as the global food transition (the place of animal products, among others) and global health (One Health). The CAS shows that plant diversification has excellent potential to help meet these challenges.

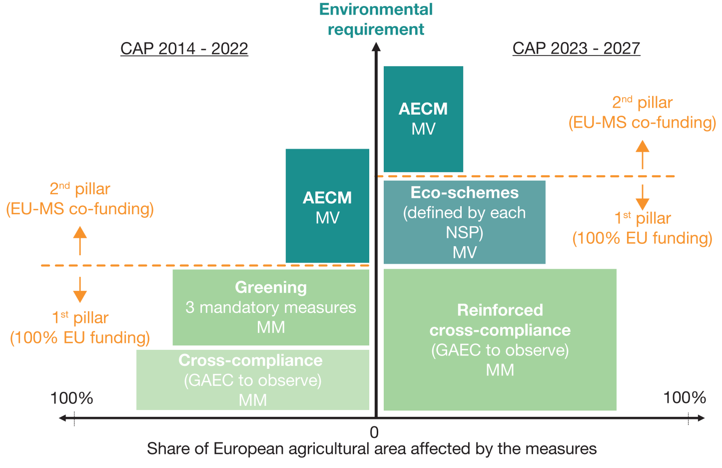
Annex. The turning point in the Common Agricultural Policy that paved the way for plant diversification

The environmental and health impacts of a highly productivist agriculture became more significant in the late 1980s with the increasing awareness of public opinion and public authorities regarding water pollution, biodiversity loss, and global warming. These impacts are part of the Brussels authorities' priorities when reforming the Common Agricultural Policy (CAP). Some authors attribute the CAP's environmental turning point to the 1992 reform, with the rise of multifunctional agriculture. Others put it later, during the Agenda 2000 reform, which established the second pillar of the CAP with the European Agricultural Fund for Rural Development (EAFRD) in 1999. However, the assertion that support under the first pillar of the CAP must be linked to the 'provision of environmental public goods' (public money for public good) first emerged with the concept of cross-compliance in 2003, then with 'greening' introduced in the 2014 reform (figure A.1). France supports this shift towards greener agricultural policies with measures that pave the way for plant diversification.

The new CAP, approved by the European Parliament and Council at the end of 2021, came into force on 1 January 2023.[76] This new programme is also part of the Green Deal, which aims to transform Europe's economy to meet sustainable development challenges by investing €1,000 billion over ten years to address climate change, promote a clean and circular economy, and halt biodiversity loss. The major innovation of this future CAP is the move from a centralised system, organised and controlled from Brussels and based on obligations on the Member States to provide resources, to a system granting greater responsibility and freedom of action to the Member States, which must set themselves objectives and demonstrate that they are achieving results. This paradigm shift is intended to foster a better application to local contexts and needs. In concrete terms, the European Commission proposes a common European framework (objectives, indicators to be achieved). Member States draw up National Strategic Plans (NSP) detailing how they intend to operationalise the broad categories of instruments provided for in the common framework. These NSP must then be approved by the Commission, which also carries out annual and multiannual monitoring to assess the results achieved by the Member States concerning the stated objectives rather than the means.

76. The negotiation process, the European Parliament and Commission renewal, Brexit and the health crisis have significantly slowed down the reform process. Hence, the CAP 2014-2020 programme was maintained in 2021-2022.

Figure A.1. Simplified representation of the architecture of Common Agricultural Policy (CAP) payments linked to environmental specifications. Adapted from Pe'er *et al.* (2022)



EU: European Union; MS: Member States; NSP: National Strategic Plan.
MM: Mandatory for MS and farmers; MV: Mandatory for MS and Voluntary for farmers.
AECM: Agri-environmental and climatic measures; GAEC: Good Agricultural and Environmental Condition(s).

Greening the 2014 reform: An admission of failure?

Green payments in the first pillar

In addition to making the payment of first-pillar aid cross-compliant with Good Agricultural and Environmental Conditions (GAEC)[77], the 'greening' of the 2014-2020 programming scheme conditioned receipt of first-pillar area payments on the implementation of three practices (figure A.1):

- Maintaining or restoring 5% of the farm's arable land as Ecological Interest Areas (EIA) for farms with more than 15 ha of arable land. EIAs include semi-natural infrastructures likely to host biodiversity (ponds, hedges, isolated trees and thickets, terraces, low walls) and areas likely to favour biodiversity by contributing to the reduction in chemical input use (fallow land, buffer strips, nitrate trap catch crops, winter cover);

77. Of the seven GAECs to be observed, three concerned plant diversification: GAEC 1 required establishing buffer strips along watercourses, GAEC 4 required minimal soil cover, and GAEC 6 required the maintenance of topographical features (hedgerows, ponds, copses). In fact, cross-compliance has proved relatively ineffective in increasing the environmental performance of agriculture due to an inadequate control system (CEC, 2008) and penalties that rarely act as a deterrent or are not even applied in the event of non-compliance with GAECs (Bodiguel, 2009; Desjeux *et al.*, 2011).

• Crop diversification. Cropping pattern must include at least two crops[78] (three for farms with more than 30 ha), with the main crop covering no more than 75% of the total area (and the minority crop no less than 5% for farms with over 30 ha);
• Maintenance of permanent grasslands[79] with a requirement not to increase the national ratio of arable land to permanent grassland by more than 5% compared with a reference period (2015 for most Member States) and a strict ban on reversing sensitive permanent grasslands (particularly those located in Natura 2000 areas, accounting for 1.18 Mha in 2021).

Yet most of the evaluation results for these measures show a very limited additional effect of these green payments on plant diversity on farms and landscapes. Simulations carried out by the Joint Research Centre of the European Commission (Louhichi *et al.*, 2018) show that at the European scale, only 4.5% of the utilised agricultural area changed allocation due to greening. The crop diversification measure, in particular, has had very little influence (only 1.8% of the area reallocated to other crops)[80].

The reasons for these globally disappointing results were documented by academic research and the European Court of Auditors (ECA, 2017). On the one hand, the targets set were relatively unambitious and already met by many European farms. In France, 85% of farms were already compliant with the greening measures before their introduction, so these measures only forced one farm in eight to introduce a new crop, on very small areas (Sauquet, 2021). On the other hand, many exceptions were introduced (farms with less than 10 or 15 ha of arable land, depending on the measure, and farms classified as 'green by nature', specifically organic farms). As a result, on the European scale, 45% of farms representing 14% of utilised agricultural area were not under greening obligations (Louhichi *et al.*, 2018). Added to this were the derogation regimes and exceptions negotiated by the Member States. In France, for example, the certification of specialist maize farms (particularly in Aquitaine) allowed these farms to maintain monoculture farming.[81] This is also the case with the extension of the definition of EIS to fallow land, leguminous crops and short rotation coppices in particular, allowing many cereal farms in central and northern France to comply with the required 5% EIS percentage without introducing natural infrastructures, only by slightly increasing their leguminous areas (Thoyer *et al.*, 2014). Regarding the permanent grassland measure, the option of a regional, rather than individual, target for the ratio of permanent grassland to arable land has also lightened the burden on farms.

Agro-environmental aids for the second pillar

The CAP's rural development policy relies, among other things, on agri-environmental and climate measures (AECMs) to support farms that voluntarily commit to developing (or maintaining) practices that combine economic and environmental performance. Specifically,

78. Crops are classified by botanical genus.
79. Area predominantly under grass or other herbaceous forage for at least five years.
80. Except in some European regions, which are characterised by intensive agriculture with a large amount of maize monoculture, such as Lombardy in northern Italy (Bertoni *et al.*, 2018).
81. Using the principle of equivalence to the green diversification measure: ensuring a winter soil cover.

AECMs are contracts signed with farmers, providing compensation for the additional costs and loss of income that these practices entail.

The 2014-2021 programme incorporates the same principles as the previous programme, with some encouraging plant diversification:

- AECMs based on a systems approach (arable farming, mixed crop-livestock farming, grazing and pastoral farming systems), thus encouraging the redesign of the cropping system at the farm level. The 'field crop' systems AECM requires a gradual increase in the number of crops (to reach a minimum of 5 different crops in year 5), the introduction of leguminous crops (at least 5% as from the second year), and a limit on same-crop rotations on a field. For 'grassland and pastoral' systems, this means maintaining the area under grass and improving biodiversity (through the presence of certain plants that indicate good health and diversity). For mixed farming, the requirement relates to the maximum proportion of maize in the forage area and the minimum proportion of grass in the utilised agricultural area (ratios set at the regional level);
- Localised AECMs to address regional agro-environmental and climate challenges. As opposed to system AECMs, localised AECMs concern commitments made only for specific fields on the farm, as well as for linear (hedgerows, trenches) or particular features (ponds, trees). Some AECMs directly concern the nature and diversity of the covers: the COUVER measures, which relate to soil cover (e.g., grass cover under woody crops, inter-row cover in vineyards, creation of grass strips), and the LINEA measures, which relate to the upkeep of hedges, trees, copses, embankments and riparian zones;
- AECMs to meet the objective of preserving genetic resources, particularly plant resources, by aiming to conserve or reintegrate into the production system locally and regionally adapted varieties threatened by genetic loss (vegetable crops, arboriculture and medicinal plants).

Given the short history of these measures, it is difficult to assess their effectiveness beyond a statistical analysis of the number of farms that committed and changes in the areas concerned. Hence, relatively few systems AECMs were used in France, particularly the one relating to arable crops, which is considered too restrictive (in 2020, according to the INRAE's Rural Development Observatory, 140 farms had committed to this AECM for 17,200 ha). For reference, an analysis of the impact of the 'systems' and 'localised' AECMs under the 2007-2013 CAP programme (Védrine and Larmet, 2021) showed that in France—except for the 'polyculture-ruminant livestock' systems AECM, which led to a significant increase in the number of crops of the order of 15 to 20% on beneficiary farms compared to equivalent non-beneficiary farms—the other measures had little or no effect on crop diversity. These findings are consistent with those obtained on the European scale, which highlight a positive average effect of the AECMs (overall) on the number of crops on beneficiary farms in Great Britain and Italy but find no significant impact for Germany, Spain and France (Arata and Sckockai, 2016). According to Védrine and Larmet (2021), localised AECMs had a moderate but real impact on improving the presence of semi-natural features in and around the fields involved.

The promises of the post-2020 CAP reform

Outlines of the environmental reform

The green payment introduced in the 2014-2020 programme is abandoned in the future programme. It was replaced by a more ambitious (reinforced) cross-compliance system that incorporates the requirements of green measures and the obligation for Member States to devote 25% of direct aid under the first pillar to 'eco-schemes' (figure A.1). Included in the first pillar, these programmes must be elaborated by the Member States as part of their NSP. They consist of annual environmental measures, proposed to voluntary farmers, that must exceed cross-compliance requirements. The total amount of aid targeted at climate and environmental issues must also reach 40% of the budgets paid out, and Member States may choose to transfer part of their budget from the first pillar to the second and vice versa. Safeguarding the budgets dedicated to the environment and climate and the increased flexibility of expenditure between the two pillars should, in theory, prevent a race to the lowest bidder and take into consideration the differing co-financing capacities of the Member States.

The French National Strategic Plan

The French NSP[82] describes, among other things, the reinforced cross-compliance measures and French eco-scheme around three key entry points. Note also that the future CAP includes a new crop insurance system in the second pillar, which may also impact farmers' diversification choices, as well as several new AECMs.

Within the first pillar, reinforced cross-compliance introduces new GAECs and strengthens existing GAECs to obtain the green payment under the 2014-2020 CAP. Obligations likely to have an impact on plant diversification now include a ban on converting permanent grassland and the protection of sensitive grassland, minimum soil cover during specific periods, a minimum threshold of 3% agroecological infrastructure on the farm and a minimum crop rotation base to reinforce crop diversity on the farm.

As for eco-schemes, according to the French Ministry of Agriculture, they are designed to be 'inclusive and non-discriminatory', 'accessible to all' and 'simple'.[83] The aim is for all production systems and all farmers to be eligible for one of the eco-schemes on offer, thereby maintaining their aid package. Several requirements were laid down in the specifications to achieve this. The eco-scheme is paid for all the hectares of the farm. There are three alternative ways of accessing this aid, each involving specific forms of plant diversification to a greater or lesser extent:

- Agro-ecological practices, in other words, implementing certain techniques that help reduce the use of pesticides, promote biodiversity and store carbon across the entire

82. https://agriculture.gouv.fr/pac-2023-2027-le-plan-strategique-national
83. Communication from the French Ministry of Agriculture on NSP arbitrations - https://agriculture.gouv.fr/reforme-de-la-pac-julien-denormandie-presente-les-arbitrages-du-plan-strategique-national (21/05/2021)

farm: maintaining a significant proportion of unploughed permanent grassland (80 to 90%, depending on the level of requirement); plant cover between rows (grass cover or mulch) for permanent crops (75 to 95% of inter-rows); maintaining cropping pattern diversity on arable land (measured by a points system, awarded according to the number of significant crop categories planted), with priority given to legumes, diversification crops and grassland;

• The 'landscape features and areas favourable to biodiversity' entry point, which involves dedicating at least 7% or 10% (depending on the level of requirement targeted) of the utilised agricultural area to agroecological infrastructures[84] or fallow land;

• Through the environmental certification of the farm, at least level 2+ certification to reach the low level, 'High Environmental Value' certification (HVE for ' Haute Valeur Environnementale')to reach the medium level, or organic farming (AB) to reach the high level.

Finally, a hedgerow bonus reflects France's ambition to restore these semi-natural features[85] by remunerating the presence of hedges (which must cover at least 6% of arable land) and their sustainable management (monitored through certification with the 'Label Haie').

The second pillar introduces flat-rate AECMs, in other words, paid per farm and not per subscribed hectare. Of note is the proposal for a new 'transition of practices' AECM with an obligation to achieve results (a personalised objective to be reached within five years), which aims to compensate for the risk of income loss associated with an agroecological transition (towards systems other than organic farming). The flat-rate remuneration will be calculated using the average characteristics of French farms (average utilised agricultural area in particular). Eligible objectives (to be prioritised by the regions) include reducing the use of pesticides by at least 30%, improving the carbon balance by at least 15%, and improving the protein autonomy of livestock farming, all of which are likely to contribute to plant diversification.

84. Excluding nitrogen-fixing crops and catch crops.

85. For the first two entry points, farmers can also claim an additional hedgerow bonus of €7/ha if they demonstrate (through certification, the principles of which must be laid down) that they manage their hedgerows sustainably, which must cover at least 6% of their utilised agricultural area.

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Vincent Martinet, INRAE, UMR[86] Paris-Saclay Applied Economics – Environmental and natural resource economics, ecological economics. Scientific co-lead.

Anaïs Tibi, INRAE, UAR DEPE. Project coordination.

Aude Vialatte, INRAE, UMR DYNAFOR – Landscape agroecology, natural regulation of pests. Scientific co-lead.

Main scientific experts: literature review

Audrey Alignier, INRAE, UMR BAGAP – Landscape agroecology: uncultivated part of landscapes, associated biodiversity and ecosystem services.

Valérie Angeon, INRAE, UR Écodéveloppement – Territorial economics, development economics; agroecological transition of overseas economies.

David A. Bohan, INRAE, UMR Agroécologie – Landscape agroecology; crop rotation diversification.

Douadia Bougherara, INRAE, UMR CEE-M – Agricultural and environmental economics, experimental economics; crop rotation and cropping pattern diversification.

Stéphane Cordeau, INRAE, UMR Agroécologie – Agronomy and agroecology; intra-field interspecific diversity.

Pierre Courtois, INRAE, UMR CEE-M – Environmental and natural resources economics; collective action coordination.

Jean-Philippe Deguine, Cirad, UMR PVBMT – Agroecology and crop protection; uncultivated part of the landscape, diversified systems in overseas France.

Jérôme Enjalbert, INRAE, UMR GQE – Population genetics, plant improvement; varietal and species mixtures.

Frédéric Fabre, INRAE, UMR SAVE – Plant epidemiology, landscape ecology; cultivated landscape diversity.

86. UMR: unité mixte de recherche (joint research unit); UAR: unité d'appui à la recherche (research support unit); UR: unité de recherche (research unit); US: unité de service (service unit).

Hélène Fréville, INRAE, UMR AGAP Institut – Evolutionary biology, population genetics, plant improvement; intra-field intraspecific diversity.

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Mourad Hannachi, INRAE, UMR SADAPT – Management sciences; coordination, collective action in territories and sectors.

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Stéphane Lemarié, INRAE, UMR GAEL – Industrial economics, innovation economics; intra-specific and interspecific intra-field diversity.

Gilles Martel, INRAE, UMR BAGAP – Zootechnics; integrated farming systems, crop diversification.

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N.B.: This list does not include researchers who may have been asked (by one of the above experts) to contribute on an ad hoc basis to the compilation of the bibliographic corpus, to the drafting of a section or the proofreading of texts. These researchers are cited in the CAS report, in the written submissions to which they contributed.

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Supervisory committee: Frédéric Fabre (INRAE, UMR SAVE), Nicolas Parisey (INRAE, UMR IGEPP), Lionel Roques (INRAE, UR BioSP), Olivier Therond (INRAE, UMR LAE).

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Supervisory committee: Corentin Barbu (INRAE, UMR Agronomie), Nathalie Delame (INRAE, UMR Paris-Saclay Applied Economics).

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Project management support

Marc-Antoine Caillaud, INRAE, UAR DEPE – Assistance for the organisation of the final symposium.

Kim Girard, INRAE, UAR DEPE – Administrative and financial management, logistics management.

Sandrine Gobet, INRAE, UAR DEPE – Administrative and financial management, logistics management.

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Figure 1.8: Wheat-pea mixture © Audrey Alignier

Figure 1.10: Examples of agroforestry systems in France: (a) *pré-vergers*, (b) barley-walnut, (c) vegetable-fruit © INRAE ; (d) Creole garden © Virginie Ravigné

Figure 1.12: Examples of semi-natural features: (a) bocage, (b) flower-filled fallow land © INRAE ; (c) grazed moors with peat bogs © Anaïs Tibi

Figure 1.15: Diversified agricultural landscape with grassland, hedgerows and woodland © Aude Vialatte

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The advent of synthetic fertilisers and pesticides freed farmers from yield-limiting environmental constraints while simplifying agricultural fields and landscapes. The environmental and health impacts of this dominant model, as well as its interrelationships with climate change and biodiversity loss, are now well established by the scientific community.

Although there is increasing societal demand for agriculture that meets food demand while respecting the environment and human health, the agro-ecological transition of cropping systems is insufficiently engaged. One of the reasons put forward for this inertia is the lack of effective alternatives to pesticides to protect crops.

This collective scientific assessment looks at crop protection strategies based on plant diversification in agricultural areas and analyses the obstacles and levers to their adoption by farmers. It is part of the Écophyto 2+ plan, which supports the production of knowledge and tools needed to reduce synthetic pesticide use.

This book is intended for teaching professionals, researchers, students, stakeholders in the agricultural world, land managers, environmental organisations and associations, and any citizen interested in such issues.

Anaïs Tibi is a research engineer at INRAE. She coordinates the production of multi-disciplinary knowledge reviews to inform public decision-making on issues at the crossroads between agriculture, food and the environment.

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