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TOWARDS PESTICIDE-FREE AGRICULTURE

Research and innovations in a future crop protection paradigm

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Foreword by Philippe Mauguin, CEO of INRAE

Éditions Quæ
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To quote this book:
Jacquet F., Jeuffroy M.-H., Jouan J., Latruffe L., Le Cadre E., Malausa T., Reboud X., Huyghe C. (eds), 2024. *Towards pesticide-free agriculture. Research and innovations in a future crop protection paradigm*. Versailles, éditions Quæ, 224 p. DOI : 10.35690/978-2-7592-3995-5

print ISBN: 978-2-7592-3994-8
PDF ISBN: 978-2-7592-3995-5
ePub ISBN: 978-2-7592-3996-2
ISSN: 1777-4624

Éditions Quæ
RD 10
78026 Versailles Cedex
www.quae.com
www.quae-open.com

Summary

Foreword

The intensification of our agriculture has led to a considerable increase in agricultural and food production, both in terms of quantity and quality making it possible to ensure an affordable food to all. But it has also generated negative impacts that are now well-documented. Chemical pesticides are at the very heart of this tension. Given their impact on biodiversity and health, gradually phasing out chemical pesticide use has become a major challenge, in France, in Europe and in many countries across the world. With this in mind, since the Grenelle de l'Environnement political meetings in 2007, the French governments have committed agricultural stakeholders to a thorough change in order to move towards more productive, agroecological agriculture that provides more respect for the environment and human health. In line with the European directive on the use and impact of plant protection products compatible with sustainable development, this commitment has been translated at the French scale into the "Écophyto" plan.

The transition of agriculture towards more sustainability while ensuring a decent income for producers and a high level of production concerns all citizens and must be endorsed by all socio-economic stakeholders. It also requires special efforts in research and innovation because the transformation of production methods must be based on scientific knowledge that offers farmers new solutions for all situations of crop protection.

To support the Écophyto plan's initiatives, the French government launched in 2020 a Priority Research Programme (known in French as a PPR) to accelerate research and the acquisition of fundamental knowledge, exploring all the horizons that can be employed for a progressive phase-out of pesticides. With a budget of €30 million and a duration of six years, the PPR was created to mobilise researchers in all relevant disciplines. An appropriate framework for the exploration of scientific fronts has been defined: the ultimate goal is to be able to produce crops with no chemical pesticides at all. As this book demonstrates, the choice of an ambitious target for the potential complete elimination of pesticides enables us to explore scientific avenues that will lead to breakthrough innovations, mobilizing systemic approaches and multiple levers that are not only biotechnical, but also organizational and societal, ultimately enabling a significant reduction in the use of pesticides. The prospect of low-pesticide agriculture, reaffirmed by the President of the French Republic at the World Biodiversity Summit in Marseille in October 2021, is in line with Europe's Green Deal ambition to reduce pesticide use and impact by 50% by 2030, i.e. in a very short space of time. The need for research and innovation is therefore considerable.

The PPR "Growing and Protecting Crops Differently", scientifically coordinated by INRAE, is currently funding 10 ambitious projects providing structure for scientific communities. These projects bring together numerous research units from France's universities and national research organisations. The approaches are mainly interdisciplinary, and their content combines fundamental research with studies on the practical application of innovative methods. For example, fundamental approaches concern our understanding of the biological mechanisms involved in crop health and the prophylactic measures needed to achieve this objective. Applied approaches are conducted in partnership with agricultural stakeholders and concern the deployment of new crop protection methods and the technical and organisational innovations required. The size and duration of these projects will encourage the long-term structuring of scientific communities on highly promising topics such as understanding plant microbiota and its influence on plant health, epidemiological monitoring methods for prophylaxis, the co-design of cropping systems, the creation of resistant varieties, species and variety mixtures, the diversification of cover crops, the spatial organisation of crops in the landscape and new biocontrol methods, alongside public policies and collective organisation.

In addition to the research projects, the programme overall management involves initiatives to maximise the impact of this research. Original approaches for impact analysis are being developed throughout the programme and its various projects. A foresight study has been conducted to figure out what pesticide-free European agriculture would look like in 2050, leading to three contrasting scenarios where biological breakthroughs are required, where the transition pathways have been documented, scenarios being illustrated through four case studies across Europe. At the same time, symposia and events involving both national and international scientific communities and agricultural stakeholders are being organised. These events provide an opportunity to share the progress of the projects, as well as their achievements, facilitating the transfer of knowledge and solutions to farmers and society at large.

All this knowledge and possibly disruptive innovations are becoming available at the very moment when, in France, a new ambitious plan is being implemented. Named Parsada, its ambition is to provide alternatives to 75 molecules that are at threat in the coming 5 years for re-approval. As they are massively used in the French cropping systems, it is compulsory to re-design cropping systems where crop protection has to be ensured. The achievements of the PPR are of upmost importance to reach these new goals.

This ambitiously titled book was coordinated by the researchers who scientifically defined and presently manage the programme. It illustrates the programme design approach through an initial review of the issues involved in phasing out pesticides, the knowledge already available and promising avenues of research that could make it possible to grow and protect crops differently without the use of chemical pesticides.

The "Growing and Protecting Crops Differently" programme demonstrates the originality of the scientific dynamics introduced. Advances in our knowledge will produce the information needed and innovations required to avoid the need for pesticides. This approach was conceived from the outset on an international and, particularly, European scale, as illustrated by the European Research Alliance "Towards a Chemical Pesticide-Free Agriculture" supported by France, Germany and presently a total of 37 research organisations from 21 European countries. This European Alliance is the cradle for emergence of ambitious projects and initiatives to foster production of knowledge, co-design of innovation and support to public policies. The ambition of both the French programme and the European Alliance is to contribute to European strategies for agroecological transition, food security and the restoration of agricultural environment.

I am convinced that those involved in research and education, as well as all the professionals concerned by the changes to be implemented in agriculture, will find in this book resources to fuel their reflections, decisions and actions. I hope that this collective effort will enable our societies to make the ambitious and essential transition to sustainable and competitive agricultural production methods that will guarantee affordable and healthy food for all, and a safe environment for future generations.

Philippe Mauguin
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l’Alimentation et l’Environnement — French national institute for research
on agriculture, food and the environment)

Introduction

Research for pesticide-free agriculture: A disruptive framework today to build tomorrow's solutions

Christian Huyghe, Florence Jacquet, Julia Jouan

Agriculture is one of the economic sectors to have undergone the most upheaval in the 20th century, seeing an unprecedented intensification of agricultural production. This intensification has made it possible to increase food production volumes, ensure food safety and reduce food costs, which were major challenges for post-war French and European agriculture. To achieve this, highly simplified cropping systems with a limited number of crops and standardised practices became widespread on most farms, whose average size and surface area per worker gradually increased. With the aim of increasing the quantity and quality of crop production, we have gradually built systems that are increasingly susceptible to pests and have created conditions that are conducive to pest development. Crop protection has therefore become a major issue. The intensive systems that have developed are, by definition, dependent on inputs: fertilisers for fertilisation and, the subject of this book, pesticides for crop protection. Throughout the book, the term "pesticide" will be used to designate both synthetic and natural pesticides with a significant impact on environmental and human health.

Over the past few decades, numerous pesticides have been developed to meet growing needs, drawing on major technological advances in the agrochemical industry. While the objective of effectively protecting crop health has been achieved, this massive use of pesticides has had a number of consequences on environmental and human health, despite the rules on toxicity and ecotoxicity that govern marketing authorisation procedures. The negative consequences for biodiversity are significant, both directly, through the biocidal effect of the substances used, and indirectly, through the profound evolution of cropping systems and the agricultural landscapes that have been shaped over time (Sánchez-Bayo and Wyckhuys, 2019), leading to a poorer control of pests (Ziesche *et al.*, 2023). Numerous scientific studies also give evidence of the multiple repercussions on human health, for pesticide users, consumers of agricultural products and neighbours living close to treated plots. All these impacts, sometimes referred to as the "hidden costs of pesticides" (Bourguet and Guillemaud, 2016), have been quantified, from losses linked to the disappearance of pollinators (Costanza *et al.*, 1997) to impacts on health, particularly for farmers (Goeb *et al.*, 2020).

Against this backdrop, reducing pesticide use is a major societal challenge that has been on French and European political agendas for more than a decade. Directive 2009/128/EC requires all European countries to reduce pesticide use and the impacts of pesticides on the environment. In France, this directive has been translated into the "Écophyto plan", which in 2008 set the target of reducing pesticide use by 50% "if possible" over 10 years. The words "if possible" reflect political caution, but also the extreme technical, economic and organisational difficulties of making such a change while ensuring a profitable crop production. The evolution of pesticide purchases in France, commented on at length every year when it is published, confirms the difficulty of the transition while, at the same time, assessments of the state of the environment, and in particular the collapse of biodiversity, confirm the urgency of the transition. In 2020, the European Green Deal, notably through the Farm to Fork strategy, took a further step forward by setting a new target: a 50% reduction in pesticide use by 2030. A recent report stresses that this objective can only be achieved at the cost of profound changes, both within agricultural sectors and in agronomic research (Guyomard *et al.*, 2020).

For many years, various research and development projects have been conducted to help reduce pesticide use. They have been supported by European and national public policies, notably the French Écophyto Plan. They showed that reductions of 20% to 30% in pesticide use are possible, in most cases without decreasing farmers' incomes. This has also been evidenced in the French DEPHY farm networks in various agricultural sectors, where farmers have been able to voluntarily deploy many of the technical levers available, benefiting from extensive support from the DEPHY network extensionists. The absence of negative economic impacts was confirmed by Lechenet *et al.* (2017) for a large majority of arable crops. Only cropping systems with a strong presence of industrial crops (potatoes and sugar beet) showed the risk of a loss of income. The changes in practices needed to reduce pesticide may take time to generalise nationwide, as pesticide use increased until 2017 (by 15% between 2010 and 2017 in total volumes) and is now showing a decline in volume in the most recent years, especially for the most harmful chemicals, while a steady increase was observed for the biocontrol products.

This inertia can be explained in part by technical bottlenecks, but above all by socio-economic factors. The entire agricultural sector is "locked in" to pesticide use. Not only farmers, but also upstream actors (equipment manufacturers and input suppliers) and downstream actors (processors and retailers), have adapted their strategies, and their relationships with other actors, to the availability of pesticides. This lock-in is reinforced by the need and weight of specific investments (Schreyögg and Sydow, 2011; Valiorgue, 2020) linked to specialised intensive systems and the production they generate, both for farmers and for downstream storage and processing companies. This lock-in also affects genetic diversity, since access to new varieties or species is limited both by the supply provided by plant breeding companies, whose programmes have long been driven by the search for intensification, and by the registration in national and European catalogues of varieties whose registration rules correspond to the dominant system (Bollier *et al.*, 2014).

Agricultural research itself is affected by this lock-in because the development of research programmes within a framework where pesticides are still used, means breakthrough or disruptive innovations are less likely to emerge. From this point of view, a review of the research projects carried out before the launch of the Priority Research Programme “Growing and Protecting Crops Differently” in 2019, both in France and at the European scale, is enlightening. While there were a few trials in conventional agriculture aiming for the total elimination of pesticides, almost all R&D projects at this date focused on the objective of a more or less significant reduction. Only a minority of projects aimed at managing pests without the use of synthetic pesticides. This raised questions about the social, economic and technical conditions that are conducive to a sharp reduction in pesticide use. The questions are still topical: do we have the knowledge and the means to reduce pesticide use on all crops? What resources do we need to avoid using pesticides? How should farmers, and the agricultural sector as a whole, adapt their activities? What is the role of research in making this change possible?

The Priority Research Programme “Growing and Protecting Crops Differently”[1] takes an original approach. Launched in 2019 to support the Ecophyto’s Plan, with a budget of 30€ million and a duration of 6 years, it posits the extreme scenario of pesticide-free agriculture, which is not prescriptive but requires the exploration of new avenues of research. It is a non-prescriptive scenario because this Priority Research Programme does not *a priori* lay down a path for farmers to follow, as this path should be debated with farmers and society in light of the knowledge currently available. The aim is to undertake research within this pesticide-free framework in order to explore new scientific fronts and develop knowledge and solutions available both for a significant reduction in pesticide use in the short term and for future innovations. In the longer term, and thanks to these innovations, the aim is to develop pesticide-free agriculture for all crops and in all regions. By setting such a course, we can both open up new avenues of research and generate the knowledge needed to build tomorrow’s solutions to meet society’s demands for pesticide-free agriculture. A similar approach was defined to build a European Research Alliance named “Towards chemical pesticide-free agriculture” which presently gathers 37 research organisations from 21 European countries. The Priority Research Programme’s ambition is to call for a change of perspective in order to promote progress on promising scientific fronts that are new or insufficiently explored. It concerns many areas of both the biotechnical and social sciences, and involves a thorough change of scientific disciplines integrating new issues and working in a coordinated way.

The Priority Research Programme is structured around three main principles of action, which form its scientific guidelines: promoting disease control, developing agroecology and mobilising all stakeholders in the agricultural sector.

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[1] https://www.cultiver-proteger-autrement.fr/eng

⏩ Promoting prophylaxis

Prophylaxis covers all the means used, apart from pesticides, to prevent the appearance or development of pests. Prophylaxis is one of the main ways of avoiding pesticide use as it aims at reducing the pressure exerted by pests, including weeds and diseases, on crops and at keeping the pest pressure below the nuisibility thresholds. The term pests used throughout this book corresponds to what we commonly regard as pests. These are organisms liable to cause direct or indirect crop losses through reduced yields, altered nutritional, organoleptic or visual qualities, or additional harvesting or grading costs (Aubertot *et al.*, 2006). Thus, the main pests include weeds, fungal pathogens and insect pests. Currently, pest control as practiced in France relies heavily on the systematic application of curative (mainly biocidal) pesticides when the pest is visible, and often when it is not. Meynard *et al.* (2009) illustrate how crop protection practices have evolved over time with the development of chemistry, genetic improvement and the disappearance of prophylaxis. It is now essential to reverse this approach and promote prophylactic approaches in the first place. Several prophylactic practices are already understood and form part of what is known as Integrated Pest Management (IPM). However, they have only been studied in a segmented way and have only concerned a small number of species or production systems. Prophylaxis often requires production systems redesigning and anticipation. The incidences of these requirements on adoption by farmers have been underestimated. Research is therefore needed to broaden the knowledge base on practices that reduce pest pressure, promote prophylaxis and enable efficient pest management. The question of the distinction between these practices and current organic agriculture practices also needs to be clarified here. Organic agriculture bans the use of synthetic pesticides, but authorises specific substances of natural origin whose effects on the environment can be negative, such as copper sulphate (Andrivon *et al.*, 2018). It also excludes the use of synthetic mineral fertilisers, which is not the case with our approach. However, organic agriculture, through its specifications, has explored practices and systems that may constitute sources of inspiration for the work done in this Priority Research Programme and, conversely, the research avenues explored in the Priority Research Programme should benefit organic agriculture.

⏩ Developing agroecology

Agroecology is a particularly rich framework for developing more sustainable agriculture. The term is polysemous, designating a scientific discipline, a set of practices and a social movement (Wezel *et al.*, 2009). Agroecology is now widely mobilised by many actors. One of the basic principles of agroecology is to increase functional diversity in order to enhance biological regulations and ecosystem services (Mauguin *et al.*, 2024). Hector (1999) published a seminal work on grasslands, demonstrating that increasing the number of plant species and functional groups can boost biomass production. Of course, this diversification concerns cash crops, with a diversification of sequences, but also intra-plot diversification, with species mixtures such as cereal-protein crop mixtures, whose prophylactic effects have been demonstrated

(Stomph *et al.*, 2020; Tamburini *et al.*, 2020; Beillouin *et al.*, 2021). Furthermore, agroecology also leads us to think differently about crop cycles and integration of cover crops. First, we need to take a rational approach to the use of service species, for their effects on trapping excess nitrogen, storing carbon in the soil (Bolinder *et al.*, 2020) and pollinator activity (Gallot *et al.*, 2016), and also for pest control (INRAE, 2022). The next step is to conduct research on the length of crop cycles and their organisation over time. For example, relay-cropping, in which crop n+1 is sown in crop n a few months before the latter is harvested, opens up an original avenue, with significant increases in production and a sharp reduction in the need for crop protection (Gesch *et al*, 2023). However, it also induces new needs for agricultural equipment and suitable varieties (Tanveer *et al.*, 2017).

The increase in functional diversity promoted by agroecology needs to be considered at different spatial scales, from the plant and the agricultural field through to the landscape, and different time scales. For example, crop diversification on a rotational scale, or grassed or flower strips around fields, contribute to an increase in functional diversity. This concerns not only plants, but also animals and microbial communities. Indeed, the communities grouped under the term “microbiota” (Rout, 2014), which are present in plants and on the surface of leaves and roots, represent an often overlooked but promising aspect of biodiversity (Dini-Andreote, 2020; Patle *et al.*, 2018). In this vision of agroecology, it is also necessary to account for soil and how it functions as this has a major influence on biological regulation, plant nutrition and therefore pest management. Finally, agroecology also concerns landscape scales, where functional diversity is also organised. Based on a study of more than 500 sites worldwide, Sirami *et al.* (2019) have shown that increasing landscape heterogeneity increases multi-trophic diversity of insects in these environments and, therefore, pest regulation capacities. Landscape heterogeneity is directly linked to crop diversity, the proportion of semi-natural areas and the average size of cultivated plots. Since a smaller average plot size is more likely to promote the spatial heterogeneity of crops and multi-trophic diversity, questions obviously arise with regard to the evolution of farms, in size and structure.

By understanding the biological mechanisms at work, agroecology allows us to take a fresh look at biocontrol levers, not as a substitute for pesticides but as a means of boosting functional diversity, promoting biological regulation and therefore limiting the impact of pests, thus reducing the needs for pesticides. Similarly, increasing functional diversity benefits to the plant nutrition and recycling of nutrients, thus reducing the needs for exogenous fertilisers. Through its various levers, the development of agroecology necessarily leads to an increasing complexity in cropping systems. This is diametrically opposed to the trend seen over the past 50 years, where the quest for on-farm economic performance has led to the simplification of cropping systems and the regional specialisation. This has led to a reduction in crop and landscape diversity, the disappearance of semi-natural areas and agroecological infrastructure, and an increase in plot size. Research is therefore needed to enable systems to become more complex, especially as this will need to be adapted to different soil and climate conditions. However, in the past, simplifying production systems enabled reducing each farmer’s workload and mental burden. Therefore, we must not underestimate the fact that the complexity of agroecology can act as a brake on its development. How can we prevent a complex system from being complicated to manage? Agricultural extension services, in particular training and advice, will have to address this issue, while digital and agricultural equipment solutions will have to support and facilitate the development of agroecology.

⏩ Mobilising all actors in the agricultural sector

The move towards more diverse production requires the mobilisation and transformation of all actors in the agricultural sector, both upstream (equipment manufacturers, input suppliers and plant breeders) and downstream (processors, retailers and consumers). Indeed, crop diversification and the introduction of new practices based on agroecology and prophylaxis will lead to new needs: the genetic improvement of diversification crops and service plants, and the adaptation of equipment for sowing in relay-cropping, harvesting of crop mixtures and mechanical weeding. Innovations are also expected to facilitate the application of biocontrol products and automatic monitoring of crop health for prophylactic control (Basso *et al.*, 2023). In addition to technical innovations to support changes in farming practices, various actors in the agricultural sector will also need to adapt their tools and strategies.

New agricultural raw biomass will be produced, leading to changes downstream: less standardised harvested products for species that are already cultivated, species harvested in mixtures, and new crops and harvested products. Therefore, it will undoubtedly be necessary to develop coupled innovations between the agricultural and agri-food sectors so that new crops meet corporate strategies and consumer demand while ensuring a profitable price for farmers (Meynard *et al.*, 2017). Product differentiation will be undoubtedly essential in order to enhance the value of pesticide-free production through consumers' identification and recognition of a product's characteristics. Pesticide-free agriculture therefore requires a rethinking of the entire food system. Digital tools can play an important role in facilitating product traceability and the ability to document raw material qualities in real time. Public policies, including official quality labels along with private standards, will be essential levers to pave the way for such a transition. Consumers will also have to change their diet if this rethinking of the entire system is to succeed. The demand for cheap and visually perfect products is not compatible with the requirement for pesticide-free production. Increasing legume production, which is essential for crop diversification and also meets the objectives of reducing nitrogen fertiliser use and greenhouse gas emissions, can go hand in hand with changes in consumption patterns and diets that include more legumes (Magrini *et al.*, 2018). Behind this necessary mobilisation of all stakeholders around pesticide-free agriculture, ultimately lies not only accounting for environmental protection and health, but also ensuring the ability of future generations to produce, as a common good.

Last but not least, it is important to stress the importance of involving, in the research that needs to be conducted, the various actors in the agricultural sector (Beaudouin *et al.*, 2022). In particular, innovations aimed at achieving pesticide-free production must be designed and managed in close collaboration with the stakeholders concerned. This approach is even more important as many of the solutions that need to be developed will not be generalisable everywhere, and will need to be adapted to each situation, in terms of soil, climate and/or biological environments, or market conditions. We therefore believe that, by implementing innovations that consider the resources, objectives and constraints of the actors involved, it will be possible to embark agricultural sector as a whole in radical transformations.

This book presents the current situation regarding pesticide use in France and develops five complementary levers for action that can be introduced and combined to grow and protect crops differently, without pesticides. The first two chapters introduce the issues addressed in the book. Chapter 1 presents the historical factors that explain the current intensive use of pesticides and the environmental and health problems to which this use has led, as well as the various initiatives that have been taken to reduce pesticide use. Chapter 2 sets out the reasons for today's dependence on pesticides, and why the two main strategies available to grow without pesticides, IPM and organic agriculture, are currently not sufficient. The following chapters develop the different levers for action for pesticide-free production. Chapter 3 focuses on the design of cropping systems, which is central to approaches that aim at in-depth changes in terms of crop protection. Chapter 4 details the innovations expected in biocontrol, illustrating the different scientific fronts that have recently been opened up and that offer new perspectives, while also analysing the current obstacles to the development of biocontrol. Chapter 5 outlines future research in plant breeding and plant genetics. Chapter 6 presents the expected developments in agricultural equipment and digital technology, enabling in particular to limit the use of herbicides, adapt equipment to different contexts and modify decision-making. Chapter 7 details the various political and organisational levers that need to be introduced to encourage the transition to pesticide-free agriculture. Finally, the conclusion puts the issue of pesticide-free production into perspective with regard to the other challenges of developing sustainable agriculture.

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Chapter 1

Overview of pesticide use

Florence Jacquet, Julia Jouan

⏩ Crop protection: A historic lever for increasing agricultural production

Crop protection as we know it today began with the development of synthetic pesticides in the 20th century. These inputs, along with other technological innovations in genetic improvement and fertilisers, significantly increased agricultural production in France and around the world. However, their impact on the environment and human health has now become a major social concern. A desire to reduce the negative effects of intensified agricultural production has emerged since the 1990s, through various reforms of Europe's Common Agricultural Policy (CAP) and changes in regulations concerning pesticide use.

Crop protection has been around since the advent of agriculture

Since the advent of agriculture, pests have represented a danger to plant production and farmers have always sought ways to protect cultivated plants. The first techniques employed were manual weeding to control weeds and hand-picking of insect larvae. For diseases caused by microorganisms, there were no means of control other than the selection of resistant varieties. However, evidence of disease control dating back to 2,500-1,500 BCE has been found, in the form of insecticides and fungicides, particularly sulphur-based, by Sumerian and Chinese growers (Oerke, 2006). In the West, throughout Antiquity and the Middle Ages, pest development was likened to divine punishment, for which the only means of control was submission to God (Poulain, 2004). Even the advent of the microscope in the 17th century, which led to the first observations of pathogenic fungi, failed to make the link between plant disease and microorganisms. It was not until 1807 that a fungus (*Tilletia caries*) was shown to be responsible for the wheat disease known as bunt: copper was then suggested as a control method. Despite this discovery, crop protection remained in its infancy. Soon after, Ireland was hit by a terrible famine (1845-1847) due to potato blight, a disease caused by the *Phytophthora infestans* oomycete. From 1864 onwards, it was France's turn to experience a major health crisis, this time caused by an insect: the grapevine aphid *Daktulosphaira vitifoliae* (Box 1.1). Imported from the United States, this aphid destroyed a large proportion of French vineyards in just a few years. It was not until more than 30 years later that a control solution was found. This comprised of grafting French vine plants onto rootstocks derived from American plants which were naturally resistant to phylloxera.

Box 1.1. The phylloxera crisis: millions of hectares of vineyards destroyed

In the early 1860s, some vines in the south of France were affected by a mysterious disease. Galls (blisters) appeared on the leaves, which gradually turned yellow, with the vines eventually dying three years later. The disease quickly spread to several wine-growing regions in France and elsewhere in Europe. Numerous experts were dispatched to the vineyards and the culprit was eventually identified. It was a sucking aphid that attacks the roots until the sap is exhausted. Its reproduction method enables it to rapidly colonise large areas on a massive scale. In spring, a wingless female hatches from an egg called a winter egg. As an adult, she lays between 40 and 100 eggs, all of which also give rise to females, without fertilisation. This is known as thelytoic parthenogenesis. This 20-day cycle is repeated several times, giving a total of five or six generations. In summer, these females transform into winged phylloxera, which spread to other vineyards with the wind, and lay new winter eggs by mating with males.

Years went by, but no solution was found to counter the aphid, despite numerous trials of various substances designed to kill the insects. The Ministry of Agriculture even went so far as to offer a prize of 20,000 francs to the person who could find an effective remedy against phylloxera. Eventually it was discovered that American vine plants, imported before the crisis, were resistant to the disease. But it took another 30 years to find the solution: grafting European plants onto American rootstocks which were resistant to the aphid. A considerable amount of work then went into rebuilding the vineyards using these grafted plants. Nevertheless, the economic consequences of the crisis were terrible. The Cognac vineyard is a striking example: in 1865, it covered 285,000 hectares, but by 1928 only 70,000 remained, bringing ruin to many winegrowers (Lachiver, 2002).

A major step forward in crop protection came at the end of the 19th century with the development of inorganic chemistry. Still based on copper, the first pesticides were developed and marketed on the basis of the scientific advances of the time, rather than a purely empirical approach (Bonnefoy, 2012). The use of copper sulphate-based fungicides (Bordeaux mixture) became more widespread for controlling certain fungal diseases in vines and late blight in potatoes. At the beginning of the 20th century, varieties resistant to mildew pathogens were developed, alongside plants resistant flax and cereal rusts. From the 1930s onwards, chemical control complemented genetic control with the rapid development of synthetic pesticides. This was closely linked to advances in organic chemistry. DDT (dichlorodiphenyltrichloroethane), the first organochlorine pesticide, was launched on the market in 1939 and gradually became the leading insecticide until the 1970s. Research into chemical weapons, and in particular poison gases, carried out during the World Wars, also led to the discovery of new organic compounds. The first organic herbicides, nitrated dyes, were used on cereals as early as the 1930s (Figure 1.1). Other pesticides, equally effective and inexpensive, were developed after 1945, such as the first synthetic insecticides (organophosphates and organochlorines). Since then, many other types of pesticide have been developed (see Box 1.2). Pesticides are one of the mainstays of conventional agriculture and have contributed to achieving food security in many European countries (Bonnefoy, 2012).

Box 1.2. Different types of pesticide

In this book, we use the term "pesticide" to refer to both synthetic and natural pesticides with a significant impact on the environment and human health. Pesticides encompass different families of products designed to control undesirable organisms. In this book, we are concerned only with pesticides used to control plant pests, or plant protection products, and therefore exclude biocides (such as disinfectants) and antiparasitics for human and veterinary use (e.g. against lice and fleas). There are three main types of pesticide, depending on their target:
- Fungicides, which target parasitic fungi.
- Insecticides, which target harmful insects.
- Herbicides, which target weeds, i.e. plants considered undesirable in crops.

There are also pesticides against other targets: bactericides and acaricides (often included in fungicides and insecticides respectively in official statistics), molluscicides, rodenticides and nematicides, as well as various substances with a repellent effect to manage depredation by birds or large mammals. In addition, certain products, which are often included as plant protection products, do not have a pest control action, but act on plant growth. Growth regulators, for example, limit the length of wheat growth and preventing lodging, which can occur in particular climatic conditions (rainstorms and strong winds).

Pesticides can also be classified according to their chemical family, their danger to the environment or health, or the way in which they are used. For example, insecticides and fungicides can be used to treat the aerial parts of plants, as well as seeds and soil. Herbicides, for their part, can be used to weed between crops of interest (such as between vines), or to destroy plant cover between two crops, in addition to or instead of tillage.

With the development of chemistry, pesticides have become progressively more complex in order to improve their efficacy (Bonnefoy, 2012). From a single active substance, several formulas can be developed, multiplying the number of pesticides marketed. In total, around 500 active substances are marketed in France in one or more of the 1,700 pesticide formulations listed in the country's Banque Nationale des Ventes de Distributeurs (Ministry for Ecological Transition, 2019).

A pesticide is generally formulated from several molecules comprising:
- The active substance producing the toxic effect on the pest.
- A diluent incorporated into the product to lower the concentration of active substance (e.g. a solvent for liquid pesticides).

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– Adjuvants, which modify the qualities of the pesticide to make it easier to use or more effective (e.g. to enable better penetration into the plant in the case of a herbicide).

So, in addition to the active substance, a marketed pesticide includes a range of other chemicals which can play a significant role in the toxicity of the final product.

Intensifying agricultural production with pesticides in the 20th century

From 1945 onwards, France, alongside other European countries, sought to increase agricultural production to feed its population and achieve food security in terms of basic agricultural products. The strategy adopted was agricultural intensification, based on three pillars: genetic selection, chemical inputs and mechanisation. Genetic selection and the use of chemical inputs considerably increased crop yields, while mechanisation facilitated the use of these inputs and farmers' work in general. Although substantial progress has been made in disease resistance, varieties have long been bred with productivity as the main goal. Varieties with high yield potential have been developed thanks to the use of fungicides and insecticides to control biotic limiting factors such as insects and disease. In addition, the more productive varieties are able to assimilate large quantities of nitrogen, which is spread mechanically. However, this nitrogen also encourages weed growth and herbicides are used extensively to eliminate them.

From the 1960s onwards, the growing gap between labour productivity in crop and livestock production led to the disappearance of livestock from arable farming areas. Forage crops no longer formed part of the crop rotation, which shortened crop rotations and led to higher population densities of weeds and certain pests (particularly telluric diseases), linked to the more frequent return of the same crops to the plots (Meynard *et al.*, 2013). Agricultural landscapes also underwent profound change, with land consolidation to enlarge fields and adapt them to new farm machinery (Jepsen *et al.*, 2015). The specialisation and intensification of systems was accompanied by advances in genetics and fertilisation management: in wheat, the development of lodging-resistant varieties and the rationalisation of fertilisation according to the nitrogen balance method led to ever-higher yields (Hébert, 1969) (see Figure 1.1). In addition to chemical fertilisers, the intensification of agriculture was also accompanied by an increase in the use of synthetic pesticides. These inputs were needed to protect crops whose sensitivity to pests had increased (diseases, insect attacks and competition from certain weeds) and the development of new pesticides made it possible to partially avoid the risks associated with pests (Lamine *et al.*, 2011). This trend towards greater dependence on pesticides was not limited to arable crops, but affected all crop production, for example, the increased use of synthetic fungicides in viticulture and arboriculture, replacing copper and sulphur. These synthetic fungicides were more biocidal and persistent, making them easier to use. In arboriculture, the development of insecticides led to the growth of specialised orchards, with fruit production concentrated on a small number of more productive varieties. Finally, the widespread practice of drainage and irrigation tends to reinforce the homogenisation of environmental conditions conducive to the spread of pests.

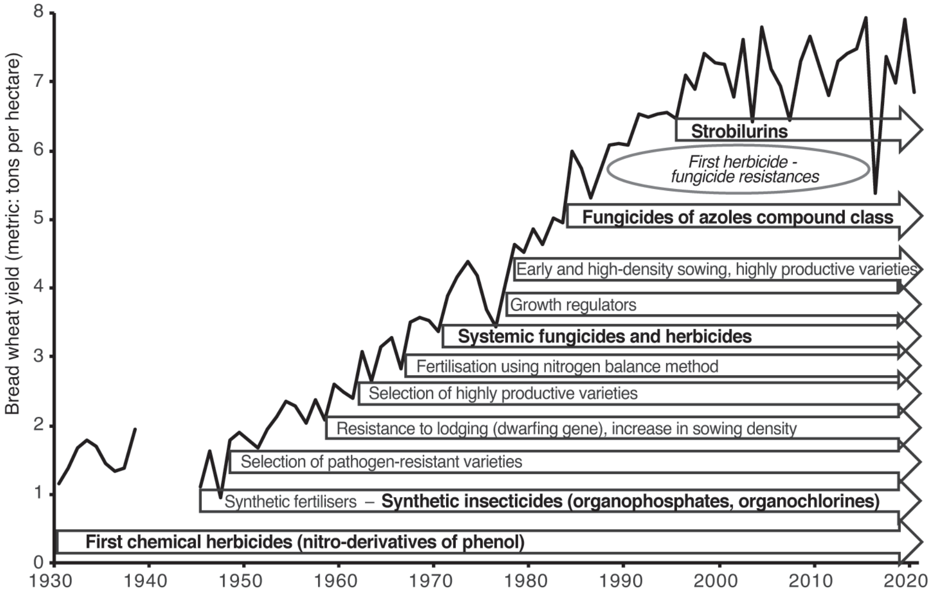

Figure 1.1. Soft wheat yield trends in France in relation to various technical innovations, including the development of pesticides (in bold), inspired by Oerke (2006), based on data from the French Ministry of Agriculture and Eurostat.

In the 1980s, the intensification of agricultural production accelerated with the development of systemic fungicides and herbicides, i.e. those whose efficacy derives from the fact that they migrate from the leaves or roots through the stems and reach all plant organs (Figure 1.1). Pesticides, hitherto used as curative solutions, now became a central component of crop management, with systematic applications designed to reduce risks and limit production losses, thereby maximising yields and/or ensuring product quality. Indeed, in the absence of crop protection, losses can be very significant and, for a given crop, highly variable between regions and between years (Box 1.3). These crop management techniques, which rely heavily on pesticide use, are also characterised by higher sowing densities and earlier sowing dates, so plants can capture the maximum amount of light energy to achieve higher maximum yields. However, these new practices also encourage pest development, making the use of pesticides even more essential. At the same time, the repeated use of pesticides induces the development of resistance in pests, which adapt over generations. To counter this phenomenon, farmers became engaged in a form of arms race, using newer pesticides such as azole and strobilurin fungicides, which were mass-marketed by the agrochemical industry.

The intensification of agricultural production thanks to pesticides is reflected in national statistics. For example, wheat yields have risen from around 1.5 tonnes per hectare at the beginning of the 20th century to an average of more than 7 tonnes per hectare at the dawn of the 2000s (Figure 1.1), and the volume of French crop production has increased 2.5-fold in 60 years. Alongside this, input use has exploded. The

Commission des Comptes de l'Agriculture Française (CCAN) shows that the volume of fertiliser use has multiplied by 1.7 and pesticide use by 8.5 in 60 years (Figure 1.2).

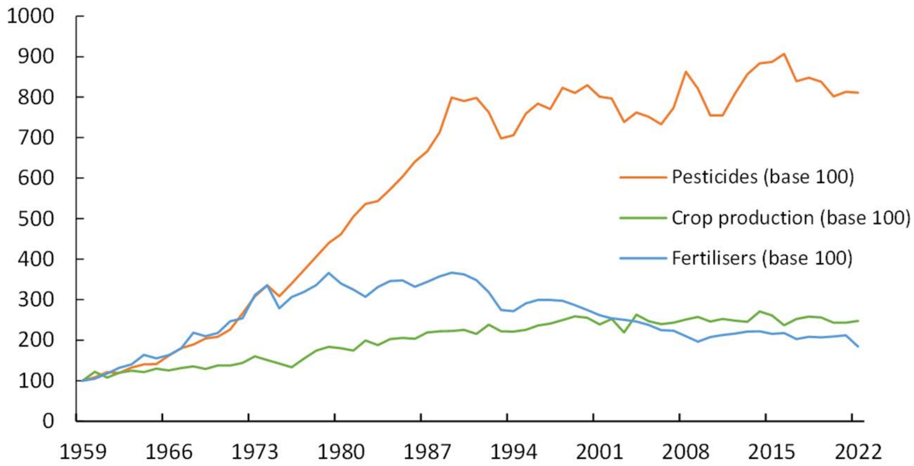

Figure 1.2. Trends in the volume of pesticides (orange) and fertilisers (blue) used and crop production (green) in France, 1959-2022 (base 100 in 1959) (INSEE, 2023).

Box 1.3. Production losses avoided by crop protection

Pesticides are used to help protect crops against pests: without protection, yields would be much lower and a significant proportion of the crop would be destroyed before harvest. The potential yield of a crop is determined by the variety used and environmental conditions, such as sunshine, temperature and CO_2. This potential yield can be reduced by a lack of water, which farmers can compensate for through irrigation, and by a lack of nutrients, which can be compensated for using appropriate fertilisation. Yields can be further reduced by reducing factors such as pests (van Ittersum *et al.*, 2013). Susceptibility to certain pests depends on the level of resistance of the chosen variety, as well as sowing date and density. Potential pest pressure will be determined by the history of the plot (e.g. the presence of fungal inoculum) and its environment. Plant protection has an influence on yield-reducing factors such as pests: all practices, both prophylactic and curative (including pesticides), help to bring actual yields closer to a plot's potential yield.

One study has estimated the percentages of monetary losses according to the type of pest causing them for all crops worldwide (Oerke, 2006). According to this estimate, crop protection prevents 32% of losses caused by fungi (and bacteria), 39% by insects and other pests, and up to 74% by weeds. However, protection against viruses, mainly through vector management, yields again of only 5% (Oerke, 2006). Equivalent data are not available for France, but it is likely that the magnitude ratios between the various pests are the same. There are many examples, depending on the crop and type of loss. In France, between 2010 and 2014, the comparative study carried out on soft wheat by Urruty (2017) between plots protected against fungal diseases and control plots shows losses varying on average from 8% in 2011 (a dry year with low disease pressure) to 30% in 2012 (a very wet year), with major differences between regions (Figure 1.3).

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This illustration for soft wheat allows us to identify three important messages concerning the impact of fungal diseases and, consequently, the services provided by chemical protection:

– Average losses can reach very significant levels, but are highly variable from one year to the next.
– Losses vary greatly from one region to another in any given year.
– It is not possible to predict losses in a given location on the basis of behaviour in previous years.

This inability to predict losses leads to a high level of insecurity, which favours the preventive use of pesticides and explains the important role played by Decision Support Systems (DSS) in optimising application management. It also justifies the weight that is given, and should be given, to the use of more disease-tolerant or resistant varieties. While Urruty's (2017) study is based on the most common varieties on the market, the treated/untreated yield gap in soft wheat cultivation is greatly reduced with the most resistant varieties. This will be illustrated in Chapter 5.

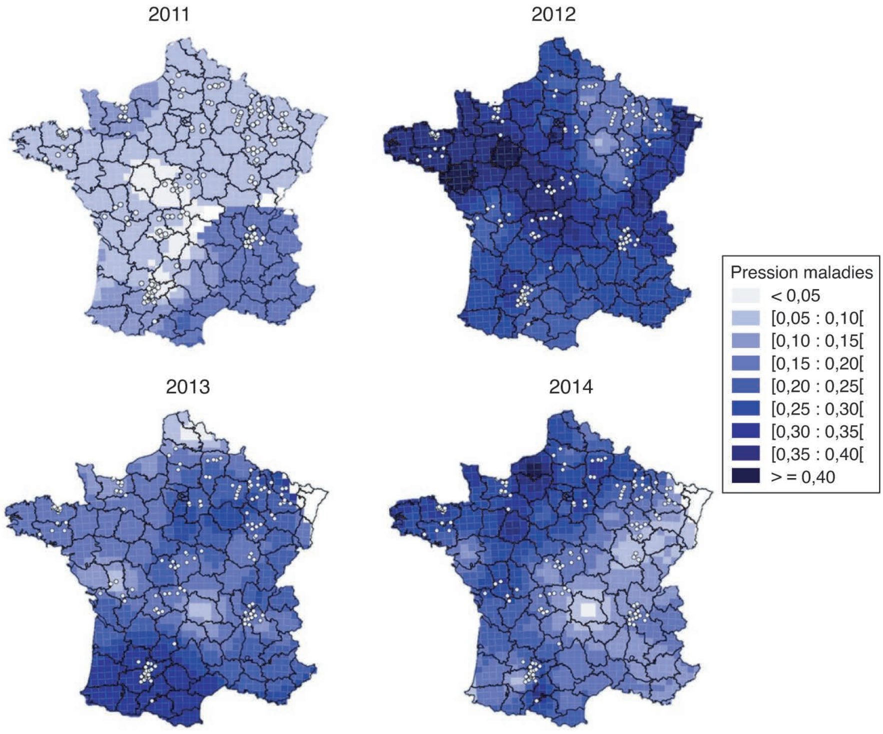

Figure 1.3. Maps of the distribution of loss differences between fungicide-protected and control plots for the years 2011 to 2014 (Urruty, 2017). *"Pression maladies" means "Disease pressure".*

The development of pesticide use was widely supported by the French State through various public policies. After the Second World War, the capital provided by the Marshall Plan and France's national agricultural policy were designed to increase agricultural production to meet the food needs of the French population. The high prices paid to producers for agricultural products encouraged farmers to produce more, by adopting the new technologies available, paving the way to more intensive practices. This national agricultural policy proved highly effective and by 1957 France had a surplus of cereals. The creation of the CAP in 1962 consolidated this policy of guaranteed prices and gave French cereal growers the opportunity to export to other European countries still in deficit, primarily Germany. In the 1960s, the main aim of the CAP was still to increase agricultural production and ensure supplies and reasonable prices for consumers. Price support and guaranteed outlets allowed production to continue to modernise and intensify. Structural policies at a national and then European level supported this process, with measures governing the evolution of farms, allowing them to grow to an economically viable size. At the same time, France supported the development of industrial infrastructure such as port facilities and processing plants (sugar mills, malting plants and starch factories), which could handle large volumes of inputs (fertilisers) and agricultural products.

This policy, combined with the technical advances described above, bore fruit, with production increasing by 50% in volume between 1960 and 1980 (INSEE, 2023). The use of pesticides, a pillar of agricultural intensification, was therefore encouraged by agricultural policies (Mahé and Rainelli, 1987). This phenomenon can be found in northern countries such as France, as well as in southern ones (Box 1.4).

Box 1.4. The Green Revolution

The Green Revolution refers to the process of intensifying agricultural production in developing countries between 1960 and 1980, through the genetic improvement of crops and the mass use of inputs, including pesticides. This often went hand in hand with agrarian reforms to redistribute land and ensure more equal access to it. By significantly increasing agricultural productivity, it helped to limit famines and from the 1960s helped to sustain unprecedented demographic growth.

The Green Revolution began in India in 1966 with the mass deployment of high-yielding wheat and rice varieties, the widespread use of chemical inputs (fertilisers and pesticides) and the development of irrigation in all of India's lower valleys. This development was underpinned by an incentive-based agricultural policy combining subsidies for inputs (seeds, fertilisers and pesticides), the state purchase of crops at guaranteed prices, and investment aid for mechanisation and irrigation. By the end of the 1970s, increased rice yields enabled India to cope with its growing population without the recurrent famines of the previous decade. The Green Revolution model was successfully exported to China and much of Southeast Asia. In most cases, it led to a significant increase in yields through the use of inputs and selected varieties, with the exception of Thailand, which took advantage of its land availability to increase its cultivated area through mechanisation. In the early 1980s, Thailand became the world's leading rice exporter, and countries such as Indonesia and the Philippines became virtually self-sufficient, despite being considered structurally deficient (Griffon, 2002).

In Latin America, the Green Revolution was applied to maize cultivation and livestock development through genetic improvement, veterinary progress and intensified grazing. This model has mainly benefited medium-sized farms, as access to land for small-scale producers remains difficult. In Africa, the impact of the Green Revolution has been more heterogeneous.

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It has been successfully applied to coffee, cocoa, palm and rubber plantations in the humid tropics. However, production in dry savannah and arid zones was not as successful as expected, as the use of high-yielding varieties and fertilisers was not adapted to the rigours and high variability of the climate in these areas.

In the 1990s, the limits of the Green Revolution began to show in India, where it had begun, with yields stagnating and the degradation of the environment becoming more visible. In particular, water tables began to dry up as a result of intensive irrigation and high levels of chemical inputs were found in the water. In fact, the economic incentives developed by public authorities, such as input subsidies, led to their excessive use. These excesses have sometimes been corrected. For example, pesticide subsidies were abolished in Indonesia in the 1990s, leading to a spectacular drop in insecticide use. However, the environmental impacts of the Green Revolution can still be found in many countries of the Global South, with problems of exposure of the population to pesticides and a significant loss of biodiversity. In the Philippines, for example, intensive rice cultivation has led to the disappearance of wild plants and fish from rice fields, which used to feed the poorest people. So, in addition to its environmental impacts, the Green Revolution has accentuated socio-economic disparities and a rural exodus in many countries, benefiting mainly farmers with access to credit and large farms (Pingali, 2012).

Pesticides today: what are they used for?

France is Europe's leading agricultural producer and also the continent's second largest user of pesticides, with around 76,000 tonnes applied annually, making it the ninth largest user worldwide (2021 figures in FAOSTAT [2024], Box 1.5). Many business sectors currently use pesticides, such as transport, to maintain railroad tracks, and the energy sector, where they are necessary for the smooth running of power grids. However, agricultural use alone accounts for 90% of pesticide consumption in France. Pesticides are used in all conventional agricultural production, both on farms specialising in crop production and those dedicated to livestock.

Box 1.5. Elsewhere in the world

Pesticide use has become widespread worldwide, reaching around 3.5 million tonnes in 2021 (FAOSTAT, 2024). There are regional variations in the quantities and types of pesticides used. Brazil alone uses more than 30% (by volume) of pesticides sold worldwide, with the USA and Indonesia in a distant second and third with 20% and 12% (Figure 1.4). However, this ranking is highly variable from one year to the next. In addition, if these volumes are expressed on a per-hectare basis, the biggest pesticide users are small tropical countries (Brunei, Darussalam, Saint Lucia and New Caledonia). In terms of the type of pesticide used, herbicides account for 52% of pesticides sold worldwide. In fact, herbicides are widely used in certain countries, such as the United States, which is linked with the development of genetically modified crops (GMO) which are tolerant to certain herbicides. In Europe, fungicides account for the majority of sales. Countries located near the tropics mainly use insecticides.

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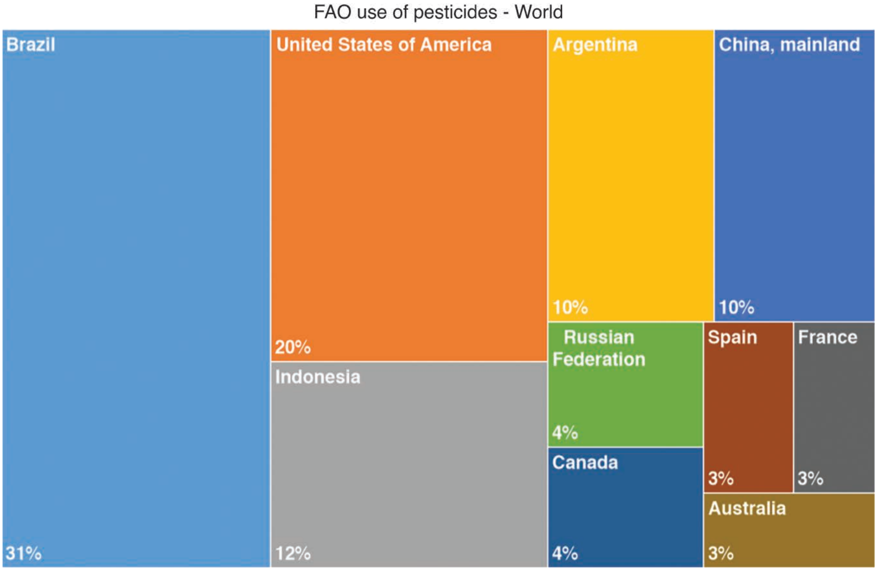

Figure 1.4. Distribution of pesticide use in 2021 among the 10 largest user countries.

Two types of production alone account for more than 80% of the pesticides used in France: arable crops, due to the surface area they occupy, and viticulture, due to a very high use per hectare (Butault *et al.*, 2010). Arboriculture and horticulture (market gardening) also use high quantities of pesticides per hectare. This distribution is reflected in the spatial breakdown of pesticide purchases. In livestock farming regions with large areas of grassland, pesticide purchases remain lower. In contrast, pesticide purchases are particularly high in wine-growing regions (Bordeaux and Champagne), in regions where arboriculture and horticulture are highly developed (Mediterranean basin) and in certain regions where industrial crops, such as potatoes, are widely grown (northern France) (Figure 1.5).

Even within crop production, there is considerable heterogeneity in pesticide use, as can be seen in the corresponding treatment frequency indicators (TFI [2]) (Box 1.6 and Figure 1.6).

In terms of the type of pesticides used in France, fungicides and herbicides dominate the market, jointly accounting for 85% of pesticide sales (Figure 1.7). In terms of quantities of substances sold (Box 1.6), one herbicide, glyphosate, is by far the most commonly purchased, accounting for 12% of total sales in 2018. Glyphosate is mainly used in the intercropping period in arable crops to control weeds and/or regrowth of previous crops (81% of applications) as well as to destroy plant cover or grassland prior to planting the following crop (19% of applications) (Carpentier *et al.*, 2020). It is also used in viticulture and arboriculture for weeding between rows and especially under rows. Sulphur, a natural fungicide, is the second most sold substance, accounting for 9% of sales. It is used to combat powdery mildew in both conventional and organic viticulture, and is now also used on cereal crops.

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[2] TFI: Number of approved doses applied to a plot over a season.

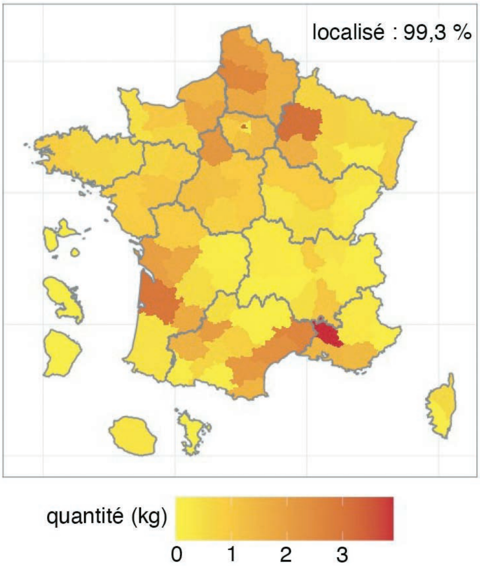

Figure 1.5. Quantity of pesticides (all active substances) purchased in 2019, per hectare (Ministry for Ecological Transition, 2021). Source: BNV-D, OFB, data by purchaser postal code, extracted on 27/11/20. SDES processing, 2021. *"quantité (kg)" means "quantity (kg)", and "localisé" means "located".*

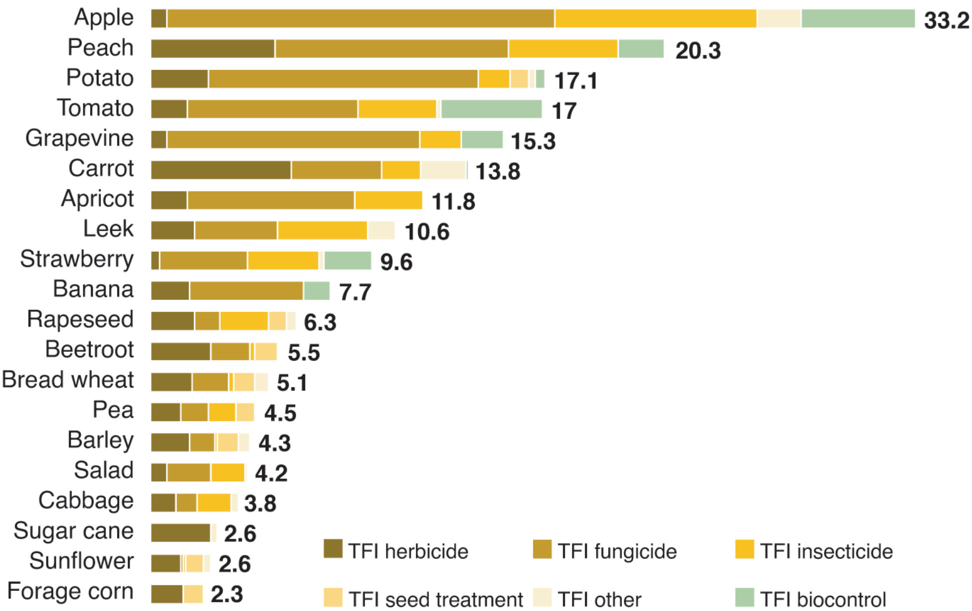

Figure 1.6. TFI for major crops (Agreste, 2018, 2019, 2020; Agreste Guadeloupe, 2018; Agreste Nouvelle-Aquitaine, 2019; Agreste Pays de la Loire, 2019).

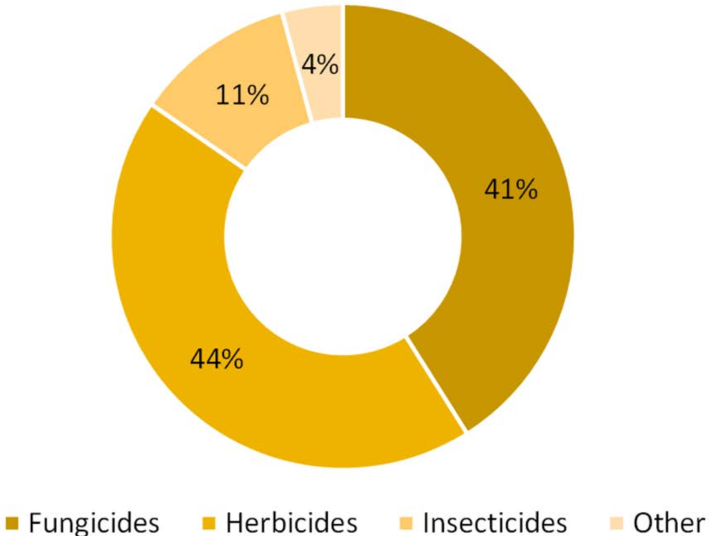

Figure 1.7. Breakdown of sales of active substances by type in 2021 in France (Ministry for Ecological Transition and Territorial Cohesion, 2022a).

Box 1.6. Indicators for monitoring pesticide use

Various indicators, defined on a European or French scale, are available to quantify pesticide use and, indirectly, the effect of policies implemented to reduce their use. As part of France's Écophyto plan, three indicators have been established to monitor pesticide use.

TFI calculates the number of pesticide doses, relative to their approved dose, used per hectare over the course of a year. It therefore takes into account the intensity of treatments, which may be partial (such as a half-dose application, for example). The TFI can be calculated for a group of fields, a farm or a territory. It can also be broken down into herbicides, fungicides, insecticides and other pesticides. The advantage of TFI is that it can be used to aggregate very different substances and therefore measure pesticide use on a crop as a whole. For farmers, the TFI makes it possible to assess their progress in terms of reducing pesticide use by reducing the number of applications or the doses applied, and to compare their practices with others in the region. However, TFI does not take into account the degree of toxicity of each product. It is therefore a limited indicator for assessing the potential risks of pesticide use for the environment and health.

The calculation of the TFI (without units) for a plot in a given year is as follows:

$$TFI = \sum_{p,t} \frac{\text{Number of doses used}_{p,t}}{\text{Number of standard doses}_{p,t}} \times \frac{\text{Treated area}_{p,t}}{\text{Whole plot area}}$$

p: pesticide
t: treatment carried out during the year

The quantity of active substances is calculated from pesticide sales data supplied by distributors. It enables us to have detailed information on the quantities of pesticides sold at a territorial level (down to the commune).

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However, these sales do not always correspond to actual pesticide use over the course of a year: there may be a discrepancy between pesticide sales and use, due to stocks held by farmers or to spatial discrepancy, as the purchase may be used to treat a distant plot, located in a different municipality to the one in which the purchase has been made. Furthermore, the calculation of the QAS does not necessarily reflect changes in pesticide use practices, as the development of increasingly concentrated products automatically reduces the quantities sold. Finally, the QAS does not reflect the degree of toxicity of active substances and therefore the risks incurred. The calculation of the QAS (in kg of active substances) is as follows:

$$QAS = \sum_{p,Sa} \text{Sold quantity}_{p} \times \text{Concentration in active substance}_{p,Sa}$$

p: pesticide
Sa: active substance

The number of dose units (NODU) is also calculated from pesticide sales data. In this case, for each substance, the quantity applied is weighted by a specific unit dose, which corresponds to the approved dose for a particular treatment. It is therefore an index similar to TFI, which can also be broken down according to the type of pesticide (herbicide, fungicide or insecticide). However, it is calculated globally, based on sales and does not consider storage and use by farmers. It is, therefore, an imperfect reflection of use. Its main advantage is that it can account for the substitution of active substances with new ones that are effective at lower doses. Its complexity stems from the fact that, for the same product applied at a constant volume, variations in maximum approved doses affect the value of the NODU, making it difficult to compare one year with another without consideration of the regulatory changes that have occurred over the period under consideration.

Based on the QAS of each active substance, the NODU (without units) is calculated as follows:

$$NODU = \sum_{Sa} \frac{QAS_{Sa}}{\text{Unit dose of active substance}_{Sa}}$$

Sa: active substance

Despite initiatives to reduce pesticide use, consumption has remained stable in recent years (Figure 1.8). The years 2018 and 2019 were notable for significant fluctuations in QAS and NODU (Ministry of Agriculture and Food, 2021). In particular, QAS saw a sharp increase in 2018 (+19%), followed by an even greater drop in 2019 (-43%). Further analysis based on data from the Réseau d'Information Comptable Agricole (RICA), France's participation in the Farm Accounting Data Network, FADN, reveals the major cause of this. The FADN is a European operation that collects annual accounting data from a sample of farms in European countries, including around 7,000 French farms (Agreste, 2021). RICA includes information on pesticides, including biocontrol products: it records inventories at the beginning and end of the financial year, as well as purchases for each farm, providing information on the net cost (after deducting changes in inventories) of pesticide expenditure. FADN data show an increase in pesticide purchases in 2018 (+13%), but also an increase in inventories created. Conversely, in 2019, purchases fell significantly (-26%), but so did stocks: farmers bought fewer pesticides as they used up their stored products from the previous year. We can therefore deduce that pesticide expenses net of stored products, which can be assimilated to actual pesticide use (including biocontrol products), fell only very slightly, by around 2% between 2018 and 2019. In 2020 and 2021, QAS has stabilised at his lowest level since the monitoring began and NODU has not fallen sharply.

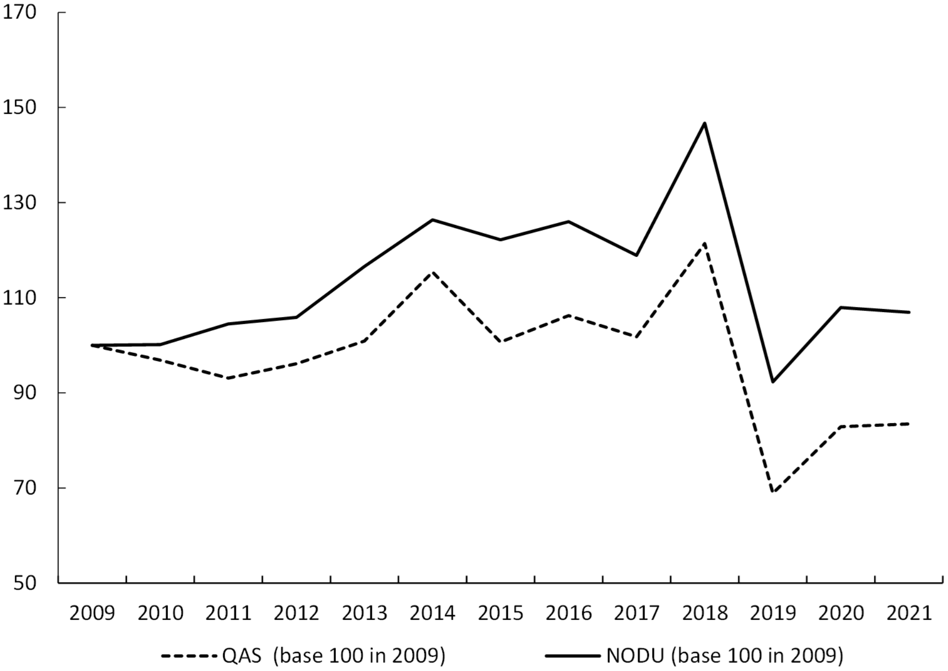

Figure 1.8. Evolution of agricultural QAS (Quantity of Active Substances) and NODU (Number of Dose Units) used to monitor pesticide consumption in France as part of Écophyto (Ministry for Ecological Transition and Territorial Cohesion, 2022b). 2021 data are provisional.

Other indicators consider the risks associated with pesticide use. Active substances can be identified as “carcinogenic, mutagenic or reprotoxic” (CMR), proven or presumed (CMR1) or suspected (CMR2). Over the period 2009-2018, the quantities of active substances decreased by 15% for CMR1 and 9% for CMR2 (Ministry for Ecological Transition, 2020a). The share of active substances classified as CMR1 or CMR2 has also been falling in relation to all substances sold since 2009 (Figure 1.9). At the European scale, the European Commission’s Harmonised Risk Indicator (HRI1) is used to estimate the risk associated with pesticides, based on the quantities of active substances sold, weighted by coefficients representing the risk associated with these substances (see section “The impact of pesticides on health”). HRI1 fell by 14% in France between 2011 and 2017, and by around 25% across the European Union (EU) (Eurostat, 2021). So, while use indicators are tending to increase (+7% for QAS between 2011 and 2017 and +10% for NODU), the use of the highest-risk substances is falling.

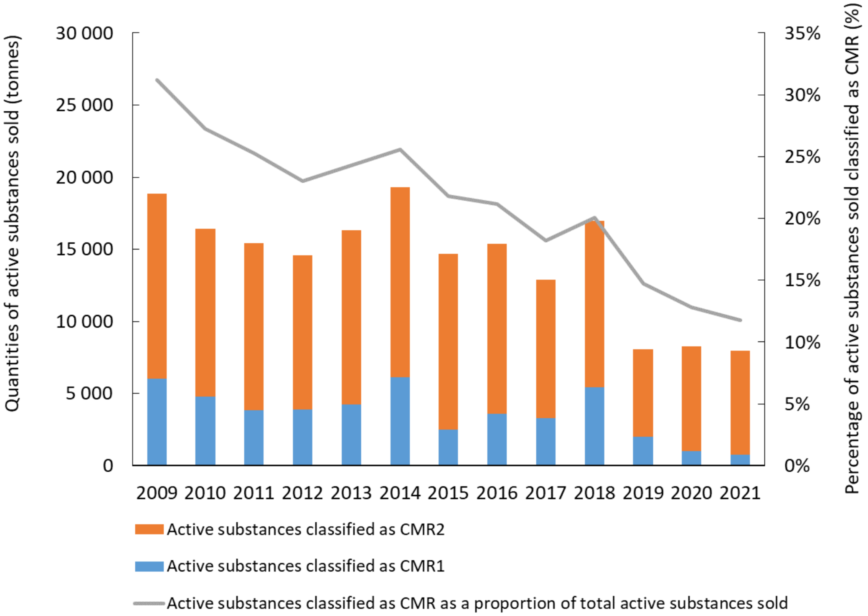

Figure 1.9. Quantities of active substances sold in France, by CMR category (Ministry for Ecological Transition and Territorial Cohesion, 2022b).

Key messages

Farmers have always looked for ways to protect crops from pests. However, the real boom in crop protection only came in the 20th century with the development of synthetic pesticides. Three phenomena underlie the mass use of pesticides. First, the boom in organic chemistry which enabled the production of molecules that were effective against pests. Different generations of fungicides, herbicides and insecticides have succeeded one another, gradually becoming a central component of crop management approaches. Second, the intensification of agricultural production, based on the use of mineral fertilisers, more productive improved varieties and simplification of farming systems, created an unprecedented need for crop protection. Third, the CAP's price support system provided farmers with a favourable economic context for the use of chemical inputs. By guaranteeing high prices for agricultural products, the State encouraged farmers to intensify production in order to achieve high yields. France is currently one of the world's biggest consumers of pesticides, with 76,000 tonnes of pesticides used in the country in 2021. These inputs are mainly used in arable crops, viticulture and arboriculture, which is reflected in the spatial distribution of pesticide sales in France. However, this mass use is not without its effects on the environment and health, and awareness of the problem has been growing since the 1980s.

⏩ Pesticide use has become a major societal concern

Awareness of the effects of pesticides on the environment began in the 1960s, notably with the publication of the book *Silent Spring*, which revealed the impact of pesticides on the environment, particularly birds (Carson, 1962). At the end of the 1980s, the significant contamination of natural waters in France, particularly by herbicides such as atrazine, increased concerns about the harmful effects of pesticides on both the environment and human health (Ministry for Solidarity and Health, 2019). The multiplication of health and environmental scandals, combined with an increasing number of scientific publications, has demonstrated that pesticide use has become a major societal concern.

The impact of pesticides on the environment

The negative impacts of pesticides on the environment mainly concern the loss of terrestrial and aquatic biodiversity. As well as fulfilling their original function of destroying certain pests, pesticides can also affect non-target organisms. This phenomenon is reinforced by the fact that some pesticides accumulate in natural environments such as water, air and soil.

The first organisms to be affected by pesticides are insects. Numerous scientific studies show very significant and perennial declines in insect populations in ecosystems (Jactel *et al.*, 2020) as far back as the end of the 19th century (Ollerton *et al.*, 2014). Currently, more than 40% of insect species are threatened with extinction, and a recent meta-analysis has shown that between 1% and 2% of insects disappear each year worldwide (Sánchez- Bayo and Wyckhuys, 2019; Wagner *et al.*, 2021). In Europe, approximately one-fifth of species assessed in a multi-taxon study are threatened with extinction, reaching 24% for invertebrates (Hochkirch *et al.*, 2023). In some protected areas in Germany, more than 75% of insects have disappeared in a decade (Seibold *et al.*, 2019). Although no equivalent study exists in France, it is likely that the evolution is similar to that observed in Germany. The case of pollinating insects in wild and cultivated ecosystems (bees, bumblebees, butterflies and hoverflies) is particularly worrying, given that more than 75% of the world's food crops rely on animal pollination (Díaz *et al.*, 2019). With insects accounting for around two-thirds of all terrestrial species, their gradual disappearance is having a profound impact on biodiversity, and has been likened by some to the planet's sixth major extinction event (Thomas *et al.*, 2004).

Several factors are responsible for the decline of insects: loss of natural habitats, climate change and pesticides use (IPBES, 2016). The main pesticides implicated are neonicotinoids and fipronil (Sánchez- Bayo and Wyckhuys, 2019). These insecticides have a particularly devastating effect on both terrestrial and aquatic insects, due to their high acute and chronic toxicity (Box 1.7). Some fungicides (azoles) also tend to reinforce the toxicity of insecticides and would therefore certainly be implicated in the collapse of honeybee colonies (Simon-Delso *et al.*, 2014). Finally, even if they are not directly toxic to insects, herbicides have an indirect impact on the population densities of insects and other arthropods because they reduce the abundance and diversity of wild plants on which these animals depend.

Box 1.7. Bees and neonicotinoids

Honeybee colonies have declined significantly in various European regions. Although parasites and disease appear to be the main factors behind this, pesticides also play a significant role, particularly neonicotinoids. Introduced on a large scale in the mid-1990s, neonicotinoids are now the world's best-selling class of insecticide. Unlike other insecticides, which are applied to crops to control the presence of insect pests, neonicotinoids are most often used as preventive seed dressings. These new insecticides are therefore "systemic", as the active substance spreads to all parts of the plant: leaves and stems, but also pollen or nectar in the case of honey plants. These insecticides are therefore particularly effective in protecting the whole plant. They are mainly used as insecticides on arable crops (maize and beet), acting on a very broad spectrum of insect pests.

Neonicotinoids act on the central nervous system of insects, particularly pollinators, by targeting nicotinic acetylcholine receptors, causing paralysis and death at high doses. At sublethal doses, however, these insecticides impair bees' immune systems, reduce their foraging capacity, affect their memory and diminish their reproductive performance. Neonicotinoids also tend to accumulate in the soil, where they break down very slowly, and eventually diffuse into the environment, contaminating untreated crops and wildflowers.

The impact of neonicotinoids on the environment led to an EU moratorium in 2013, restricting the use of three neonicotinoids (clothianidin, imidacloprid and thiamethoxam) on crops attractive to bees. In France, the law for the restoration of biodiversity has supplemented this moratorium with a total ban on all outdoor crops since 2018. A recent analysis of neonicotinoid use prior to the ban shows that in the vast majority of cases a non-chemical alternative method could have replaced them (Anses, 2018). Derogations to their ban are nevertheless requested, and granted, as in 2021 and 2022 on beet crops (Jactel *et al.*, 2019; Sánchez-Bayo and Wyckhuys, 2019; Wintermantel *et al.*, 2020).

The scarcity of insects also affects many other living organisms that feed on them, particularly birds. In France, bird population densities in agricultural environments have fallen by 33% in a decade according to France's commission for sustainable development (Commissariat Général au Développement Durable, 2018). A recent study shows that Europe is losing an average of 20 million birds a year, or 800 million fewer than in 1980. According to the authors, the main cause of this collapse is the intensification of agricultural practices, which increased the use of pesticides and the disappearance of nesting areas (Rigal *et al.*, 2023). Indeed, the use of insecticides seems to be the main cause (Hallmann *et al.*, 2014). Fish population densities are also affected by the decline in aquatic insects (Jactel *et al.*, 2020; Yamamuro *et al.*, 2019). A particularly revealing monitoring indicator is the trend in bat population density. Bats must eat a third of their weight in insects every day and their population density has fallen by 38% in a decade in France (Commissariat Général au Développement Durable, 2018).

The impact of pesticides on the environment concerns not only living organisms, but also the environments in which they evolve. Air, water and soil suffer long-term pesticide contamination as a result of transfers between treated fields and these compartments. These transfers mainly take place *via* spray drift, volatilization, infiltration and runoff from treated areas (Pelosi *et al.*, 2021). A study conducted in a French cereal-growing region shows that all the soils studied, whether conventional or organic agriculture plots, contain pesticides. Although not exceeding regulatory thresholds, this contamination is responsible for a reduction in the abundance of microorganisms in the soil, as well as macroorganisms such as earthworms (Pelosi *et al.*, 2021). This alters the quality and biological functions of soils, in particular through reduced decomposition of organic matter. In aquatic environments, pesticide contamination affects both surface water and groundwater.

Numerous pesticides are present in watercourses, despite their presence falling by around 20% in France between 2008 and 2017. This contamination affects the production of drinking water as well as the organisms living in these environments. Pesticides are also found in almost 80% of groundwater in France, and the trend is growing. Of the 300 substances detected in 2018, around a third were already banned at that time (Ministry for Ecological Transition, 2020b). So, the accumulation of substances or their metabolites, which degrade only very slowly, is responsible for long-term pollution. An emblematic example of this problem is chlordecone pollution in the French West Indies (Box 1.8).

A recent study analysed around 300 water samples in water intended for human consumption in France. Of the 157 molecules tested, 89 were quantified at least once (Anses, 2023). Taken individually, the concentrations of these molecules do not exceed the health thresholds set by the authorities, but the question arises of the cocktail effect of these pollutants on health (Box 1.9).

Box 1.8. Chlordecone soil contamination in the French West Indies

Chlordecone is an insecticide that was used on a massive scale in Guadeloupe and Martinique from 1971 to 1993 to control banana weevils (*Cosmopolites sordidus*). Each banana plant received an average of 30 g of chlordecone every year. Chlordecone is not very mobile, not very soluble and not very volatile. It fixes itself long-term on soil organic matter and degrades extremely slowly in aerated soils. Chlordecone is the cause of chronic agricultural soil pollution. In 2018, the risk of pollution by this substance concerned 40% of the utilised agricultural area in Martinique (i.e. 10,000 hectares) and more than 25% in Guadeloupe (i.e. 14,200 hectares) (DAAF Guadeloupe, 2018). Degradation of chlordecone is very difficult in terrestrial environments, meaning its persistence can extend to five or six centuries, depending on soil type. The insecticide has not only contaminated the soil: plants and particularly roots and tubers are also contaminated. As a result, it is now forbidden to grow root vegetables (yams, carrots and sweet potatoes) in polluted areas where chlordecone levels exceed 100 mg/kg of dry soil. Animal feed is also significantly contaminated on the most polluted soils (INRAE, 2020).

Chlordecone is now classified as a persistent organic pollutant and recognised as an endocrine disruptor, potential carcinogen and is reprotoxic. The West Indian population can be exposed to it *via* the ingestion of contaminated water or food: it is estimated that more than 90% of the population on both islands is exposed to various levels of chlordecone, with proven risks of premature births and prostate cancer (Santé Publique France and Anses, 2018).

The impact of pesticides on health

Exposure to pesticides particularly affects the people who use them, primarily farmers, and, indeed, the entire population. In the general population, exposure is linked to contact with contaminated environments such as soil and air, particularly near areas treated with pesticides, as well as the ingestion of pesticide residues present in food and drink. In the workplace, exposure to pesticides can occur during product manufacture, preparation for application (dilution of the commercial product), application, and during the filling and cleaning of the equipment used to apply it (Anses, 2016). These substances enter the body *via* three routes: skin, respiration and digestive (or oral). The first two routes concern mainly professional use, while the digestive route concerns the entire population, whether through the ingestion of food and drink, or the ingestion of dust, particularly among children. A final route also exists, the *in utero* route, where the foetus is exposed *via* transplacental passage of substances to which the mother is herself exposed (Institut National du Cancer, 2014).

Due to their great diversity, the substances contained in pesticides can have highly variable impacts on human health, characterised by both acute and chronic effects. Acute, or immediate, effects are linked to short, high-dose exposure. They may remain local (chemical eye burns and skin lesions) or affect one or more organs and become systemic, with potentially serious consequences (neurological effects and liver disorders). Apart from domestic accidents, acute effects mainly concern agricultural professionals following exposure to substances during pesticide application or during incidents before or after application (preparation of the mixture, tank filling and cleaning of spraying equipment) (Inserm, 2013). Organophosphate pesticides and carbamates account for most acute poisoning.

However, some substances can induce chronic effects by accumulating in the body through repeated low-level exposure over the long term. Epidemiological studies of agricultural workers have shown links between pesticide exposure and the risk of cancer, neurological pathologies and reproductive disorders (Inserm, 2013).

A recent Inserm report, based on a critical analysis of the international scientific literature, confirms the strong presumption of a link between pesticide exposure and various pathologies: non-Hodgkin's lymphoma, multiple myeloma, prostate cancer, Parkinson's disease, cognitive disorders and certain respiratory diseases (chronic obstructive pulmonary disease and chronic bronchitis) (Table 1.1). It has also been possible to identify links (strong presumption) between certain pesticide families and diseases, such as between organochlorine insecticides and Parkinson's disease. Medium-presumption links have also identified, notably with Alzheimer's disease.

Less obviously, links between pesticides and certain reproductive disorders or chronic inflammatory conditions such as endometriosis are suspected due to the endocrine-disrupting nature of certain pesticides (Box 1.9). A recent study conducted in Brazil shows a significant deterioration in birth outcomes (+5% in infant mortality rate) for populations downstream from locations that are likely to have relatively increased the use of glyphosate (Dias *et al.*, 2023). In addition to adult pathologies, a strong presumption of a link has been identified between certain childhood cancers and pesticide exposure, both in the child and in the mother during pregnancy (Inserm, 2021).

Table 1.1. Presumption of a link between pesticide exposure and the occurrence of a pathology in adults, based on the summary of data analysed by Inserm (2021)

Pathologies	Populations concerned by excess risk	Presumption of a link
Prostate cancer	Farmers, pesticide applicators, production industry workers	++
Non-Hodgkin's lymphoma	Farmers, pesticide applicators, production industry workers	++
Multiple myeloma	Farmers, pesticide applicators, livestock producers	++ +
Parkinson's disease	Agricultural professionals	++
	General population or people living near treated areas	+
Cognitive disorders	Farmers, with or without a history of acute poisoning	++
Kidney cancer	Agricultural professionals	+
Leukaemia	Farmers, pesticide applicators, production industry workers	+
Alzheimer's disease	Farmers	+
Thyroid pathologies	Agricultural professionals	+
Soft tissue and visceral sarcomas	Farmers, wood sector workers, gardeners, livestock producers	+
Anxiety and depressive disorders	Farmers, pesticide applicators	+
Brain tumours	Farming populations	+
Bladder cancer	Agricultural professionals	+
	General population	+
Breast cancer	Agricultural professionals	±
Endometriosis	General population	±
Hodgkin's lymphoma	Agricultural professionals	±
Amyotrophic lateral sclerosis	Farmers	±
Impaired respiratory health	Professionals	+ to ++
	General population (proximity, domestic use)	± to + (depending on pathology)

Strong presumption: ++; medium presumption: +; weak presumption: ±.

Box 1.9. Pesticides suspected of being endocrine disruptors

Endocrine disruptors are substances that disrupt the hormonal function of living organisms and can therefore lead to adverse effects on health and environmental functionalities (Anses, 2019a). In particular, some of these substances can have deleterious effects on reproduction by reducing fertility or disrupting foetal development. Endocrine disruptors are present in many products: food additives, plasticisers, cosmetics, solvents, flame retardants etc. and various pesticides. This means that organisms can be exposed to multiple substances by several routes (ingestion, inhalation and skin contact). While acute effects at high doses are clearly established for certain endocrine disruptors, the identification of chronic effects linked to hormone disruption at low doses and over the long term, even across several generations, remains a major challenge.

Identification is all the more complex because endocrine disruptors do not necessarily correspond to the principles generally accepted in conventional toxicology:
- No threshold effect: endocrine disruptors are suspected of acting even at low doses, i.e. there is no level of exposure at which the body's defence mechanisms can prevent the emergence of effects on health.
- Non-monotonic dose-response relationships: endocrine disruptors can be more harmful at low doses than at higher ones, so the "dose makes the poison" principle is not verified (Vandenberg *et al.*, 2012).
- Windows of exposure: sensitivity to endocrine disruptors can vary according to life stage, with increased sensitivity during foetal-embryonic development, infancy and puberty.
- Cocktail effect: the properties of endocrine disruptors and their toxicity can be modified when they are combined, with an effect multiplied by 10 or even 10,000 (Gaudriault *et al.*, 2017).

Since 2018, substances identified as endocrine disruptors have been banned, but their identification remains problematic. The complex effects detailed above call into question the foundations of pesticide risk assessment as practiced by regulatory agencies. In particular, the individual assessment of pesticides does not take into account cocktail effects and recommendations in terms of acceptable daily doses are not adapted to the absence of a threshold effect.

The entire population is potentially concerned by chronic effects linked to long-term exposure to pesticide residues in food, water and air. According to a study published in 2018 by the non-governmental organisation (NGO) Générations Futures, almost three-quarters of non-organic fruit and 41% of non-organic vegetables have quantifiable traces of pesticides. Although these contamination levels are below the maximum residue limit (MRL) in the vast majority of cases (averaging 97.5% for fruit and 96.5% for vegetables), this study shows the ubiquity of pesticides in our food (Générations Futures, 2018).

The hidden costs of pesticides

In addition to the costs of pesticide application paid by farmers, pesticides also have costs for society as a whole, both public and private, due to their negative impact on the environment and health. These hidden costs may exceed the economic benefits of the increase in agricultural productivity made possible by pesticide use. In the 1990s, the cost-benefit difference of pesticide use in the USA was estimated as $13 billion: pesticides would have brought in around $27 billion, but at a cost in the order of $40 billion (Bourguet and Guillemaud, 2016). Although these figures are necessarily approximate and dated (many pesticides used at the time are now banned), they help illustrate the fact that the economic rationale for pesticide use is questionable when negative externalities are factored in. In this study, hidden costs were defined in four categories:

– Regulatory costs corresponding to mandatory measures, whether private or public, to protect the environment or human health from the potential impacts of pesticides and/or to repair damage already inflicted. For example, monitoring and decontaminating tap water can be considered a regulatory cost.

– Environmental costs corresponding to the impact of pesticides on biodiversity. These therefore include the loss of certain ecosystem services, such as a lack of pollination. The impact on crops of pests that have become resistant to pesticides can also be associated with these costs.

– Health costs are the expenses associated with acute or chronic pesticide poisoning. They include the health costs borne by private parties, mainly agricultural workers because of their increased exposure to pesticides, but, above all, the costs borne by society as a whole through the social security system.

– Defensive expenditure covers all expenditure by farmers and society to avoid exposure to pesticides, such as the cost of drinking bottled water or the extra cost of buying organic produce.

Within these four categories, health costs, particularly those linked to chronic exposure, appear to be the key point: they account for half of all hidden costs. However, it is extremely difficult to estimate such costs for various reasons: estimating the value of human lives lost and multifactorial causes of chronic diseases etc. (Becker, 2017). An English study, for example, estimated the costs associated with pesticide contamination of water (£120 million in 1996), but the authors did not include the costs of chronic pesticide exposure in the analysis (Pretty *et al.*, 2000). To date, there are no studies analysing the health costs of pesticides at a European or French scale. However, this type of study could help public decision-makers decide what action to take to avoid these costs, and contribute to the reduction of pesticide use by raising the overall awareness of their impact.

Key messages

Pesticide use is not without consequences for the environment and health. The negative impacts of pesticides on the environment mainly concern the loss of biodiversity. The first organisms to be affected by pesticides are insects, which are disappearing at a rate of 1% to 2% a year worldwide. As insects account for around two-thirds of all terrestrial species and play a key role in most trophic chains, their progressive disappearance is a matter of great concern. Air, water and soil are also subject to long-term pesticide contamination, as a result of transfers between treated fields and these compartments. Pesticides are therefore omnipresent in our environment and exposure to these substances in water, air and food represents a risk for the entire population. Acute and chronic effects are apparent, particularly among agricultural workers, in the form of cancers, neurological pathologies and reproductive disorders. However, the hidden costs of pesticides, such as the price of covering health costs, are not taken into account in economic assessments. Although very difficult to quantify, these costs to society as a whole may outweigh the economic benefits provided by pesticides. If these costs were known, society's rational choice would be to avoid them.

⏩ From the 1990s to the present day: numerous but not very effective initiatives to reduce pesticide use

Public policies aimed at reducing the intensity of agriculture

In the 1990s, there was a need to reverse the trend towards the intensification of agricultural production by developing appropriate public policies for two main reasons (Figure 1.11). First, the explosion in agricultural production had led to production surpluses, which the EU wanted to reduce. Second, the environmental impact of pesticides and other chemical inputs had become increasingly well identified and criticised, prompting public decision-makers to define policies to reduce their use.

The 1992 CAP reform, known as the "MacSharry reform", introduced for the first time the objective of reversing the trend towards intensification. The aim was to "encourage the extensification of production in order to reduce production surpluses, contribute to environmental protection and promote quality food products" (Jacquet, 1993). This reform marked a turning point in the history of the CAP, replacing agricultural price support with direct per-hectare aid, which was then gradually decoupled from production. The countries taking part in the GATT (General Agreement on Tariffs and Trade) negotiations undertook to ensure that all agricultural policies would evolve towards greater market neutrality and reforms in this direction were introduced in both Europe and the United States. On the domestic front, the move away from price support was also aimed at reducing the cost of managing surplus production by limiting the incentives to produce. It was also accompanied by measures to reduce overproduction (set-aside and maintenance of milk quotas). It was thought that lower prices would encourage the development of less intensive farming systems by modifying the relationship between input and output prices (Figure 1.10). For example, before the reform, it was profitable to produce wheat at 8 tonnes per hectare with high input costs. This was no longer the case afterwards, when production at 7 tonnes per hectare with a 30% reduction in input costs proved to be more profitable (Jacquet, 1993). Numerous modelling studies were conducted at the time to analyse the *ex ante* impacts of the CAP, and all tended to show that this de-intensification would take place (Boussard *et al.*, 1997; Boussemart *et al.*, 1996; Donaldson *et al.*, 1995).

Even so, the expected de-intensification has not clearly taken place. However, the reform has led to greater efficiency in input use, with a reduction in "wastage". This is particularly true for fertilisers, where numerous research and development initiatives have been introduced to teach farmers how to reduce the quantities of fertilisers used by optimising the fractioning of doses and application dates. Figure 1.2 shows a decline in the volume of fertilisers purchased from the early 1990s onwards, and a marked slowdown in the increase in the quantities of pesticides purchased.

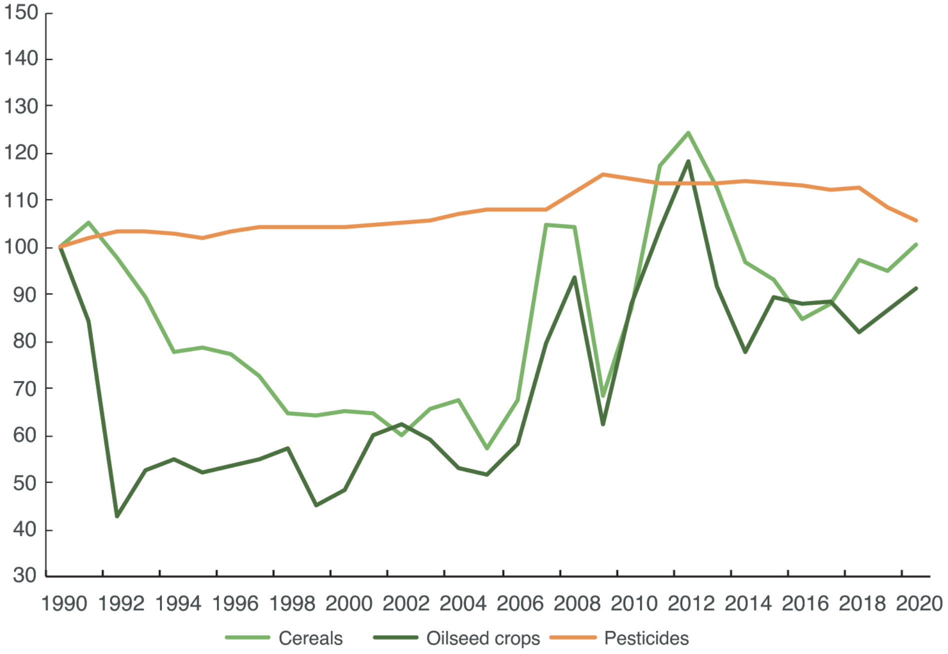

Figure 1.10. Price index for crops (cereals and oilseeds) and pesticides in France from 1990 to 2020 (base 100 in 1990), based on INSEE IPAMPA and IPPAP data (2021).

The 1999 CAP reform introduced new incentives, notably the creation of agri-environmental measures (AEM or MAE in French). These measures are part of the second pillar of the CAP, which groups together socio-structural, agri-environmental and rural development measures. AEM are a voluntary aid scheme designed to support farmers who commit to changing their farming practices over a limited period of time. Support for conversion to organic farming, as well as other AEM targeted at specific issues (biodiversity protection, water quality etc.) and territorialised from 2007 onwards, are aimed at reducing pesticide use. These measures have, in some cases, led to an effective reduction in pesticide use (Kuhfuss and Subervie, 2018), particularly when used to protect water resources in certain territories. However, they have generally been insufficiently adopted by farmers and have therefore not led to a profound change in agricultural practices.

Since 2003, support under the first pillar of the CAP has been conditional on compliance with good agricultural practices: compliance with the directives in force, in particular the Nitrates Directive and the Water Framework Directive, and compliance with “good agricultural and environmental conditions”. The 2013 CAP reform reinforced these environmental requirements by adding, from 2015, new obligations that give entitlement to specific “green” payments. At first glance, these obligations, such as the requirement for a minimum area of ecological infrastructure or compulsory crop diversification, appeared to be effective incentives for reducing pesticide use. However, the fact that these measures were not very restrictive with regard to current practices logically had little effect on pesticide use. Other levers, acting directly on the profitability of pesticides, could nevertheless be developed (Box 1.10).

The 2023 CAP reform replaced this greening with eco-schemes, which set aside 25% of the CAP's first pillar budget for measures targeting the climate and the environment.

Box 1.10. Pesticide taxation

From an economist's point of view, taxing pesticides is the most effective and least costly way of encouraging farmers to reduce their use. Although limited in scope, a tax on pesticides was introduced in 1999, when the general tax on polluting activities (known in France as TGAP) was extended to include plant protection products. In 2006, this was replaced by a diffuse pollution levy (known in France as RPD), paid by distributors on the basis of the quantities of active substances sold. The rates of this tax, graduated according to the hazardousness of the products, have been modified several times: in 2011, they varied between €0.9/kg and €5.1/kg of pesticides, and since 2019, the maximum rate has reached €9/kg for substances classified as carcinogenic, mutagenic and reprotoxic (Senate, 2018). In 2017, the amount of the tax generally represented between 5% and 6% of the price of the pesticides sold (OECD, 2017). These figures can be compared with the cost of depollution to preserve water quality, which has been estimated at around €60,000/kg of pesticides (Bommelaer and Devaux, 2011). As we shall see in the next section, no tangible reduction in pesticide use has been recorded since the introduction of the RPD. In comparison, Denmark, and more recently Norway, have taxed pesticides much more heavily. In Denmark, herbicides and fungicides are taxed at 33% and insecticides at 54% (Pedersen and Nielsen, 2017). The tax rates used in Norway are of a similar magnitude (Finger *et al.*, 2017). Although pesticide use fell sharply immediately after the introduction of the tax in Denmark, the targets set for reducing pesticide use were not achieved over time in the country (Pedersen and Nielsen, 2017).

Apart from the CAP, two European directives have been involved in the regulation of pesticide use, demanding that Member States implement national policies. In 2000, the Water Framework Directive (2000/60/EC) obliged states to achieve good chemical and ecological status for surface water and good chemical status for groundwater. Directive 2009/128/EC, known as the "Pesticides Directive", sought directly to reduce pesticide use. The directive established "a framework for Community action to achieve a sustainable use of pesticides". It laid the foundations for a number of regulatory measures aimed at reducing the use, risks and impacts of pesticides (training of farmers, monitoring of spraying equipment etc.). It also required each Member State to adopt a national action plan; in France, this is the Écophyto plan. Écophyto I was launched in 2008, with the aim of reducing pesticide use by 50% "if possible" within 10 years (Box 7.2). In view of the lack of progress in terms of reducing pesticide use, the plan has been revised several times, incorporating new actions such as "plant protection product saving certificates" (known as CEPP in French) (Box 1.11). In addition to Directive 2009/128/EC, other texts which are also part of the "pesticides package", aim to support the reduction in pesticide use, such as Directive 2009/127/EC on machinery for pesticide application, Regulation (EC) 1185/2009 on pesticide statistics and 1107/2009, which governs applications for marketing authorisations. These various texts, which are now over 10 years old, have not had the desired effect, as pesticide use has not fallen. In 2020, the European Green Deal set a new target of reducing pesticide use by 50% by 2030.

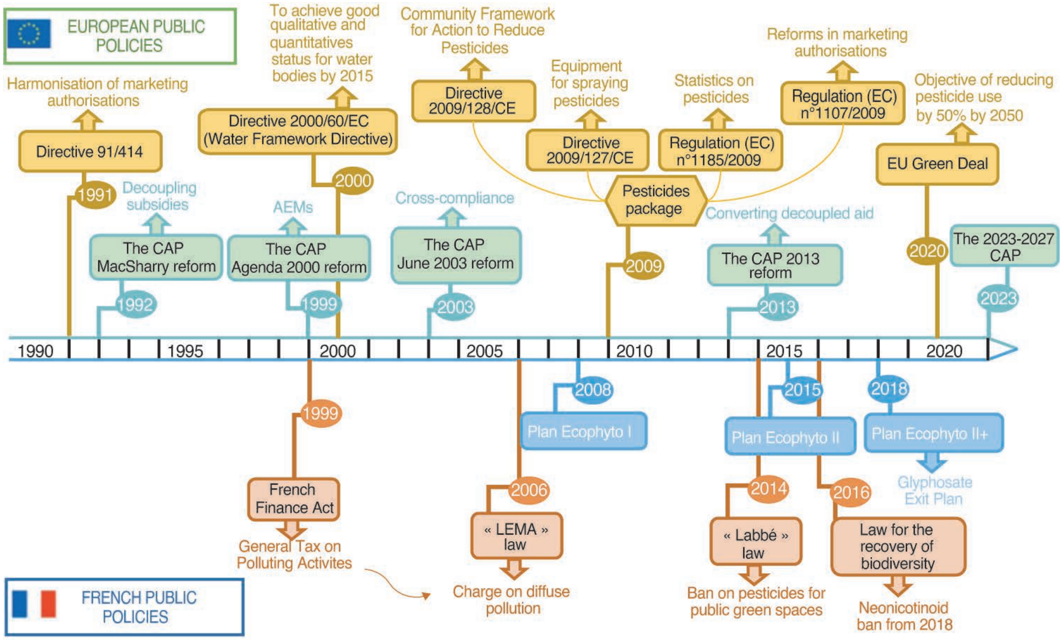

Figure 1.11. French and European regulatory developments to limit and reduce pesticide use since 1990.

Box 1.11. Plant protection product savings certificates (CEPP)

France's CEPP scheme, largely inspired by the energy-saving certificates scheme, was launched on an experimental basis under law number 2014-1170 on October 13, 2014. Compared with other regulatory schemes such as taxation or the withdrawal of marketing authorisations, CEPP are a major break, since the aim is to promote the implementation of practices and cropping systems that lead to a reduction in the use and impact of pesticides. It is based on a dual rationale.

The first step is to design, validate and implement action sheets with standardised pesticide-saving values. Under the CEPP scheme, a certificate is awarded when an action has enabled a one-point reduction in treatment frequency indicators (TFI) (see Box 1.6) for one hectare. This makes it possible to have common frames of reference for all production sectors, while dealing in a unique way with different crops and levers for action to reduce pesticide use. Action sheets are drawn up on the basis of proposals from actors in the agriculture sector (seed companies, equipment manufacturers, research and development actors etc.), and are then validated by an independent commission of the Ministry of Agriculture.

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The logic is one of obligation, and therefore of obliged parties. The scheme is aimed at pesticide distributors, which in France are mainly cooperatives and agricultural merchants, whose obligation is proportional to their historical sales volume, quantified using NODU (see Box 1.6). These obligated parties work with farmers to promote the adoption of practices and systems for which certificates are issued on the basis of action sheets. If an obligated party fails to meet its obligations for a given year or period, it is liable to sanctions (risk of suspension of their approval for sales).

By September 2021, more than 530 initial action sheets had been suggested and evaluated, of which 62% had been accepted and translated into 102 action sheets available in the official catalogue. This scheme continues to evolve and has become part of the landscape of pesticide use reduction. The next two important steps are the inclusion of seed treatments in the calculation of obligations and the extension of the scheme to France's overseas departments and regions.

Regulations governing the sale and use of pesticides

Developments in pesticide regulation are linked, on the one hand, to innovations in crop protection, bringing new active substances and products to the market and, on the other, to evidence of the harmful effects of these products on the environment or human health, which then have to be regulated. In 1978, European unification imposed the first common legal framework and banned certain active substances. The aim of this ban was twofold: to reduce the risks to public health and the environment, and to avoid unfair competition between Member States that did or did not authorise certain substances (Box 1.12). Subsequently, the desire to establish a large homogenous market for agricultural inputs and products sped up the implementation of a range of environmental and health policies (Bonnefoy, 2012). In 1991, Directive 91/414 introduced the first European harmonisation of procedures for approving active substances. Member States lost their individual choice of active substances and had to apply a uniform procedure for marketing authorisation applications. However, this procedure was fraught with red tape and did not produce convincing results. Marketing authorisation application procedures were therefore reformed in 2009 through a new regulation (EC) 1107/2009, included in the "pesticides package". Among other things, it incorporated stricter exclusion criteria for the approval of active substances, the extension of the approval requirement to other compounds contained in pesticides, such as adjuvants, and mutual recognition of authorisations between Member States.

Marketing authorisation applications are currently made in two stages: the first at the European level and the second in each Member State. The active substance evaluation procedure is the first stage: it does not concern the formulated pesticide (i.e. the active substance in combination with the other components in its formulation), but only the active substance. For this, the company applying for authorisation must submit a dossier proving the efficacy of the active substance and the absence of unacceptable risks to health and the environment. The dossier is analysed by the European Food Safety Authority (EFSA), which, if it gives a positive response, forwards it to the European Commission for market authorisation of the active substance. The second stage is the procedure for placing the commercial product on the market and is the responsibility of Member States. The company applying for authorisation submits a dossier demonstrating the product's efficacy and the absence of unacceptable risks for the uses concerned. In France, this dossier is assessed by the Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail (Anses, France's agency for food, environmental and occupational health and safety), which, if positive, forwards it to the Ministry of Agriculture for authorisation. Once all these stages have been completed, the product containing the active substance is authorised for sale (Anses, 2019b).

During both stages, the company submits a dossier which must prove that the level of risk is below a certain limit. This dossier must be based on a corpus of studies assessing toxicity on different organisms, as well as on models predicting concentrations of the active substance in the environment and consider the potential exposure of agricultural workers and the rest of the population. These studies must be independently peer-reviewed, but many NGOs have denounced the opacity of the procedure (Citizens for Science in Pesticide Regulation, 2018). Another problem is that pesticide assessment is confined to the notion of acute exposure, which makes it possible to assess the immediate danger represented by the product (and the active substance) and therefore to define an acceptable exposure dose. This dose is determined by laboratory tests, followed by field tests with volunteer farmers to estimate their level of contamination, and to compare it with this acceptable dose. Epidemiological studies assessing the risks associated with actual conditions of use and long-term chronic exposure are therefore not included in the assessment (Jouzel, 2019).

In addition to marketing authorisation applications, re-evaluations of active substances and pesticides follow the same procedure. These re-evaluations regularly lead to product withdrawals, corresponding to total or partial bans on certain uses. As shown in Figure 1.12, the number of authorised pesticides rose until the 1980s, before falling sharply from the 2000s onwards due to an increase in withdrawals and a reduction in new authorisations. The banning of certain pesticides also falls outside the scope of these re-evaluations, by excluding certain uses. For example, France's "Labbé law" in 2014 banned the use, from 2017, of all synthetic pesticides by public bodies (the State, local authorities and public establishments), for the upkeep of green spaces and roadways in particular. This ban was extended to private individuals from 2019.

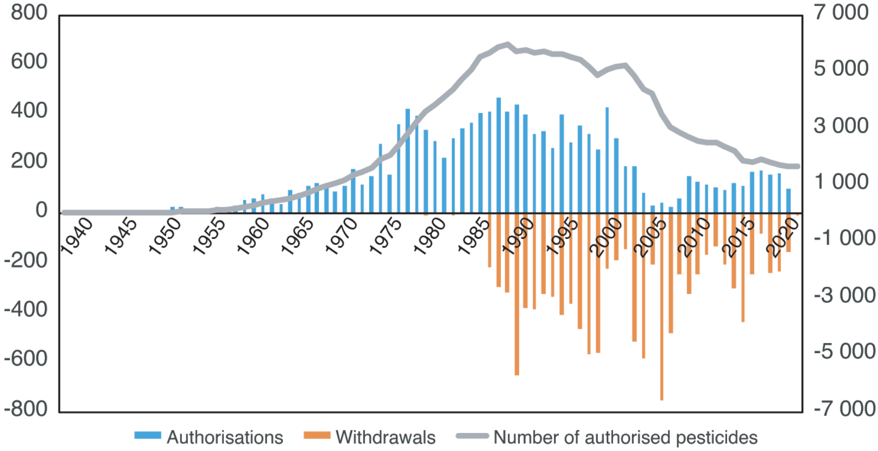

Figure 1.12. Pesticide authorisations and withdrawals (plant protection products in *stricto sensu*, excluding adjuvants) based on data from the Ephy catalogue (Anses, 2021).

Box 1.12. National regulations and the global pesticide market

Regulations governing the use of pesticides differ widely from country to country, which can lead to unfair competition on international markets, with some countries allowing or not allowing certain pesticides. For example, more than a quarter of the pesticides used in US agriculture are banned in the EU, particularly herbicides (Donley, 2019). Furthermore, even though the EU seems to offer fairly strict regulations, some of the pesticides banned for use in the EU are in fact produced in Europe and then exported to countries with more relaxed regulations. For example, the NGO Public Eye shows that in 2018, the EU exported around 80,000 tonnes of pesticides whose use it bans around the world, with 30% exported to the USA (Public Eye, 2020). In addition to the USA, the main importers of these banned pesticides are countries with less stringent regulations, which in turn export agricultural products to Europe on a massive scale, for example, wheat from Ukraine and fruit from Mexico and Morocco. This is all the more worrying as conditions for pesticide use are sometimes difficult to comply with in these countries, leading to higher risks of contamination for both local farmers and consumers (WHO and FAO, 2019). It is considered that 97% to 98% of vegetables and fruit produced in Europe comply with regulatory thresholds, but this share is lower, around 90%, for imports (DGCCRF, 2019). So, despite European regulations which are among the strictest in the world, European consumers are faced with more or less regular chronic exposure and may find prohibited pesticide residues on their plates.

Key messages

A desire to reduce the negative effects of the intensification of agricultural production emerged at a European level in the early 1990s. From 1992 onwards, successive CAP reforms introduced incentives to change farming practices: lower prices for agricultural products, agri-environmental measures, conditions for aid and green payments. However, these various measures, which in reality are not very restrictive, have not had the desired effect on changes in practices. In addition, the 2009 “pesticides package” included a number of directives and regulations designed to promote the reduction of pesticide use. Directive 2009/128/EC obliges Member States to introduce national action plans. It was within this framework that France’s Écophyto plan was launched (Box 7.2). Pesticide marketing authorisation procedures have also been reformed, incorporating stricter criteria for the approval of active substances and mutual recognition of authorisations between EU Member States. Active substances are first assessed at a European level, then pesticide formulations containing these active substances are evaluated by Member States. Risk and toxicity assessments remain controversial. Since the early 2000s, the number of authorised pesticides has fallen considerably and the most dangerous pesticides are gradually being withdrawn from the market, though overall pesticide use has not reduced.

⏩ Conclusion

Over the course of the 20th century, pesticides became a central component in crop management approaches. Different generations of fungicides, herbicides and insecticides followed one another thanks to the development of organic chemistry. These inputs supported the intensification of agriculture, which made it possible to significantly increase agricultural production and introduce simplified cropping systems which, however, are highly susceptible to pests and diseases. The use of chemical inputs was also encouraged by the CAP price support scheme, which encouraged farmers to achieve ever-higher yields. However, this intensification of production has not been without consequences for the environment and health. Biodiversity, in particular, has been widely impacted by pesticides, from insects to most trophic chains. Air, water and soil have also been hit with long-term pesticide contamination, leading to the exposure of the entire population to these substances. Acute and chronic effects occur, particularly among farmers, leading to significant health costs. Other hidden costs, such as the cost of decontaminating natural environments, are difficult to quantify, but undoubtedly represent a much greater cost to society than the economic benefits generated by pesticides.

A desire to reduce the negative effects of the intensification of agricultural production emerged at a European level in the early 1990s. From 1992 onwards, successive CAP reforms introduced incentives for changes in agricultural practices: lower prices for agricultural products, agri-environmental measures, conditions for aid, green payments etc. However, these various measures had relatively little effect on changes in agricultural practices. To reverse the trend, National Action Plans have been introduced, such as France's Écophyto plan in 2008. Pesticide marketing authorisation procedures have also been reformed, incorporating stricter criteria for the approval of active substances. Although the assessment of pesticide risks and toxicity remains controversial, the number of authorised pesticides fell considerably in the 2000s. Nevertheless, France remains one of the world's biggest consumers of pesticides, with 85,000 tonnes of pesticides used in the country in 2018. These inputs are mainly used in arable crops, viticulture and arboriculture, which is reflected in the spatial distribution of pesticide sales in France. Agriculture's dependence on pesticides is due to a number of technical, economic and organisational factors, which act as a lock-in for the sector and limit the development of pesticide-free production methods.

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Chapter 2

Why do we need to change our crop protection strategies?

Florence Jacquet, Julia Jouan

French agriculture is currently heavily dependent on pesticides: from cropping systems, through to farms and to upstream and downstream companies, the entire operation of our agricultural and agri-food sectors relies on pesticide use (Figure 2.1). However, strategies do exist for reducing or even avoiding pesticide use altogether. One approach, Integrated Pest Management (IPM), seeks to limit the use of inputs as much as possible. The second, organic agriculture, involves specifications that prohibit the use of synthetic pesticides.

⏩ Pesticide dependency in agricultural systems: what are the obstacles to change?

At the cropping system scale: a vicious circle that encourages the use of pesticides

Three factors make the use of pesticides indispensable in conventional cropping systems. First, these cropping systems are generally based on a limited number of plant species and varieties, planted for several years in the case of perennial crops (arboriculture and viticulture) or frequently recurring in the same plot in the case of arable crops. Both cases encourage the development of pests. Second, over the years, varieties have been bred primarily for their high yields rather than for their pest resistance, which has made them progressively more susceptible. Today, however, disease resistance is part of the selection and listing criteria in official catalogues for the vast majority of cultivated species. Third, crops are planted at high densities, and increasingly earlier in the season for arable crops, with heavy reliance on fertilisation, which maximises yields but also encourages pest attacks. Given this context, synthetic pesticides have become essential to protect plants effectively against pests. The characteristics of today's cropping systems — low diversity, low-resistance varieties and high densities — have therefore developed through the use of pesticides (Delecourt *et al.*, 2019; Meynard and Girardin, 1991). Pesticides are regarded as inputs in the same way as seeds or fertilisation, and not as products with a curative purpose treating plants on an ad hoc basis. Indeed, they are often used as a preventive measure. Among pesticides, insecticides applied to vegetation also reduce the abundance of many non-target insects. By reducing the presence of beneficial organisms, pesticides reduce the potential for natural regulation, making pesticide use all the more necessary (van der Sluijs, 2020). A recent study suggests that insect biomass and biodiversity losses — including antagonistic species — may be contributing substantially to the upward trend in certain agricultural pest populations (Ziesche *et al.*, 2023). This situation is exacerbated by the disappearance of landscape features such as hedgerows and fallow land, further limiting beneficial populations that used to find refuge there. So, to maximise the surface area and frequency of the return of the most profitable crops, farmers favour practices that encourage pests, limit crop resistance and make pesticide use indispensable: they have become a "keystone" of cropping systems (Guichard *et al.*, 2017).

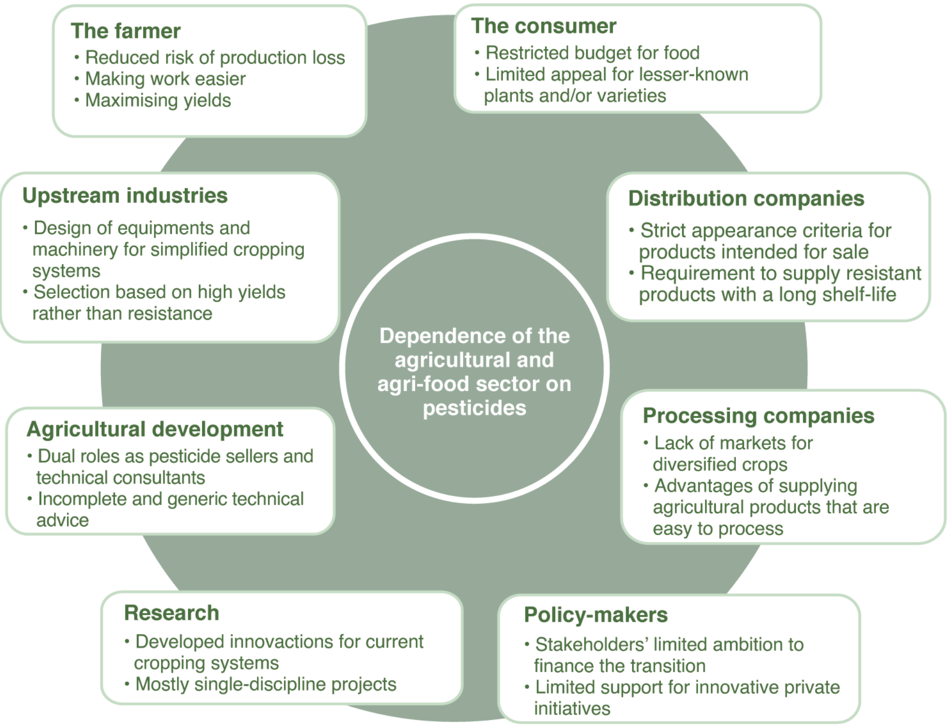

Figure 2.1. All actors in the agricultural and agri-food sector are dependent on pesticides.

Simultaneously, the repeated use of pesticides induces the development of pest resistance. Through this process, pests adapt to the active substances contained in pesticides, contributing to their ineffectiveness and in turn leading to more frequent treatments. This is particularly true for cereal herbicides, with the development of sulfonylurea-resistant flora in vulpine, wild oats and ryegrass (Chauvel *et al.*, 2009). To counter this phenomenon, farmers therefore find themselves involved in a kind of race, using more pesticides and new active substances to limit resistance (Bakker *et al.*, 2020), hampered by the lack of discovery of new modes of action. These two trends — a reduction in the number of beneficial organisms and an increase in resistance — has led to the emergence of a vicious circle which is at the root of mass pesticide use.

At the farm scale: pesticide use is subject to the economic context

Pesticides are an effective and inexpensive tool for controlling pests and limiting the risk of production losses (Chèze *et al.*, 2020). Since the late 1990s, the ratio of crop prices to pesticide prices has favoured pesticide use. So, although technical alternatives to pesticides are available, few of them are implemented because pesticides represent a simpler, quicker and, above all, cheaper solution to pest control, as long as we ignore the hidden costs linked to the negative externalities of pesticides (Box 2.1). The dependency of crops on pesticides is therefore closely linked to economic factors (Carpentier, 2010). Pesticides have also made the work of farmers easier. Coupled with increasingly high-performance farm machinery, they have made it possible to carry out tedious tasks, such as weeding, much more quickly and with unrivalled efficacy. This has made it possible to produce more with fewer farm workers, leading to an increase in farm size. The trend towards larger farms now represents a major obstacle to reducing pesticide use, especially as reducing pesticide use can increase the need for labour in some cases (in market gardening in particular) and therefore the associated production costs (Forget *et al.*, 2019). However, many agronomic solutions exist and already enable some farmers to reduce their pesticide use without reducing their income.

However, pesticide use is not always part of maximising income. For example, in order to achieve ever-higher yields, some farmers have a very high pesticide consumption, which reduces their gross margins and therefore does not allow them to maximise their income (Boussemart *et al.*, 2013; Nave *et al.*, 2013; Pedersen *et al.*, 2012). Others also overuse pesticides in order to minimise the risk of crop losses: here, pesticides serve as an insurance tool, particularly when agricultural products have a high added value (Aubert and Enjolras, 2014). In addition, farmers' lack training and information on natural regulations and the widespread use of pesticides has undoubtedly led to a lack of knowledge about how agroecosystems function, reinforcing the dependence on pesticides. Finally, farmers' intentions to reduce pesticide use seems strongly determined by whether other farmers also take the initiative (Bakker *et al.*, 2021; Stallman and James, 2015).

Box 2.1. The cost of dropping glyphosate use

France is Europe's biggest user of glyphosate. Due to widespread criticism of glyphosate's health and environmental effects, the use of the herbicide is being called into question (see Chapter 1). In order to assess the consequences of a potential ban, studies have been conducted on the additional costs generated by dropping glyphosate use in the three agricultural sectors that consume the most: arable crops, viticulture and arboriculture.

For arable crops, glyphosate is mainly used to control perennial weeds, regrowth and destroy plant cover. Crop management programmes using and not using glyphosate were reconstructed in several cereal-growing regions to compare costs. Without glyphosate, the extra costs obtained ranged from +€6.5/ha for frequent tillage through to +€80/ha for direct seeding, which is highly dependent on glyphosate. To measure the impact at the farm scale, these additional costs were applied to gross operating profit (GOP). They were relatively limited for farms using frequent tillage (around 1.5% of GOP), but had a much greater impact on no-till farms (from 14% to 23% of GOP, depending on the region). The question of ending glyphosate use in arable crops is therefore closely linked to the evolution of tillage strategies and, indirectly, to the market potential of non-glyphosate cropping systems (Carpentier *et al.*, 2020; Reboud *et al.*, 2017).

In viticulture, glyphosate is mainly used for inter-row weeding, and especially under-row weeding, as this area is very difficult to manage without herbicides. The alternative to glyphosate relies mainly on mechanical weeding and the costs of this technique have therefore been calculated for several vine management methods (in particular row spacing) and in several wine-growing regions. Including depreciation of the equipment required for mechanical weeding, the average extra cost obtained was +€210/ha for wide vine rows and +€408/ha for narrow vine rows, with results varying widely from one wine-growing region to another. In terms of EBE, additional costs represented less than 5% of EBE in several winegrowing regions, around 7.5% in the Loire Valley and Languedoc-Roussillon and up to 11.5% in Alsace (Jacquet *et al.*, 2019b).

In arboriculture, glyphosate is also used to weed under the row, i.e. beneath the trees, where the irrigation system is often located. The additional costs associated with mechanical weeding vary enormously, depending on the data analysed and the fruit grown. For example, it is +€478/ha for plum trees and +€724/ha for apple trees. In arboriculture, the extra cost would represent between 6% and 20% of EBE (Jacquet *et al.*, 2019a).

For these three sectors, the costs of phasing out glyphosate could be offset by public aid or the market. In particular, the development of value chains for glyphosate-free practices could be envisaged, as well as the strengthening of research and development (R&D) policies to make alternative solutions more competitive.

Beyond the farm: the entire agricultural sector is in a state of socio-technical lock-in

Today's cropping systems have developed in coherence with the organisation of upstream and downstream sectors, which have also structured themselves around pesticides. All actors have adapted their strategies, and their relationships with other actors, to the use of pesticides, with each actor's strategy reinforcing those of others

(Guichard *et al.*, 2017). This has led to a lock-in of the agricultural sector around pesticide use (Wilson and Tisdell, 2001). A system is technologically locked-in when self-reinforcing phenomena perpetuate dominant techniques, making it difficult to change to new techniques, even if they are potentially more desirable (Liebowitz and Margolis, 1995). This lock-in is found first and foremost upstream in the value chain: pesticide sellers are often also those who most directly advise farmers and therefore have a vested interest in proposing technical solutions based on pesticide use (Pedersen *et al.*, 2019). The separation of sales and advice, now enshrined in French law, seeks to address this situation. Development organisations also tend to favour specialised advice designed to identify a solution to a specific problem — in other words, a pesticide for a pest — rather than developing a more systemic approach that tackles all problems simultaneously and proposes several solutions in synergy. Plant breeding companies also contribute to this self-reinforcement by prioritising yield as the main selection criterion, thereby producing varieties that require pesticide protection to express their yield potential. So, genetic diversity also reflects this lock-in, since access to new varieties or species is limited both by the supply provided by breeding companies and by the inclusion in a national or European catalogue of varieties whose inclusion rules correspond to the dominant system (Bollier *et al.*, 2014). Some authors consider that lock-in is also caused by the patenting of living organisms (Orsi, 2002), but in the context of plant breeders' rights, it is mainly the first two processes at work. What's more, agricultural machinery companies have invested in technologies adapted to the production systems which are the most widespread (Fitzgerald, 2008).

Downstream in the value chain is also affected by the lock-in on pesticide use (Lamine *et al.*, 2010). One of the main factors contributing to this lock-in is the lack of investment and dedicated sales channels for diversification crops, limiting their value and therefore their profitability for farmers (Meynard *et al.*, 2018). For example, in a cooperative, it is the investment in storage facilities that induces the importance of filling these facilities and makes diversification and the introduction of new species difficult. Beyond this problem, the lack of added value is certainly the most important factor limiting the implementation of practices using little or no pesticides. Since the products resulting from these practices are not sold at higher prices than conventional products, farmers have no incentive to introduce them.

Another example concerns the varieties offered by breeding companies and cooperatives. These have been developed primarily for their yield, but also to optimise their use in agri-food companies' processing operations: their ability to resist pests is not included in this strategy (Nuijten *et al.*, 2018). Further downstream, some distribution and marketing channels also indirectly favour the use of pesticides, as they impose marketing criteria based on the absence of visual defects. This is particularly true in the fruit and vegetable sector (Carpentier, 2010).

Agricultural research is itself affected: most research programmes are designed to produce innovations that can be integrated into current farming systems, without considering any genuine redesign of these systems. Innovations to reduce pesticide use are more focused on optimisation or substitution solutions that enable pesticide use to be gradually reduced rather than system redesign (Vanloqueren and Baret, 2009). For example, research into biological control tends to develop alternatives to pesticides that function as substitutes, but are less effective and less widespread (Guichard *et al.*, 2017;

Raymaekers *et al.*, 2020). It is only in recent years that research has given sufficient importance to work that will lead to breakthrough agroecological innovations, ultimately enabling a substantial reduction in pesticide use and having beneficial spin-offs beyond the strictly agricultural perimeter. The launch of the Priority Research Programme "Growing and Protecting Crops Differently" is part of this change. As explained in Chapter 1, one of the underlying reasons for continued pesticide use is that their impact on health and the environment is not considered in assessments (Becker, 2017).

Key messages

The dependence of agricultural systems on pesticides exists at different scales. First, the simplification of cropping systems has made the use of pesticides unavoidable, a phenomenon reinforced by the emergence of pesticide resistance. Second, pesticides often represent the cheapest solution for limiting production losses on farms and help keep labour costs down. Third, all actors in the sector have developed their activities in a coherent way, based on the use of pesticides. This has led to a lock-in of the entire agricultural sector. For example, upstream companies offer equipment and services adapted to the use of pesticides, while downstream companies favour varieties adapted to their processing operations, but do not take into account their sensitivity to pests and do not offer outlets for diversification crops. Finally, a lack of added value for pesticide-free products does not encourage farmers to change their practices. Achieving pesticide-free agriculture therefore requires not just a change in farmers' practices, but a profound change in the agricultural sector as a whole.

⏩ IPM and organic agriculture: two dominant strategies for avoiding pesticides but reaching their limits

IPM: an overall strategy that is not widely applied

The concept of Integrated Pest Management (IPM) first appeared in the 1950s, when California entomologists proposed a combination of chemical and biological control of aphids in alfalfa fields (Stern *et al.*, 1959). Since then, the concept has evolved considerably and has been used in many contexts. It is now the cornerstone of Europe's pesticide reduction policy. According to the European Commission, IPM means "careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment" (European Commission, 2017). From this general definition, various principles follow:

– The prevention and/or suppression of pests must be based on a coherent set of agronomic practices.

– Pests must be monitored using appropriate methods and tools, integrating field observations, epidemiological surveillance and advice from qualified professionals.

– Based on the results of this monitoring, farmers must decide whether or not to apply pesticides, taking into account threshold levels of pest populations and climatic conditions.

– Biological and physical control methods, as well as any other sustainable non-chemical methods, should be preferred to chemical pesticides if they provide sufficiently effective pest control, with chemicals envisaged only as a last resort.
– The pesticides applied must be as specific as possible for the target pest and have the fewest possible side-effects on human health and the environment.
– Farmers must limit pesticide use to what is strictly necessary, using reduced doses and frequencies in order to limit the development of resistance in pests.
– When the risk of resistance is proven but pest pressure requires repeated pesticide applications on crops, anti-resistance strategies must be implemented, such as the use of several pesticides with different modes of action.
– On the basis of pesticide use records and pest monitoring, farmers must verify the success of crop protection interventions.

The aim of IPM is not to eradicate pests, but to manage them, keeping their populations below economically damaging levels while minimising pesticide use (Stenberg, 2017). To achieve this, a range of practices are employed (Table 2.1). They can be prophylactic, i.e. they reduce the appearance and/or excessive development of pests, or curative, while avoiding the use of chemical pesticides wherever possible. For example, beneficial organisms can be introduced directly into the environment to regulate the populations of certain pests. Prophylaxis combines actions at the plot and farm scale. In particular, it involves the introduction of long rotations, the use of appropriate cultivation techniques (adapted sowing dates and densities, and tillage), choosing varieties that are resistant or tolerant to pests, balanced fertilisation, the presence of fixed landscape elements (hedges, grass strips etc.) and all practices that encourage the presence of beneficial organisms.

The diversity of practices presented in Table 2.1 may involve more or less significant changes in cropping systems. This means we can speak of weak or strong IPM. The latter is particularly the case when several practices have to be combined. For example, the introduction of specific landscape organisation, combined with longer rotations and varietal mixes, necessarily leading to an in-depth rethinking of the cropping system, represents strong IPM. In contrast, simply reducing pesticide doses does not generally call into question the entire cropping system and represents weak IPM. This gradation of IPM can also be assessed with reference to the ESR conceptual framework (Efficiency-Substitution-Redesign) (Hill and MacRae, 1996). Weak IPM is confined to practices seeking to increase the effectiveness of pesticides (E), or substituting them with other means of control (S). In contrast, strong IPM requires the introduction of several complementary practices, leading to a profound redesign of the cropping system (R). Unsurprisingly, weak IPM is more readily accepted by farmers than strong IPM. Furthermore, implementing IPM practices is not just an individual choice, but may require a degree of coordination at the territorial scale. For example, setting up landscape infrastructure (hedges and fallow land) to encourage the presence of beneficial organisms requires coordination between farmers if it is to be effective (green corridors). Similarly, the use of mating disruption [3] in viticulture and arboriculture requires concerted action between the various producers in a given area.

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[3] Sexual confusion is a biological insect control method used in arboriculture and viticulture. By diffusing artificial sex pheromones, it reduces reproduction by scrambling the communication between males and females.

Table 2.1. Practices implemented as part of an IPM approach in three types of production within the DEPHY EXPE network (ÉcophytoPIC, 2020)

Management levers	Arable crops	Arboriculture	Market gardening
Action on stock, inoculum, populations	Ploughing False seedbeds Rotation: cover crops Rotation: diversification of cropping periods Rotation: resistant crops Residue management Trap crops	Leaf crushing Irrigation management Organ removal	Soil cultivation False seedbeds Rotation: green manure Intermediate crops Solarisation Residue management Trap crops
Avoidance	Shifting sowing date Landscape organisation		Shifting sowing/planting date Landscape organisation
Mitigation during cultivation	Fertilisation management Irrigation management Sowing density/spacing Mowing (meadows)	Tree aeration Fruit aeration Ground cover Manual thinning/pruning Sucker removal Rotary slashing Vigour control	Fertilisation management Irrigation management Sowing/planting density Mulching/ridging Climate management Growing on substrate
Genetic control	Varietal mixes Competitive varieties Resistant/tolerant varieties	Varietal/specific diversity Resistant rootstock Resistant/tolerant varieties	Resistant varieties Grafting
Physical control	Mechanical weeding Tillage Destruction of regrowth/weeds	Mechanical weeding Clay, talcum powder Sucker mowing Rain covers	Manual weeding Mechanical weeding Insect repellent nets Biofumigation
Biological control	Through conservation	Through conservation Microorganisms Sexual confusion Mass trapping Inoculative/inundation release Animals (poultry)	Microorganisms Pheromones Mass trapping Biodisinfection Macroorganisms
Chemical control	Localised application of pesticides Reducing pesticide doses Use of DSS Seed treatments	Localised application of pesticides Reducing pesticide doses Use of DSS Defence stimulators Phytotherapy	Localised application of pesticides Use of DSS Defence stimulators Phytotherapy Natural substances

Within the European Union (EU), IPM is the cornerstone of European policy on pesticide reduction. European Directive 2009/128/EC requires Member States to set up National Action Plans to achieve "a use of pesticides compatible with sustainable development". In France, this is the Écophyto plan in its successive forms. However, this IPM-based strategy has not proved effective on a European scale: the deployment of IPM has remained relatively limited and the results in terms of pesticide reductions are poor. This low impact can be explained by various factors: (i) confusion over the definition of IPM; (ii) inconsistencies between the concepts, practice and policies supporting IPM; (iii) lack of understanding of the ecological concepts underlying the strategy (Deguine *et al.*, 2021). Furthermore, the wide range of practices associated with IPM mean that farmers adopt only the most accessible options, which are potentially the least effective in terms of pesticide reduction (Lefebvre *et al.*, 2015). So, the implementation of practices included in strong IPM is often reserved for innovative farmers, as their large-scale deployment still remains a challenge (Lamichhane and Messéan, 2016). Finally, the dependence of the entire agricultural and agri-food sector on pesticides, as well as the priority given to alternative solutions, limits the spread of IPM and the potential for its continuous improvement.

Organic agriculture: a production method that creates added value but with limited yields

Organic agriculture emerged in France in the 1950s as a counter-current to the intensification of agriculture that was taking place at the time. Farmers, doctors, researchers and citizens came together to defend a "natural diet", criticising the excesses of the agri-food and farming industries (Box 2.2). Over the years, organic agriculture became more structured with the creation of commercial brands and producer and consumer associations, followed by the introduction of the first technical specifications in the early 1970s (Leroux, 2015). With public authority recognition of organic production, it developed more significantly in the 1980s and has seen a real boom since 2010. Between 1998 and 2022, the area of French farmland cultivated organically has increased tenfold, with an average annual increase of +13% since 2010 (Figure 2.2). In 2022, around 14% of French farms were organic, corresponding to 10.7% of the country's certified agricultural area, a significant proportion of which is dedicated to grassland and forage crops (Agence Bio, 2024).

Organic agriculture is a systemic production method, aimed at strengthening the health of the agrosystem and preserving biodiversity, as well as enhancing soil geochemical cycles and biological activity. Its specifications prohibit all synthetic chemical inputs, such as mineral fertilisers and synthetic pesticides and strongly limits the use of antibiotics (Box 2.3). Mineral fungicide treatments, particularly copper, are used, especially in viticulture. Organic agriculture favours a preventive approach to a plant's nutritional and crop protection requirements. When converting to organic production, a major redesign of the cropping system is generally required, including long, multi-annual rotations including legumes and plant cover crops, and spreading livestock manure (FNAB, 2019). Organic production is therefore traditionally based on a mixed system combining crops and livestock (Nowak *et al.*, 2013). However, due to the specialisation of farms and regions, many organic farms do not include livestock and must therefore import organic fertilisers for their crops if the nitrogen supply from legumes is not sufficient. The availability of soluble phosphorus then rapidly becomes a limit in organic cereal systems. In terms of crop protection, there is a heavy reliance on prophylaxis through crop rotation, tillage and the creation of landscape infrastructure that encourages the presence of beneficial organisms. Mechanical pest control is also widely practiced. The lower availability of nutrients and the difficulty of crop protection explain the lower yields observed in organic systems, with average reductions of 20% (Röös *et al.*, 2018). This also explains the importance of grasslands in organic systems. On the one hand, grass-legume combinations limit yield reductions and the incidence of pests in grasslands is low. On the other, the presence of animals is favourable to all crops by completing nutrient cycles.

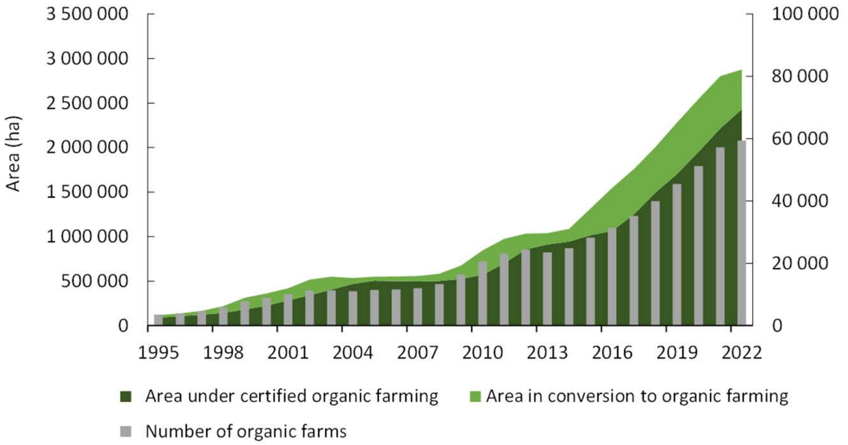

Figure 2.2. Surface area and number of farms involved in organic agriculture in France (1995-2022) (Agence Bio, 2024).

Box 2.2. Organic agriculture: from an ideological trend to a dedicated sector

At the beginning of the 20th century, a number of European scientists and researchers developed what would become the technical and theoretical foundations of organic agriculture. In particular, the work of Germany's Rudolf Steiner on biodynamic agriculture,

Britain's Albert Howard on organic farming, Switzerland's Hans Peter Rusch on the link between microorganisms and soil fertility, and Japan's Masanobu Fukuoka (Besson, 2009). In France, it was not until the 1950s that farmers who did not see themselves as part of mainstream farming practices took up these ideas and championed a "natural diet". Associations bringing together doctors, farmers and pharmacists were formed to defend "healthy" eating and a "natural" diet.

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In the early days of the "natural medicine" movement, they drew on rather traditional, even reactionary, currents of thought. With little support from their peers, they turned to the peasant and biodynamic farming networks that were emerging at the same time. This choice, which led them to refuse the application of modern technologies, had consequences for the adoption of organic agriculture, leading to a certain mistrust among other farmers and an anecdotal dimension to its development.

In the early 1960s, increasing numbers of farmers' and consumers' associations denounced the intensive practices of the agricultural and agri-food sectors. From this plurality emerged two main movements that would influence the history of organic agriculture in France. First, was the "Lemaire-Boucher" method, which dominated the organic sector until the mid-1970s. Its founders, Raoul Lemaire and Jean Boucher, developed fertilisers and high-yield wheat seeds, eventually creating their own brand under which many farmers united. In reaction to this commercial approach, the Nature & Progrès movement was created in 1964. Closer to the social and political movements of the late 1960s, this association welcomed many neo-ruralists and defended small producers with an anti-capitalist vision. In the 1970s, Nature & Progrès brought together various actors in the agricultural and agri-food sectors (producers, processors and distributors), including consumers, and helped organise the organic sector. It created the first technical specifications, and was at the origin of purchasing groups for organic products, enabling consumers to obtain supplies at more affordable prices than through the usual channels. The impact of this association was therefore decisive: it gave impetus to the federative dynamic that would enable organic farmers to embark on the road to recognition by the public authorities in the 1980s.

Nevertheless, until the end of the 20th century organic agriculture remained a marginal movement, both in terms of the number of affiliated farmers and the values defended. Based on a critique of the productivist system, and even of capitalism, the movement struggled to become more popular. Its political proximity to the extreme left, its practices sometimes perceived as esoteric and its tendency to make nature sacred marginalised organic agriculture among the farming profession. It was not until the 2000s, with the multiplication of health scandals that profoundly altered public opinion about the excesses of intensive agriculture, that organic agriculture became more popular and more a mode of production than a way of life (Leroux, 2015).

Box 2.3. Main elements of organic specifications for crop production

Organic production is closely linked to the specifications successively assigned to it. The first private specification appeared in 1972. In 1980, France officially recognised organic production as "agriculture without synthetic chemicals" and then approved and harmonised the various existing specifications. In 1991, a European regulation was introduced for organic crop production, which was extended to animal production in 1999. These regulations harmonise the practices of the various Member States (INAO, 2016). Table 2.2 summarises the main elements of the specifications for organic crop production (FNAB, 2019).

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Table 2.2. The main elements of the specifications for organic crop production (FNAB, 2019)

Theme	Content of specifications
Conversion	Annual crops (cereals): 2 years before sowing Permanent pasture and fodder: 2 years before use in organic animal feed Perennial crops (vines, fruit trees): 3 years before first harvest
Soil management and fertilisation	Soil fertility and biological activity are preserved and enhanced through: • Crop rotation, including legumes and green manures • Spreading of livestock manure or organic matter If the nutritional needs of crops are not covered, only the organic fertilisers and soil conditioners listed in Appendix I of the specifications may be used. They must not be derived from industrial livestock farms.
Crop protection	Preventing damage caused by pests relies mainly on: • Protecting natural predators • Choice of species and varieties • Crop rotation • Cultivation techniques • Thermal processes In the event of a proven threat to a crop, pesticides may be used provided that the active substances are listed in Annex II of Regulation n°889/2008*. Unlike other active substances, copper has a specific quantity limit under organic regulations. The maximum copper dose is 6 kg/ha/year.
Seeds and seedlings	Seeds and seedlings must be organic. When organic options are not available, seeds and seedlings can be purchased: • As a priority, from a production unit in conversion. • If this is not possible, conventional agriculture (untreated).
GMO	It is forbidden to use genetically modified plants in organic farming.
Mixed	In principle, an entire farm is managed organically. However, it is possible to have both organic and conventional areas on the same farm, provided that only different and easily distinguishable varieties are grown at the same time.
Monitoring	The certification body carries out an on-site inspection (physical and documentary) at least once a year.
Plant production logbook	A plant production logbook must be kept up to date and be available. In particular, it includes: • Documents attesting to the need to use derogated inputs. • Documents certifying that the products purchased are authorised for use in organic production.
Cleaning	Only products complying with the criteria listed in Appendix II of the French specifications (known as CCF) may be used for cleaning and disinfecting buildings and plant production facilities.

* Official Journal of the European Union, Commission Regulation (EC) No 889/2008 of 5 September 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control, 250 OJ L, (2008) http://data.europa.eu/eli/reg/2008/889/oj/fra

The productive performance of organic agriculture is traditionally assessed by comparing the yields of organic crops with those of conventional ones. Numerous studies show that organic production is generally characterised by lower yields than a conventional approach, with yield differentials varying according to the crops and practices used (de Ponti *et al.*, 2012; Ponisio *et al.*, 2015; Seufert *et al.*, 2012) and partly due to the choice of hardier varieties. A recent meta-analysis revealed that the yield of organic production is 18.4% lower than that of conventional production, with large variations depending on climatic conditions (de la Cruz *et al.*, 2023). Furthermore, organic yields are more variable, which increases the risks for farmers (Knapp and van der Heijden, 2018). Despite these constraints, organic agriculture remains a profitable production method for farmers due to higher selling prices, which help to compensate for lower yields. These higher sales prices stem from consumers' high levels of willingness to pay these prices, considering organic products to be healthier, fresher and with better organoleptic qualities (Schleenbecker and Hamm, 2013; Wier *et al.*, 2008). Demand for organic agricultural and agri-food products has grown strongly in recent years. The proportion of organic consumers in the French population has risen from 46% in 2009 to 71% in 2019. Due to food inflation, the attractiveness of organic products has been declining in recent years, with only 60% of French people saying they had consumed organic products in 2022 (Agence Bio, 2024).

With regard to the profitability differential between organic and conventional farms, it is difficult to draw any general conclusions (Guyomard, 2013). However, organic agriculture is clearly the most economically efficient system for reducing pesticide use. This is highlighted by the results of experiments in arboriculture conducted in France's DEPHY network, which show that pesticide reduction leads to a drop in yields in all systems, but that this is offset by higher prices for fruit from organic farms (Écophyto Dephy, 2018). Organic agriculture's ability to dispense with pesticides while generating income comparable to conventional farming is particularly clear in sectors where the product is sold directly to consumers, without processing and with few intermediaries: wine, fruit and vegetables and, to a lesser extent, beef (Dedieu *et al.*, 2017; Grémillet and Fosse, 2020).

The evaluation of organic agriculture's performance must also take into account the externalities it generates. Compared to conventional agriculture, organic production generates more positive externalities for biodiversity (Maeder *et al.,* 2002) and fewer negative externalities in terms of pollution (of water and soil) and exposure of the population to pesticide residues (Sautereau *et al.,* 2016). However, several questions remain unanswered about the benefits of organics and its large-scale development. The development of organic production in large-scale market gardens growing protected crops and arable farms, as we are currently seeing, raises questions about an "industrialised" model for organic production, with heavy reliance on external inputs (such as organic fertilisation), high energy expenditure and, as a result, an undoubtedly unfavourable carbon footprint. In addition, the use of crop treatment products authorised for use in organic farming is not without its environmental impacts, copper being a case in point (Box 2.4).

Finally, organic agriculture's lower yields raise the question of its ability to "feed the world". On this point, most authors agree that because organic production requires more land to produce the same quantity of products (Seufert *et al.*, 2012), its widespread adoption implies adapting the entire food system, consuming fewer animal products and limiting food waste (Muller *et al.*, 2017; Poux and Aubert, 2019). Finally, it will undoubtedly be difficult to achieve a high share of organic food products in consumption without increasing the budget that consumers dedicate to food, unless eating habits change (fewer animal products). Questions of social equity then arise, with the poorest people finding it difficult to access certified organic products.

Box 2.4. Copper-based treatments: the need for alternatives

Copper is traditionally used to prevent or treat certain fungal and bacterial diseases, mainly in viticulture, arboriculture and vegetable production. It has become indispensable to organic farming, as it is the only active substance approved for use in organic production with a strong fungicidal effect and a wide range of action.

Copper is mainly used in ionic form, in formulations based on salts (sulphate or hydroxide) combined with various adjuvants. Bordeaux mixture (copper sulphate plus lime) is emblematic of this type of formulation. It is generally sprayed on the aerial parts of plants, but can also be applied locally (as a slurry on tree wounds), or used as a seed treatment for cereals. Copper is registered for more than 50 uses in plant protection, each defined by a combination of pathogen(s)/crop. Among these uses, three can be considered major: downy mildew in grapes, apple scab and late blight in potatoes.

Repeated copper applications are the main source of copper pollution in agricultural soils. The massive use of Bordeaux mixture to combat downy mildew is responsible for very high copper levels in wine-growing soils: from 200 mg/kg to 500 mg/kg, and even 1,000 mg/kg in extremely contaminated soils (Michaud *et al.*, 2007), compared with 3 mg/kg to 100 mg/kg in natural soils. Excess copper in soils has deleterious effects on most plants, and also on soil microfauna and macrofauna (such as springtails). Because of these environmental impacts, restrictions on its use have been introduced in France and most EU countries: the maximum authorised dose of copper metal is 4 kg/ha/year. Although actual copper consumption is often well below the maximum authorised doses, it remains high, and is highly dependent on climatic conditions that are favourable to pathogens.

A large number of studies have shown that a significant reduction in the quantities of copper applied is nevertheless possible by maintaining the frequency of use but drastically reducing the doses per pass and improving the quality of spraying. For example, 1.5 kg of copper metal per hectare per year provides very satisfactory disease protection, compared with 3 kg/ha/year in most conventional programmes. In addition to dose reduction and the generalisation of prophylactic approaches to reduce inoculum sources, alternative methods to copper can be employed, such as rain protection, varietal mixes or antagonistic microorganisms (Andrivon *et al.*, 2018). A few pilot experiments have shown that these systems combining several levers make it possible to do without copper altogether, but their effectiveness is highly dependent on the genetic characteristics of varietal resistance or the prophylactic measures introduced. The adoption of such systems therefore implies major ruptures that require significant adjustments throughout production chains (Andrivon *et al.*, 2018).

Although organic agriculture currently enables farmers to be adequately remunerated while limiting the negative externalities associated with pesticide use, its lower yields, technical difficulties and, more generally, the reluctance of a large number of farmers are still major obstacles to its widespread use. The third path we offer in this book aims to go beyond IPM and organic approaches to imagine a pesticide-free agriculture based on the principles of agroecology and emphasising the full range of prophylactic measures.

Key messages

Two strategies are currently being developed to reduce pesticide use. The first is IPM, which aims to manage pest populations in order to limit economic losses while minimising pesticide use. The EU has instructed Member States to develop action plans to deploy IPM on a large scale, which in France is reflected in the Écophyto plan. However, this strategy has not proved effective: farmers have mainly implemented the most accessible IPM practices, based on pesticide substitution, without necessarily designing new systems to promote prophylaxis. The difficulty of implementing strong IPM practices without being able to promote them to consumers also explains this failure. The other effective strategy for reducing overall pesticide use is the development of organic agriculture. This approach bans all synthetic chemical pesticides, which automatically leads to a reduction in pesticide use when a farm converts to this production method. Organic farming often requires a major redesign of the cropping system to ensure satisfactory plant protection and nutrition. Thanks to lower input costs and higher market prices, organic agriculture is a profitable production method. It is even more profitable than conventional agriculture in some areas, such as viticulture. Nevertheless, its lower yields and consequently higher prices for consumers, are a major obstacle to its large-scale development.

⏩ Conclusion

Today's agricultural systems are dependent on pesticides due to a combination of factors. The simplification of cropping systems, combined with the emergence of pest resistance, has made the use of pesticides unavoidable. Pesticides make it possible to protect crops at a relatively low cost to farmers, while limiting their workloads. But beyond the farm gate, the entire agricultural and agri-food sectors have become structured around the use of pesticides: upstream companies offer equipment and services adapted to pesticide-using systems, while downstream, few value the efforts made by farmers to limit pesticide use. In particular, the introduction of IPM practices is hampered by the lack of differentiation for products derived from this production method. In contrast, organic farming has seen strong growth in recent years, thanks to effective product differentiation which, combined with limited input costs, ensures a certain level of profitability. Nevertheless, this production method has lower yields than conventional agriculture and certain technical impasses remain in terms of crop protection. Against this backdrop, we propose a third path beyond IPM and organic production: pesticide-free agriculture based on the principles of agroecology, with a focus on prophylaxis.

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Chapter 3

Agroecological cropping systems to reduce pesticide use

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The issue of low pesticide use in agricultural systems is not new (no or very few pesticides were available in the 19th century). But once these inputs were developed, they gradually became the keystone of agricultural systems (Meynard and Girardin, 1991). The identification of links between agriculture and environmental problems and, more recently, human health problems has stimulated the development of research dedicated to reducing the use of these inputs, and the emergence of public policies both in France and across Europe. However, we are still a long way from a sifgnificant reduction of pesticide use in practice. Indeed, for many stakeholders in agriculture, pesticides remain emblematic of technical progress and many farmers in northern countries use them to improve yields and product quality. Furthermore, their high efficacy and low cost have led, during a long period, to leave out research on alternative methods. Agronomists' investment in integrated crop protection began (timidly at first) in the 1970s and 1980s, with work on Integrated Pest Management and only gained momentum in the later years of the 20th century, with the development of systems agronomy (Lucas and Meynard, 2000).

⏩ Growing without pesticides requires a radical change in the way agricultural practices are managed

Current cropping systems are built around pesticides

In Western Europe, the intensification of farming systems, which began in the 1950s, still has a strong influence on current agricultural practices: in spite of the environmental, health and social challenges agriculture faces, most cropping systems still rely on pesticides to achieve maximum production or to control product quality. The various limiting factors occurring during crop cycles, such as diseases, insects, weeds, nitrogen deficiency, water stress and lodging, are controlled by inputs, such as pesticides, nitrogen fertilisers, irrigation water and growth regulators. Technical innovations, successively proposed since the 1950s, were consistent with the availability of these inputs and made their use increasingly necessary for farmers, putting them at the heart of farming systems. For example, in wheat, choosing highly productive varieties (but not more resistant to pests), earlier sowing dates, and higher sowing densities (to capture more radiation from the start of the cycle), and the search for non-limiting nitrogen nutrition supported this intensification, thus requiring the use of fungicides and growth regulators (to control lodging), and the more frequent use of insecticides in autumn (Meynard and Girardin, 1991). In winegrowing systems, the implementation of foliage management practices, such as deadheading and leaf thinning, has mostly been developed in relation with the balance between carbon supply in the leaves and carbon demand in the developing grapes (based on crop vigour indicators; Merot and Wéry, 2017), but less so for the objective of managing the microclimate around bunches. Yet an aerated microclimate limits the development of cryptogamic diseases (Fernaud *et al.*, 2001). In short, once it was understood that pesticides could be relied upon to deal with pest damage, there was no longer any fear that other techniques would increase risks and prophylaxis was neglected: pesticides became inescapable. However, the more widespread the use of pesticides was, the more pest populations have adapted through the development of resistance to active substances and their modes of action. For example, in some regions, the large areas of oilseed rape have led to an increase in insect populations affecting these crops, resulting in high levels of insecticide use (Schott *et al.*, 2010). This practice led to the emergence and spreading of pyrethroid resistance in flea beetle and bud weevil populations (Terres Inovia, 2019), which is now leading farmers to abandoning this crop or resorting to another molecule with a problematical toxicological/ecotoxicological spectrum (phosmet). The same trends have been described, for example, for cotton in Thailand (Castella *et al.*, 1999) and soybean in Argentina (Salembier *et al.*, 2014). Pesticides were used so much that they became less effective, then farmers used them even more to successfully control pests, building in the long term to a kind of deadlock, reinforced by the regulatory withdrawal of many molecules and the lack of discovery of new modes of action.

Consequently, only a systemic approach, reconfiguring the rationale behind crop management, will make it possible to do without pesticides while limiting yield losses linked to pests. Indeed, a significant reduction in pesticide use will require a radical change in the initial objectives targeted when planning crop management, aiming at limiting the risks of pests emergence and development during the crop cycle (Loyce *et al.*, 2008; Jacquet *et al.*, 2011). But the low cost of pesticides (compared with the hidden costs of their impacts), their ease of use, the dominant logic of crop management (based on their availability) and the organisation of most agricultural advice based on these inputs, currently make this change in rationale extremely difficult. The overall coherence of agricultural systems, from the plot to the territory, needs to be questioned, leading to a necessary profound change in the activities and organisation of current R&D.

Growing without pesticides requires a systemic approach aimed at prophylaxis

To avoid the need for chemical control (or its use only as a last solution), several categories of techniques can be used to control pests, either before their emergence, through prophylactic measures (agroecological crop protection, Deguine *et al.*, 2023) or curatively (curative control): genetic control, physical control, biological control and cultural control (Attoumani-Ronceux *et al.*, 2011). The major success in reducing pesticides relies on implementing prophylactic measures (genetic and cultural control), explicitly aimed at reducing pest risks before an epidemic and at limiting the damage and impact they may cause (Meynard *et al.*, 2003). In the case of perennial crops (orchard and vineyard systems), these techniques need to be considered as soon as the planting stage, as there is less room for manoeuvre during the crop cycle, compared to annual crops (Box 3.3). More specifically, practices should be reasoned in the view to affect different stages of the pest and crop cycle, so as to limit the emergence, the development and the incidence of pests, as well as crop contamination and derived losses. These methods involve various strategies:

- Reducing the initial stock (inoculum), with the aim of limiting pest populations.
- Escaping, based on avoiding the overlap between the pest's contamination phase and the period when the crop is susceptible.
- Crop mitigation, designed to reduce damage when the pest is present in the crop.
- Remedial solutions, to limit damage when the above levers have not been sufficient to prevent attacks leading to unacceptable losses.

Applied and adapted for each major pest type (fungi, insects, weeds etc.), these major principles have been summarised in operational methodological guides for arable crops (Attoumani-Ronceux *et al.*, 2011), vineyard systems (Barbier *et al.*, 2011), vegetable systems (Launais *et al.*, 2014), orchards (Laget *et al.*, 2015), and tropical systems (Bruchon *et al.*, 2015). These principles, allowing to identify a wide range of usable practices, have been widely used for the redesign of farming systems aimed at major reductions in pesticide use, within the framework of the innovative cropping systems joint technology network (known as RMT SdCi, Petit *et al.*, 2012b). Ratnadass *et al.* (2012) specify the biological processes that are activated in multi-species intercrops: (1) dilution of resources available for pests, and visual disturbance, (2) spatial cycle disruption, (3) temporal cycle disruption, (4) allelopathic effects, (5) suppressive effect of soil microfauna and macrofauna on pests, (6) physiological crop resistance, (7) conservation of natural enemies and facilitation of their action against aerial pests and (8) direct and indirect architectural/physical effects (Box 3.1).

Box 3.1. The BE-CREATIVE research project: co-designing pesticide-free territories (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

BE-CREATIVE was built on the conviction that a project for pesticide-free agriculture requires systemic thinking and management at a territorial scale. The project is developing an innovative approach to co-design pesticide-free territories, based on a disruptive approach of ecological, socio-economic and technical dynamics, with and for local stakeholders. To bring this project to fruition, an ambitious research programme has been established in 10 case studies throughout mainland France, where the consortium's researchers are already working with local partners toward putting an end to pesticide use.

...

...

The project has three main objectives: (1) defining the design target on the basis of socio-technical diagnoses conducted in the case study areas, (2) generating solutions using innovative design approach, in order to design pesticide-free territories, (3) evaluating the performance, impacts and services of the solutions built and implemented in the case study areas (INRAE, 2024a).

As each practice has a partial effect on pests, controlling them without pesticides requires a combination, over time and space, of several cultivation techniques. Furthermore, as the effect of each technique depends on the other techniques implemented (strong interactions between techniques), and on the climatic and biological conditions, it is virtually impossible to precisely predict the expected effects of implementing a technique in a given context. It is therefore illusory to attempt to precisely quantify the partial effects of each individual technique and then to add up their effects, insofar as these partial effects are conditioned by the other levers employed. In each situation, therefore, we need to use a rationale adapted to local conditions, with the aim of developing combinations of practices which best provide agroecological crop protection (Deguine *et al.*, 2021), based above all on prophylaxis.

This approach presupposes systemic reasoning about the links between the expected results, the biological, ecological and physico-chemical processes that may be involved in the cycle of target pests and the practices likely to modify these processes. For example, to reduce pesticide use in wheat, it is essential to radically change the rationale behind the management of the crop and to combine several technical choices explicitly aimed at reducing pest risk (Meynard *et al.*, 1991; Loyce *et al.*, 2008; Figure 3.1):

– A late sowing date, to reduce the risk of infestation by ryegrass and blackgrass, the two major weeds in wheat, and of attacks by autumn aphids, but also to limit early nitrogen requirements, which influence the risk of lodging and disease.
– A low sowing density to reduce nitrogen requirements and early stem growth, thus dispensing with growth regulators.
– Choosing a disease-resistant variety, or varieties mixtures, to reduce the risk of airborne diseases and fungicide use.
– Choosing a variety that is tolerant to early nitrogen deficiencies and has good bread-making capacity, even with limited nitrogen nutrition, in order to maintain high quantitative and qualitative production.
– A lower and later nitrogen fertilisation strategy, which also reduces the risk of airborne diseases and weakens the growth of nitrophilous weeds.
– A rotation with fewer cereals to reduce the risk of telluric diseases and thereby eliminating some fungicides.

As Lefèvre *et al.* (2020) have shown in protected vegetable systems, combining longer crop rotations, multi-species intercrops, the introduction of beneficial organisms, solarisation and various inoculum-reduction measures can help control pests and diseases while significantly reducing pesticide use. In the case of perennial crops such as vines, some levers such as rotations simply cannot be used, and changes in crop cycles are limited and uncertain. However, other alternative practices do exist, such as leaf thinning, controlled grassing, the use of mating disruption, de-budding and sucker removal[4] to reduce pesticide use, or the choice of grape varieties resistant to mildew and powdery mildew when planting new vines (Barbier *et al.*, 2011).

This reasoning assumes new knowledge to be available on technical alternatives, and on the biological processes to be exploited, mostly neglected until now, as agronomists had focused, in the second half of the 20th century, on the management of water, organic matter and mineral elements (Caron *et al.*, 2014). Indeed, for successful prophylaxis, current knowledge is still scarse on diversification species, service companion plants, the allelopathic effects of some plant species, natural plant defence systems and how to activate them, the effects of agroecological infrastructure on crop pests and beneficial organisms, the effects of various practices and combinations of practices, and the conditions for establishing and maintaining biological regulation of crop pests over time. Recent work has also demonstrated the value of a global approach to plant functioning. Based on a broad literature review, Husson *et al* (2021) show that pest development and attacks are correlated with spatio-temporal variations in the Eh (redox potential) — pH (hydrogen potential) homeostasis in plants. Research into this Eh — pH equilibrium should be enhanced, as this homeostasis could become a key factor in the future as a powerful tool for developing a systemic approach of the health of soil, plants, crops and animals, as part of a One Health approach.

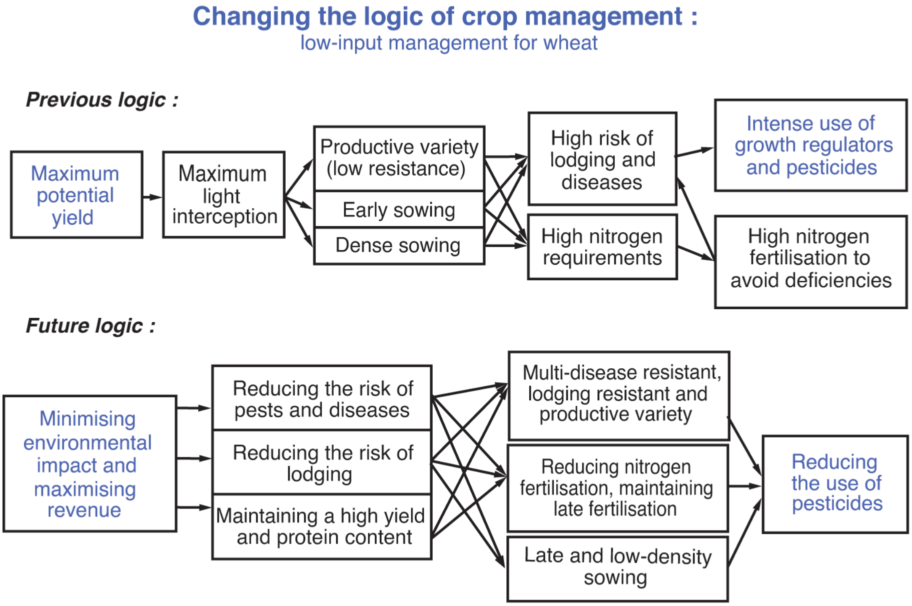

Figure 3.1. Former and alternative rationales for managing wheat crops, based either on non-limited input use (former logic aiming at maximum production), or on reduced input use (alternative logic based on the use of prophylaxis).

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[4] Pruning consists of eliminating the non-fruiting branches which grow on the rootstock, and de-budding involves the removal of all the buds or beginnings of unwanted branches. This provides better aeration of the vegetation and a better health status, in particular by reducing the risk of primary contamination from diseases such as mildew.

Key messages

In France, most current cropping systems heavily rely on pesticides to achieve maximum production and/or control product quality. However, deadlock situations are more and more numerous, such as pest resistance to pesticides and pest population explosions in monocultures or short rotations. To overcome the dependence on pesticides that is characteristic of today's agriculture while ensuring a high level of production, it is essential to enhance biological regulations, combining different scales of action (plant, crop, plot and landscape). In order to ensure major transformations in practices, it is therefore essential to implement a systemic approach, designed to reduce pest risks before their emergence, by promoting prophylaxis *via* combinations of practices adapted to and valuing local conditions and by relying on a redefinition of the performances and services expected from agroecosystems and the criteria for their evaluation.

⏩ Existing agronomic solutions for reducing and eliminating pesticide use

Diversifying rotations, cropping plans and landscapes

Extending crop rotations is a highly effective lever for reducing pesticide use, as demonstrated by the frequent use of this practice in organic farming systems. In conventional farming systems, we have also observed lower Treatment Frequency Indexes (TFI) (see Box 1.6) (reductions of up to 30%) on crops included in long successions (e.g. Burgundy, Table 3.1). However, crop sequences have become much shorter since the 1970s, and this trend is continuing, even if it is tending to slow down (Mignolet *et al.*, 2004; Schott *et al.*, 2010). For example, in some French departments, wheat crops follow wheat in more than 20% of fields in 2017 (according to the French Land Parcel Identification System — LPIS — 2018-2019; IGN, 2021). Among the levers that can be employed in crop diversification, alternating between winter and spring crops enables sowing dates to be varied, with a strong effect on the nature of emerging weeds (Chauvel *et al.*, 2001) and is therefore an effective technique for weed control (Chikowo *et al.*, 2009). Introducing a species from a different family into the rotation breaks the pathogen cycles likely to develop in the plot. For example, rotations with fewer cereals lead to lower risks of eyespot, fusarium foot rot and take-all (Colbach *et al.*, 1997) and of some weeds, particularly ryegrass and blackgrass (Chauvel *et al.*, 2001).

In the 1990s, the frequent return of pea crops in a same plot in some of the departments within the Paris Basin led to infestations of a root disease caused by *Aphanomyces euteiches*, which today prevents peas from being grown in the affected fields. The same problem has arisen in regions where lentils are grown under quality labels (AOC and AOP — "Appellation d'Origine Contrôlée" [Controlled Designation of Origin], and "Appellation d'Origine Protégée" [Protected Designation of Origin]), their high profitability leading farmers to shorten rotations by growing lentils more often in the same fields, with the surface area eligible for the quality label being limited by the small size of the label-authorised area. Conversely, introducing peas or another legume into a short rotation (Box 3.2), based exclusively on cereals and oilseed rape (the OSR-wheat-barley rotation which is very common in France), helps to limit several pests (Box 3.2), particularly weeds and some soilborne diseases, and reduces the amount of pesticides applied (Carrouée *et al.*, 2012). In the south of the Paris Basin, beet sometimes plays this diversification role. The same effect of diversifying the species grown in rotation has been observed in vegetables in France (Puech *et al.*, 2021) and in the arable cropping systems of the Argentine pampas, where diversified sequences (compared with the quasi-monoculture of soybean that dominates crop rotations) allow to reduce not only the use of glyphosate, but also of other herbicides, which are used to deal with weeds that have become resistant to glyphosate (Salembier *et al.*, 2016).

Table 3.1. Comparison of Treatment Frequency Index (TFI) by pesticide category (herbicide, fungicide and insecticide) and total, in short successions (oilseed rape (OSR) and straw cereals) or more diversified successions (with protein crops) and for crops (OSR and wheat) included in these successions. Example of Burgundy. Source: SSP — Agreste (2017)

	TFI_Herbicide	**TFI_Fungicide**	**TFI_Insecticide**	**TFI_Total**
Succession				
OSR – straw cereals	1.77	1.30	0.73	3.81
With protein crops	1.43	1.22	0.77	3.42
Difference	**- 19 %**	**- 6 %**	**+ 5 %**	**- 10 %**
Oilseed rape				
In OSR – straw cereal succession	2	1	2.5	5.6
In a succession with protein crops	1.8	1	1.9	4.7
Difference	**- 10 %**	**=**	**- 25 %**	**- 16 %**
Soft wheat				
In a OSR – straw cereal succession	1.7	1.3	0.2	3.2
In a succession with protein crops	1.6	0.9	0.2	2.7
Difference	**- 1 %**	**- 32 %**	**=**	**- 15 %**

At a landscape scale, there are numerous examples showing how the diversity of cropping systems and the presence of semi-natural habitats can help reduce pests and diseases. Indeed, cropping system mosaics, by creating a functional heterogeneity of cultivated landscapes, both spatial and temporal, linked to the diversity of crop phenology, of their growth cycle, of the techniques applied and of the crop sequence, play a key role in ecological processes, in particular the biological regulation of crop pests through the dynamics of arthropod populations (Vasseur *et al.*, 2013).

For example, a lower frequency of oilseed rape in a small agricultural region is correlated with lower pesticide use on each plot containing this crop (Schott *et al.*, 2010; Figure 3.2), the pests multiplication being disadvantaged by the lower frequency of host crops in the landscape. Furthermore, a higher proportion of forests and semi-natural habitats in the landscape, as well as the frequency of fields where oilseed rape, cultivated the previous year, is followed by reduced tillage (so as not to destroy beneficial organisms that spend part of their life cycle in the soil), explain the more effective biological control of pollen beetles (insect pests of oilseed rape) by beneficial organisms in these plots (Rusch *et al.*, 2012). In vineyard systems, flights of *Eudemis* and *Cochylis* and insecticide applications to reduce their impacts are much more frequent in simplified landscapes, compared with landscapes in which vines are surrounded by semi-natural habitats (Paredes *et al.*, 2021). In orchards, landscape composition has a strong effect on the presence of pests such as codling moth (Ricci *et al.*, 2009).

Moreover, agroecological infrastructure (flower strips and hedgerows) are designed to maintain, multiply and enhance the effectiveness of crop beneficial organisms, with the aim of controlling crop pests. To increase their effectiveness, i.e. to achieve conservation biological control (Landis *et al.*, 2000), while minimising the damaging effects on the crop, it is essential to carefully consider the composition of this infrastructure, as well as the management of neighbouring crops. For example, a plant mixture of 10 species (chosen on the basis of knowledge of their entomological populations) in a hedgerow bordering a pear orchard has helped to maintain a diverse range of beneficial organisms that are active against pear psyllid, one of the main pests in pear production (Simon *et al.*, 2009). The combination of species has made it possible to provide various groups of beneficial organisms with a succession of resources and habitats: hibernation shelters (evergreen species), food at times when it is scarce and qualitatively important for reproduction (pollen from early-flowering species), substitute prey (species-specific phytophagous insects), and nectar and pollen throughout the season. So, the composition of this infrastructure must have a clear and precise rationale to ensure the availability and accessibility of resources in sufficient quantity and quality throughout the year. In addition, infrastructure must provide the conditions to promote a favourable habitat and microclimate, conditions essential to the management of arthropod communities likely to provide effective control of insect pests (Gardarin *et al.*, 2018). The decisive role of the landscape leads to the need to conduct collective reflections on a territorial scale to design new landscapes that favour regulations and are resilient to emerging pests.

A synthesis of the effects of crop diversification and reduction in plot size, and of the presence of semi-natural spaces, leading to greater landscape heterogeneity, has been performed by Sirami *et al.* (2019). By observing seven taxa (plants, bees, butterflies, hoverflies, carabid beetles, spiders and birds) in 435 landscapes, the authors show that rich trophic chains enable more regulation. All of the elements highlighted in the various examples described above are present, with evidence of non-linear relationships and numerous interactions between levers, leading to heterogeneity in agricultural landscapes. This underlines the importance of designing landscapes that are conducive to regulation (Tscharntke *et al.*, 2021).

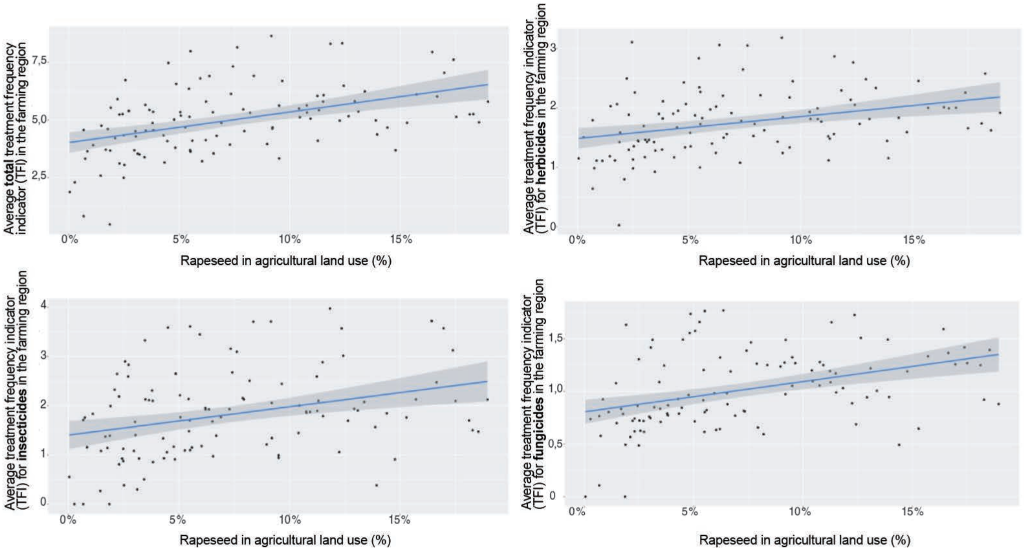

Figure 3.2. Relationship between the proportion of oilseed rape (OSR) in the UAA per small agricultural region (x-axis) and the pesticide treatment frequency index (TFI) per OSR plot. Sources: SSP — Agreste (2017) and IGN (2021).

Box 3.2. The SPECIFICS research project: designing pesticide-free cropping systems rich in pulses (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

The aim of SPECIFICS is to identify and evaluate various levers enabling the transition to pesticide-free arable cropping systems that include pulses by seeking new sources of resistance, integrating greater biological diversity over time (rotation) and space (intra- and interspecific combined crops, agroecological infrastructure etc.), and studying solutions for developing and promoting these systems. The project gathers together agronomists, geneticists, pathologists, entomologists, ecologists, economists and sociologists to design varieties, practices, crop management plans, and valuation and advisory methods that will help achieve the economic and agronomic sustainability objectives of pesticide-free cropping systems incorporating a significant proportion of pulses. The experiments are based on agroecology experimental platforms, in which pesticide-free cropping systems rich in legumes are widely implemented, as well as on an extensive system of surveys and economic data processing.

The project combines three approaches at three different scales to provide tools and recommendations for all actors involved in the transition. At the plant level, the aim is to work on the varietal resistance of legume crops to control a diversity of diseases and pests, from the production of knowledge on plant locus, genes, mechanisms and protective traits, to the design of varieties that are resilient to pests, and their multi-criteria evaluation. At the cropping system level, the project includes prototyping and evaluating innovative systems aimed at drastically reducing pesticides in order to analyse the coevolution of crops, pests and beneficial organisms in systems based on cultivated and associated biodiversity. At the level of agricultural and food systems, an analysis of lock-ins will help to understand the obstacles and levers to the deployment of pesticide-free cropping systems rich in legumes and to define solid incentives for stakeholders (INRAE, 2024b).

Introducing diversity in cultivated varieties and species within fields

The introduction of diversified sequences is a highly effective means (at least in annual crops) of reducing pesticide use, but it is rarely sufficient, requiring additional techniques. Growing resistant varieties is another effective lever for reducing pesticide use, particularly fungicides (Loyce *et al.*, 2008; Pertot *et al.*, 2017). For example, in winegrowing systems, growing of resistant grape varieties has increased in recent years, enabling a drastic reduction in fungicide TFI of 80% to 90% (Delière *et al.*, 2017). However, the frequency and spatial organisation of resistance genes in the landscape, as well as cultural practices that have an effect on the genetic evolution capacities of pests, must be carefully rationalised so as not to stimulate the resistance breakdown, but to maintain it in the long-term (Aubertot *et al.*, 2006; Delière *et al.*, 2017; Papaïx *et al.*, 2013).

To promote crop multi-resistance in cover crops to the diversity of pests likely to infest them in a given location, growing varieties mixtures, chosen for their complementary resistances, is also very effective and enables yields to be maintained or even slightly increased (Borg et al., 2018; de Vallavieille-Pope *et al.*, 2006). This technique was imposed in the 1990s for spring barley in eastern Germany, leading to a massive reduction in pesticide applications. It has also been widely used in rice in China, resulting in a reduction in the number of fungicide treatments from seven to zero, a very significant reduction given the severity of blast disease and an increase in yields (Zhu *et al.*, 2000). Similar efforts have been made in coffee crops in Colombia to combat orange rust. In France, despite the effectiveness of this technique, demonstrated in wheat against rusts and septoria (de Vallavieille-Pope *et al.*, 2006), to control scab in apple production (Parisi *et al.*, 2004), to protect willows against rust and potatoes against blight (Pilet, 2003), it has so far been little used by farmers. There are several reasons for this. First, collectors (cooperatives, wholesalers etc.) and the initial industrial processors, who prefer to work with pure varieties better adapted to current transformation processes. Second, a lack of adaptated regulations linked to the processing and marketing of varieties, favouring pure varieties (Guichard *et al.*, 2017). Regulations allowing the marketing of varieties mixtures were adopted in France as early as 2004 for forage species, but only at the end of the 2010s for annual crops. Furthermore, excessive phenological delays can disturb harvest. In vineyard, varietal mixtures are found in labour-intensive systems, rather than in those that are highly mechanised. However, the use of varietal combinations is increasing: while they covered less than 1% of France's wheat acreage in 2010, they accounted for more than 12% in 2020 (FranceAgriMer, 2020; Arvalis, 2021).

Another highly effective way of controlling a broad spectrum of pests through the crop canopy is to combine different species (Stomph *et al.*, 2020). Control can then be linked to various mechanisms: dilution of host density (efficient for diseases and insects), more ventilated microclimate in the canopy, a physical barrier effect slowing down the physical dispersal of pathogens, or increased temporal and spatial competitiveness with weeds. While species mixtures remain rare in conventional arable crops, legume-based mixtures are cultivated, particularly by organic farmers, where they also represent a means of cultivating legumes, the success of which is more uncertain when sown as a pure crop (Lamé *et al.*, 2015; Verret *et al.*, 2020).

While mixing varieties and species is becoming more widespread in arable crops, it is still very rare in other agricultural systems (vineyard, orchards and market gardening), particularly in contexts where the constraints imposed by downstream actors or quality labels are very high. However, research is exploring innovative ways of rethinking plant diversity in orchards, with the aim of "breaking" genetic monotony. One example is the Z experimental orchard (Simon *et al.*, 2017; Penvern *et al.*, 2018), a multi-species, multi-variety system (apple trees with stone and nut fruits, small fruits etc.). This highly innovative concept seeks to make the production space hostile to pests, thanks to the nature and spatial and temporal organisation of species and varieties, as well as the introduction of agroecological infrastructure in a circular orchard (Figure 3.3). Similarly, mixed vegetable — fruit tree systems are emerging on farms —, but still pose questions on work and profitability in both the short and long term (Paut *et al.*, 2021a).

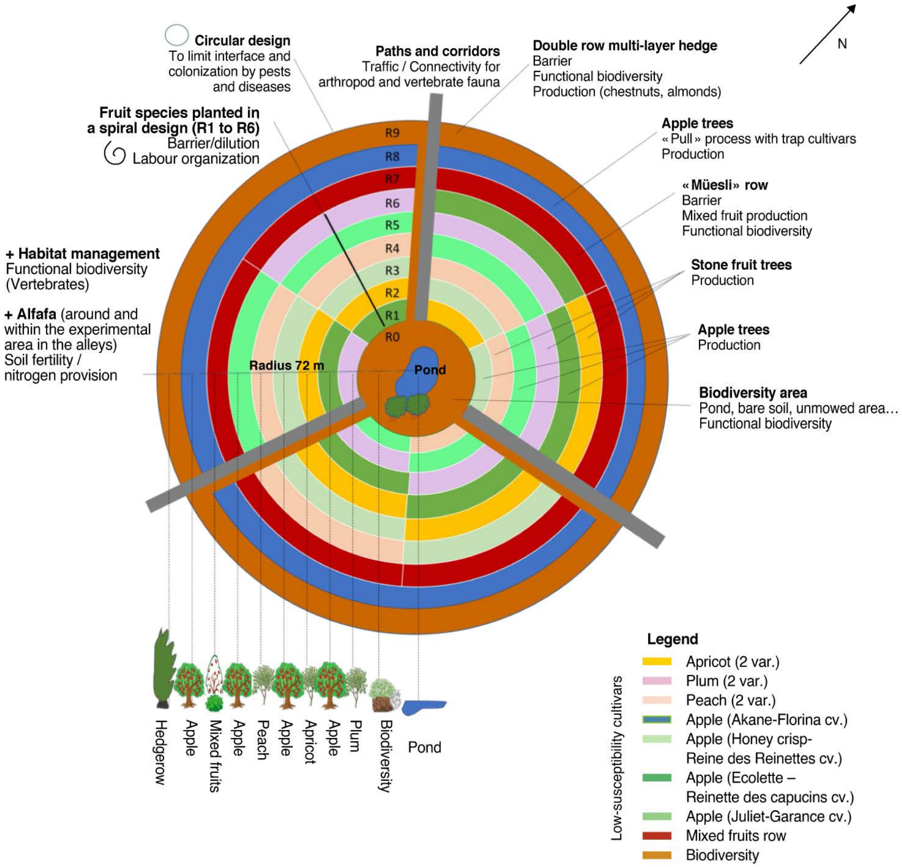

Figure 3.3. Description of the Z orchard, designed to promote the regulation of pests, planted in 2018 at INRAE's Gotheron experimental unit. The general objective was to create a "suppressive" fruit production space vis-à-vis pests, using biodiversity and spatial layout to limit the arrival, installation, development and dispersal of fruit tree pests. In this pesticide-free orchard, the main levers for action are barrier-dilution effects, diversified fruit planting material with low susceptibility to certain pests, prophylaxis and reinforcement of predation by planting and developing biodiversity zones favouring vertebrate and invertebrate beneficial organisms. Each circle targets several of the functions listed in the figure, and each function is performed by several components. The orchard, co-designed with local stakeholders, was planted over a total area of 1.7 hectares. (SaVAGE team, INRAE Gotheron, March 2018).

To support a large reduction in pesticide use, the management of varietal or multi-species mixtures must also be adapted. For example, combinations of wheat varieties are frequently chosen only to simplify work organisation and stabilise yields and harvest quality at the farm scale, and are therefore not associated with a significant reduction in pesticide use. As noted by de Vallavieille-Pope *et al.* (2006) and Jeuffroy *et al.* (2010), varietal mixtures are more efficient in reducing pesticide use when sowing density and early nitrogen fertilisation are reduced, and even when sowing date is delayed to reduce disease risk. Similarly, in apple orchards, a significant reduction in pesticide use involves combining disease-resistant or low-susceptibility varieties with agronomic methods such as mechanical weeding of the tree row and biological control (mating disruption and microbiological control), management of tree architecture through pruning to promote aeration inside the tree and limit humidity, as well as plant cover in orchard alleys and multispecies border hedges to provide resources and habitat for beneficial organisms (Simon *et al.*, 2017).

Alongside plants harvested for their production, growing service plants, not harvested but cultivated (and therefore chosen) for the services they provide to the agroecosystem, is another practice which encourages the introduction of cultivated biodiversity and is likely to help reduce pesticide use. These service plants, grown between two harvested crops (or partly during their cycle), can simultaneously produce various ecosystem services, with varying degrees of efficiency, depending on the species sown, their management, the soil and climate conditions, and the cash crops to which they are linked. The services provided concern (i) nitrogen management (nitrate trap effect), (ii) soil protection against erosion, (iii) carbon storage, (iv) reduction of pests (weeds and pathogens), (v) pollination, and (vi) landscape aesthetics. For example, intercropping oilseed rape with frost-sensitive legumes, sown at the same time, can reduce weeds (thanks to the competitiveness of the cover; Lorin *et al.*, 2015; 2017), and certain insects (thanks to an olfactory or visual confusion effect of the companion plants, which divert insects from their target; Breitenmoser *et al.*, 2020), leading to a reduction in the use of herbicides and insecticides. Biocontrol effects are also achieved in legume-cruciferous intercrops through various mechanisms: allelopathic effects, mixtures of host and non-host plants and trap crops, soil cover and use of abiotic resources, and increase in soil matter. However, the underlying processes need to be studied in greater depth before they can be effectively mobilised *via* adapted techniques (Couëdel *et al.*, 2017). In orchards, service cover crops can be managed to control pests. For example, a cover crop of white clover on the row of peach trees not only controls weeds, but also limits the development of brown rot in the fruit by promoting regular fruit enlargement, thereby limiting the formation of microcracks in the epidermis, which are entry points for *Monilinia* spores (Mercier *et al.*, 2008).

Managing pests and diseases through soil tillage

Tillage has well-known effects on weeds. In particular, ploughing buries weed seeds deep in the soil, leading to the loss of all or part of their germinative capacity before they are brought to the surface by later ploughing (Colbach *et al.*, 2000). However, in the case of weeds with low annual decline rates, the number of viable weeds may remain high even after several years of burial, thus limiting the effect of frequent ploughing on weed control. Similar effects are observed for soil pathogens. In the case of phoma stem canker (a cryptogamic disease) in oilseed rape, for example, burying crop residues limits aerial infestations linked to spore dissemination, with effects varying according to the equipment used for tillage (Schneider *et al.*, 2006). For example, a comparison of different cropping system mosaic scenarios aimed at controlling phoma showed that tillage was more effective than spatial management of varieties (depending on their resistance) in managing the disease and the resistance durability (Hossard *et al.*, 2018). However, depending on the crop succession, ploughing can also have the opposite effect and favour pests. For example, in the case of eyespot in wheat, Colbach and Meynard (1995) have shown that if ploughing follows a host crop, it buries the primary inoculum, thereby protecting the following host crop. However, if the previous crop is not a host of this pathogen, but the antecedent one is, then ploughing brings the inoculum to the surface, increasing the risk of infestation of the crop following ploughing. It should be noted that the use of ploughing as a means of pest control must also be considered in light of its effects on soil biological activity.

Different tillage tools are available, with varying effects on the inversion of soil horizons and the burial of seeds or crop residues remaining on the surface after harvesting (Schneider *et al.*, 2006). Repeated stubble ploughing after weed emergence is effective in destroying cohorts of seedlings, but has the disadvantage of drying out the soil during the summer, when rainfall is generally scarcer, which can hamper the emergence of subsequent crops (e.g. oilseed rape). In organic farming, but also increasingly in conventional systems to reduce the use of herbicides, various mechanical weeding tools are used to destroy weed seedlings that emerge during cultivation: tine harrows, rotary hoes, hoeing machines, scalpers etc. However, they are generally not sufficient to destroy weeds and are used instead as complementary tools to other techniques aimed at reducing weed populations upstream (Casagrande *et al.*, 2009). To make an effective contribution to pest control, the rationale behind tillage cannot therefore be independent of other cultivation practices and the condition of the plot status, and must be adjusted on a case-by-case basis.

Given the multiple effects of tillage on pests, their control becomes complex in no-till systems, whose primary environmental objective is to preserve soil quality by maximising the return of organic matter to the soil's surface horizons. No-till systems are currently arising, as they limit the amount of time spent and energy consumed when tilling the soil, they promote microbial biodiversity and soil fertility (Zuber and Villamil, 2016), reduce erosion and, when no-till is combined with near-permanent soil cover as in conservation agriculture (Scopel *et al.*, 2013), improve soil carbon storage. Organic conservation agriculture (known as "ABC" systems in France) is a real challenge due to the difficulty of controlling weeds (Vincent-Caboud *et al.*, 2017). Cover crops are often grown in these systems to create strong competition with weeds during the cover crop cycle, then to limit weed seed germination thanks to the mulch composed with plant residues left on soil surface (Peigné *et al.*, 2015). However, a canopy with problems in seedlings emergence, that is uncompetitive with weeds and cereal regrowth can stimulate the development of weed seed stocks and the multiplication of take-all inoculum (Ennaifar *et al.*, 2005). The technical difficulties linked with crop management are numerous in such systems. More specifically, canopy establishment must be rapid and growth must be strong to ensure the expected effects, both depending on the choice of species and varieties, sowing date and density, destruction date, and nitrogen and water availability (Vincent-Caboud *et al.*, 2019). The critical nature of these choices means fine-tuning is needed, not only for the annual management of the crop but also the field management each year. To promote quasi-permanent soil cover, relay intercropping is an interesting solution (Amossé *et al.*, 2013). However, its management requires excellent technical skills: either to (i) sow the cover crop into the cash crop, so that it is well established by the time the latter is harvested, while avoiding too much competition between the crop and cover crop during the period both are combined, or (ii) to sow the cash crop into the cover crop that has not yet been destroyed, limiting as far as possible the periods when bare soil could enhance weed emergence and development. This latter requires specific, adapted equipment (Vincent-Caboud *et al.*, 2019). The objective of reducing pesticides, particularly herbicides, has therefore led to a change in posture that is reflected, among other things, in the vocabulary used. Where we used to speak about weed management, we now deal with managing associated vegetation so as to maximise its benefits and limit competition with the main crop. In addition to the primary role of reducing herbicides, maintaining a cover crop in perennial row crops limits erosion and enables farmers to go back to the plot more quickly after rainfall.

Identifying the many other levers that can be used

Alongside these best-known levers, many other techniques have effects on pests and can be implemented to reduce pesticide use. The efficacy of their effects requires to consider the links with the biological characteristics of the target pests (Table 3.2; Meynard *et al.*, 2003; Chauvel *et al.*, 2001). These techniques are not always available or easily accessible to practitioners.

Adjusting the sowing date to avoid certain pests is, for example, an effective technique in several annual crops. For wheat crops, delaying the sowing date, in interaction with soil moisture, significantly reduces the emergence of blackgrass (Colbach *et al.*, 2005), one of the most frequent and damaging weeds in current wheat crops. The delay also makes it possible to avoid flights of autumn aphids, which are often virus vectors, and to reduce contamination of wheat by diseases in autumn, limiting epidemics during the following spring (Colbach *et al.*, 1997). Advising earlier wheat sowing in the 1970s and 1980s aimed at increasing intercepted solar radiation and thus yields, and this was only made possible by the availability of pesticides (Meynard and Girardin, 1991). Very early oilseed rape sowing dates (Dejoux *et al.*, 2003), in situations of high soil nitrogen availability, has several benefits: (i) it favours crop competition with weeds, thanks to large growth and nitrogen uptake in autumn, (ii) it reduces phoma attacks by shifting the periods of crop susceptibility and pathogen spore dissemination, and (iii) it reduces slug damage, due to the often dry summer weather, which is unfavourable to slug activity, and higher leaf area index developed by crops in September-October, when humidity conditions become favourable to slugs.

Reducing crop nitrogen nutrition is often an effective way of limiting pests. For example, limiting nitrogen availability in the soil hinders the growth of nitrophilous weeds (Singh *et al.*, 2017), but reduces the crop's ability to compete with weeds

(Kristensen *et al.*, 2008). A crop with a high nitrogen content enhances aphids to multiply, providing them with a more balanced diet (in terms of C/N balance). Increased early nitrogen nutrition of oilseed rape also favours the development of phoma (Aubertot *et al.*, 2004), unless the crop is sown early, reducing its susceptibility to attack during periods of spore flow (Dejoux *et al.*, 2003). The link between nitrogen nutrition, vigour and fungal attacks is well known in winegrowing systems: the more vigorous the vine, the more leaves it produces and the more susceptible it is to fungal attacks (Valdes-Gomez *et al.*, 2011).

Table 3.2. Examples of agronomic techniques for controlling selected pests (according to Chauvel *et al.*, 2001; Valdes-Gomez *et al.*, 2011)

Pest	**Biological characteristics of the pest**	**Suggested cultural practices**	**Expected effects of practice on the pest**
Blackgrass (Alopecurus myosuroides Huds.)	Short persistence of seeds in soil Germination limited to the first centimetres of soil and low dormancy Preferred emergence period is autumn Nitrophilous species, in competition with crop for nitrogen	Deep ploughing with soil inversion after crop with high degree of vulpine seed production Deep tillage; false seedbed Delayed sowing date; introduction of spring crops into the rotation Low nitrogen fertiliser input	Increased seed mortality in the soil Before sowing, remove successive cohorts of seedlings Shifting the preferred germination period for seeds Reduced seed production
Downy mildew	Develops in a humid microclimate Develops when bunches are tightly packed Develops on young leaves and vigorous vines Transmitted by splashing from floor to vine stock	Practice of topping, trimming and leaf removal Aeration of bunches through pruning, disbudding and de-stemming Topping Grass cover	Reduced humidity in bunches, better penetration of treatment products Reduced humidity in bunches, better penetration of treatment products Reduces plant sensitivity Reduces contamination

Grapevine leaf thinning modifies the microclimate within the canopy, thereby reducing the wetting time of aerial organs and therefore the germination of spores of parasitic fungi such as botrytis (Fernaud *et al.*, 2001). Similarly, centrifugal management of apple trees, compared with a more conventional raw-centred management, reduces infestations of rosy apple aphids and red spider mites though the effects on green aphids are more variable (Simon *et al.*, 2009).

Moreover, the allelopathic effects of some species (for example, cruciferous plants, oats and sorghum) have so far been little studied, despite their expected effects on soil pathogens and weeds (Couëdel *et al.*, 2017). The toxicity of molecules derived from the residues of these crops (for example, certain *Brassicaceae* are responsible for the production of isothiocyanates with a fungicidal effect) could be employed to control certain pests. This effect has been studied for a crop of brown mustard grown between two cash crops to control rhizoctonia in beet production. However, in this particular case, the effects observed are highly variable, being higher if the residues are buried, the duration of the mustard crop is longer and the biomass produced is greater (Motisi *et al.*, 2009).

Exploiting the complementarities between crops and livestock to control pests and diseases

The combination of crops and livestock is also an excellent lever for reducing pesticide use. Indeed, in the French DEPHY network of farms engaged in a strong reduction of pesticide use, the presence of livestock on the farm is a highly discriminating variable in the level of pesticide use on cultivated plots (Lechenet *et al.*, 2016). On these farms, the presence of grassland and longer rotations generally explains this result. The introduction of medium-duration grassland into rotations is also used in organic agriculture as a means of weed control. However, the effectiveness of grassland in controlling weeds presupposes that it is mown regularly, to prevent the species from seeding, which could, on the contrary, encourage infestations. On these farms, composting manure is also an effective way of deactivating the seeds contained within it, and avoiding seeding plots with the seeds contained in manure.

The reintroduction of animals within arable systems, orchards or vineyards is also being used by innovative farmers to control various pests, weeds and soil pathogens (Paut *et al.*, 2021b). For example, sheep are grazing on vineyard inter-rows to limit competition between vines and sown cover and/or weeds, hens feed on potentially pathogenic larvae in vineyards or orchards (Clark and Gage, 1996), sheep are grazing to control young thistles, ducks have been introduced in rice fields and pigs in orchards to control weeds (Buehrer and Grieshop, 2014). However, managing these techniques is still in its infancy and should benefit from further research. Managing ducks in rice fields for weed control has become widespread in Asia, with significant effects (Li *et al.*, 2012), but questions remain: at what development stage should the rice be? How old should the ducks be? How do we encourage the ducks to learn their role?

Learning to combine practices for pest control

The existence of a diversity of practices likely to reduce pests and therefore pesticide use, is not enough to achieve the objective of being pesticide-free. Indeed, the choice of techniques to be combined must be thought on a case-by-case basis, according to the characteristics of the target pests and other components of the cropping situation. In particular, it is essential to consider synergies and antagonisms between levers, which is no easy task given the lack of knowledge about the decisive biological and ecological processes that have long been neglected by research.

To control thistles without herbicides, for example, several strategies have been studied: limiting dispersal, weakening root reserves, extracting roots from the soil, increasing competition with other crop species and physically destroying thistle plants. However, none of these techniques, taken in isolation, is sufficiently effective to ensure satisfactory long-term thistle control. As emphasised by Favrelière *et al.* (2020), studies on combinations of practices are therefore necessary, as it is for many other pests. However, for blackgrass weeds, the processes are better understood and the combination of deep ploughing after a crop that has produced blackgrass seeds, delayed sowing of the cereal crop, alternating spring and winter crops in the rotation, and reduced nitrogen fertilisation provides very good control of this weed (Table 3.2; Chauvel *et al.*, 2001).

Furthermore, the effect of practices varies according to the targeted pest and the state of the crop or environment. Farmers have to manage numerous pests, both in the short and long term and often have to make compromises to manage antagonistic effects. For example, after oilseed rape, ploughing is advised to control phoma and bury weed seeds. However, ploughing reduces biological control of pollen beetles by destroying soil-nesting beneficial organisms.

In order to design low-pesticide, or even pesticide-free, systems adapted to the diversity of pests and agricultural situations, it is essential to enhance agronomic research efforts aimed to understand and model the interactions between the various control and prophylactic practices. While knowledge on this subject remains insufficiently developed to enable farmers and their advisers to design pesticide-free cropping systems and suppressive landscapes without risk of errors or increased uncertainty, these actors will find it difficult to give up pesticides, whose efficacy remains extremely high in most cases. To achieve this goal, research organisations should enhance studies in agronomy and support a deep renewal of the research methods.

Box 3.3. The VITAE research project: growing grapevine without pesticides: towards agroecological vineyard socioecosystems (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

Moving away from pesticides means integrating combinations of levers, often with partial effects, and moving from a curative approach to an agroecological approach based on prevention and agrosystem resistance. Research must provide knowledge on how agrosystems function in order to identify credible new approaches and improve the effectiveness of the technical innovations currently available. It also involves identifying the most effective combinations of levers, based on situations that already exist in practice.

VITAE's interdisciplinary approach integrates the findings of biology, agronomy, ecology, oenology and the economic and social sciences, and is tackling research fronts that have been insufficiently explored to date, while questioning the extent of the social changes required to promote this agroecological breakthrough. To achieve pesticide-free viticulture, VITAE is looking at the development of biocontrol, the use of genetic resistance in vines, prophylactic practices, the use of cover crops chosen for the functions they offer to the agrosystem and practices that modulate the microclimate and physiology of vines to make them less susceptible to pests. VITAE is also tackling the issue of a change in scale and taking into account the determinants of transition. Finally, an interdisciplinary and participatory foresight study will generate scenarios for the phasing out of pesticides at the level of value chains and territories (INRAE, 2024c).

Key messages

The diversification of crop sequences, crops (varietal and species intercrops) and landscapes, the management of service plants and agroecological infrastructures, the rational use of different tillage and non-tillage methods, the coupling of crop and livestock production, the adaptation of sowing dates, nitrogen fertilisation strategies, pruning or leaf-thinning methods, are all levers that can be used to manage pests without pesticides. But their effect on pest control will only be successful if (i) these techniques are coherently managed with each other, so as to exploit the functions that affect pests, (ii) they are implemented in coherence with the characteristics of the situation. The production of knowledge on the effects of these practices and their combinations is therefore essential to support farmers' technical choices.

⏩ Growing without pesticides requires a renewal of working methods and knowledge production for agronomists

What are we looking for?

Withdrawing pesticides in conventional farming systems requires deep changes in farming practices. To achieve this, new performance targets (going beyond maximum yield alone, which has long been the preferred goal) and new evaluation criteria should be set out. New knowledge about natural regulation processes, which are still often poorly understood, should also be mobilised (Caron *et al.*, 2014). Furthermore, the characteristics of the pesticide-free systems to be designed are not known and are extremely variable from one situation to another. While chemical pest control solutions are generic and applicable to every situation, nature-based solutions need to be adapted to the specific characteristics of the farming situation (e.g. soil and climatic conditions, value chain, workload) (Médiène *et al.*, 2011; Meynard *et al.*, 2003; Rusch *et al.*, 2012). However, to date the effects of alternative practices have rarely been studied in a wide range of environments and cropping systems, as R&D was organised to produce generic recommendations based on a few experiments. The required adaptations that are necessary can be based on the experience of pioneering farmers as part of an open innovation process (Chesbrough and Bogers, 2014).

Until now, new production objectives, in particular improving input use efficiency to reduce environmental impact, were achieved by gradually improving cultivation techniques. Today, to meet the new challenge of pesticide-free crop management, it is no longer enough to improve resource-use efficiency or to substitute some inputs with others, but rather to fundamentally change the basis of agronomic reasoning toward system approach, leading to their in-depth redesign (Hill and McRae, 1996). This new challenge is leading agronomists to change their working methods and mobilise the scientific advances offered by innovative design (Hatchuel and Weil, 2009; Prost *et al.*, 2016). This refers to a process of exploration during which new solutions are devised to satisfy completely new expectations. Innovative design requires creativity, but also the ability to make evolve, during the process, the objectives being pursued, the knowledge to be used or produced, the evaluation criteria to be favoured and the collaborations to be fostered. As such, it is part of a multi-year process whose timeframe is specific to each farm. The work of agronomists therefore undergoes a major shift, from a posture of knowledge production and technical prescriptions that may be used by practitioners, to a posture of developing approaches and tools that encourage the design, by farmers themselves, of systems adapted to their objectives and contexts (Salembier *et al.*, 2018).

For a long time, agronomists have based the design of new ways of managing crops on the use of models. These models account for biophysical processes influenced by climate and management methods, across a wide range of agricultural conditions. They also simulate interactions between techniques, and between techniques, environmental and crop conditions. However, the processes considered in models are often restricted to water, carbon and nitrogen, and rarely include pests (or only one at best). Furthermore, many studies have found that models are not widely used outside the research sphere. These observations have led to the development of new models, which can be managed by farmers or by advisors, to promote their autonomy in the design of changes in practices. As an example, the quantitative PerSyst model (Ballot *et al.*, 2018) simulates all cultivation techniques and crop sequences in arable crops, based on expert parameterisation. The qualitative hierarchical IPSIM model simulates pest infestations as a function of techniques and biotic and abiotic environmental conditions for a diversity of agricultural conditions (Aubertot and Robin, 2013). However, despite having been built with their future users, these tools are not yet widely used, not only because they require a specific step of local parameterisation, but also because they are tools dedicated to strategic reasoning of techniques, while farmers are more accustomed to using DSS for the tactical management of their practices.

Alongside models, in recent years, agronomists have reinforced studies on methods to support design processes (Dogliotti *et al.*, 2014; Meynard *et al.*, 2012; Prost *et al.*, 2018), in particular by involving more frequently actors in their actual work situation, leading to investigations which are increasingly oriented towards open innovation, in which design is distributed among a diversity of actors who each partly contributes to it (Chesbrough and Bogers, 2014). Examples are now increasingly frequent, showing the successful implementations of this type of participatory approach to transform agricultural systems (Bakker *et al.*, 2021; Moraine *et al.*, 2016; Pelzer *et al.*, 2020; Périnelle *et al.*, 2021), even though these transformations are often hampered by lock-ins in socio-technical systems, which involve many agricultural and value chain stakeholders well beyond farmers alone (Meynard *et al.*, 2018).

System experiments

For a long time, experimentation was the agronomist's method of choice, to demonstrate biological laws, test the effect of a factor on crop performance, compare different technical options and so on. These factorial trials were the dominant practice for generating knowledge about a new technique or several interacting modalities, with the aim of identifying optimal options, based on statistical analyses which were used for the foundation of proof. However, as soon as the question concerns crop management or cropping systems, which are combinations of techniques consistent with the farmer aim and situation, factorial trials in which the effect of a single factor is studied are no longer appropriate. New ways of experimenting, system experiments, were suggested in the 1980s and 1990s, first to assess the abilities of crop management plans (Meynard, 1985) or innovative cropping systems (Debaeke *et al.*, 2009) to achieve the objectives for which they had been developed, but also to contribute to their design, through an iterative process based on progressive assessment and adaptation of the techniques under experimentation (Havard *et al.*, 2017; Meynard *et al.*, 2012).

Knowledge production derived from these system experiments has evolved considerably. In the 1990s, Reau *et al.* (1996) proposed conducting these experiments on the basis of decision rules, combining a function linked to objectives and constraints (what for?), a solution (how to do it?), and an evaluation criterion to verify that the function has been fulfilled. These decision rules have made it possible to reconcile flexibility in adapting techniques to the diversity of agricultural situations, with a formalisation that enables all the experimenters in a network (or the same experimenter for several successive years) to take consistent decisions, thereby facilitating the comparison of the systems tested and the dissemination of technical options and their results (Reau *et al.*, 1996). The decision schema, a chronological visual description of the technical actions implemented, the functions they were designed to achieve and the overall objective sought for the system, was suggested in the 2000s as a means of sharing concepts, strategies and tested and successful technical options (Petit *et al.*, 2012a). By the 2010s, a network of around 100 system experiments had been established by R&D in France, on the initiative of the RMT SdCi. Some systems aimed, in particular, at significantly reducing pesticide use (Petit *et al.*, 2012b). R&D agronomists then worked together to produce new resources describing the systems tested, with a view to disseminating the principles and technical choices satisfying for their pilots. In the early 2010s, a network of eight system experiments designed to test the total removal of pesticides (Res0Pest [5]) was set up in France. This network has made it possible to (i) design and experiment pesticide-free cropping systems in various production situations, (ii) assess their agronomic, economic, environmental and social performance, and (iii) generate knowledge on the functioning of these particular agroecosystems, in particular on population dynamics and biological regulation within ecosystems. The results of these experiments, consolidated over the long term (the first year of experimentation was in 2012-2013, with the exception of the Grignon trial, which started in 2008) are beginning to be published, providing rare references in the scientific literature on conventional pesticide-free production systems (Colnenne-David *et al.*, 2017; 2024).

System experiments conducted on experimental stations have also provided a forum for exchanges with a wide range of actors in the agricultural world, renewing interactions with practitioners in the knowledge production process (Cardona *et al.*, 2018). When implemented in multilocal networks of farmers' plots, these system experiments make it possible to not only to evaluate new ways of growing crops, but also to test the feasibility of the practices imagined, and to determine the conditions for the success of such disruptive systems (conditions under which the system(s) tested give satisfactory results), with a view to preparing the extrapolation and dissemination of their results.

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[5] https://www6.inrae.fr/reseau-pic/Projets/Res0Pest

Participatory design workshops

For many years, agronomic innovations derived from scientists and were disseminated to farmers who applied them in their fields. However, the need for disruptive innovations to achieve new targets, adapted to the situations in which they are to be implemented, means that farmers and other stakeholders directly concerned by changes in practices contribute fully and actively to the design process. In particular, they are able to fuel the design process with their knowledge of production constraints. Participatory design methods have been widely developed since the 1990s, as has the production of cognitive resources to feed the process (Le Gal *et al.*, 2011; Salembier *et al.*, 2018; Quinio *et al.*, 2022). Participaroty design workshops are one such method. They mobilise a collective of stakeholders to explore a complex problem and build new solutions *in abstracto*, often breaking with existing practices. This method has been widely deployed, in particular *via* the SdCi RMT, with R&D actors, leading to the design of innovative cropping systems that are very different to current practices, but realistic (tested in experimentation), and that address new challenges, specifically a major reduction in pesticide use (Reau *et al.*, 2010). Using such collective creativity and broadening the knowledge basis mobilised allowed to design pesticide-free systems, which were then tested (Colnenne-David *et al.*, 2015; Penvern *et al.*, 2018). Based on convergences and divergences arising from a dozen case studies of such design workshops, methodological lessons to achieve design workshop objectives have been established (Jeuffroy *et al.*, 2022). They concern: (i) the choice of stakeholders to be invited to the workshops, (ii) key elements for defining a design target that is both ambitious and realistic, (iii) ways of effectively organising the design of agronomic innovations, and in particular their systemic character, (iv) ways of sequencing and leading successive workshop sessions, depending on the situation, and (v) new criteria, consistent with the diversity of objectives targeted in the workshops, to assess the success of a design workshop.

Until now, these workshops have mainly focused on the design of plot-centred cropping systems, with a view to producing either systems to be experimented (with a view to evaluating and improving them; Colnenne-David *et al.*, 2015), or practices to be implemented by a specific farmer (Guillier *et al.*, 2020), or more generic systems adapted to a given region (Pelzer *et al.*, 2017). However, in line with the specificities of pests, the objects to be designed in such participatory workshops are diversifying. Indeed, the wide spatial distribution of some pests (insects in particular), as well as the effects of landscape composition, make it increasingly necessary to design mosaics of cropping systems with a view to reducing pesticide use. For example, rapeseed phoma stem canker is influenced by the spatial and temporal management of resistant varieties, by ploughing after oilseed rape (burying infested crop residues reduces spores spreading to new plots), by sowing date (shifting the crop's susceptible stages outside the spore release periods) (Aubertot *et al.*, 2004), and by nitrogen fertilisation (high nitrogen nutrition favours autumn development of the disease) (Aubertot *et al.*, 2004). Thus, building scenarios based on a specific spatial organisation of cropping systems can make it possible to limit infestations on a territorial scale, provided that the diversity of stakeholders' objectives and activities are taken into account by involving them in the design process (Hossard *et al.*, 2013). However, as can be seen from these examples, the design of cropping systems and their spatial organisation requires a wide range of knowledge, which is only partially available, both on biological processes and on the effects of techniques and their interactions on the concerned processes, taking into account the effects of the environment (Caron *et al.*, 2014).

The socio-technical lock-in of current dominant agricultural systems, in which pesticide dependency is at the heart (Vanloqueren and Baret, 2008; Guichard *et al.*, 2017), involves all actors from agriculture and supply chains. It is therefore useful and even necessary to involve all these actors in the design of the solutions that will enable the farmers to move away from pesticides (Meynard *et al.*, 2018). Thus, for example, some agronomic practices are only possible if (i) the right equipment and the skills to manage it are available, leading some stakeholders to co-design and build specific and adapted equipment (Salembier *et al.*, 2020); (ii) markets are established, enabling sufficient added value to be achieved for harvested products (Magrini *et al.*, 2018, Meynard *et al.*, 2018); (iii) processors agree to modify their practices to take into account the environmental advantages of some agricultural practices (for example, the cultivation of late blight-resistant potato varieties, hitherto rejected by processors as ill-suited to current industrial processes); (iv) if regulatory frameworks allow the introduction of these solutions, such as wine AOC labels ("Appellation d'Origine Contrôlée" — Controlled Designation of Origin), which do not yet accept resistant grape varieties, or which do not allow low planting densities. Involving stakeholders in the design workshops has the major advantage of opening up the exploration of solutions considering expert knowledge and concrete implementation, without lock-in to solutions based on the (generally incomplete) state of scientific knowledge.

More generally, it seems essential to implement participatory design approaches that enable the coupling of innovations traditionally independently designed by different stakeholders (e.g. agricultural practices and agricultural equipment, varieties and agricultural practices, processing and agricultural practices), and include the design of organisational innovations that facilitate stakeholder coordination (Meynard *et al.*, 2017). Involving a diversity of stakeholders in the participatory design of disruptive agronomic innovations is at the heart of many projects (CASDAR and ANR — French National Research Agency projects in France, and projects supported through European funding), leading researchers to generate methodological advances anchored in concrete case studies.

Tracking innovations and sharing knowledge within a distributed agricultural knowledge and innovation system (AKIS)

Like agroecological systems in general, pesticide-free farming systems are highly diverse, depending on the local pedoclimatic and socio-economic conditions. Some innovative farmers invent and implement highly original, atypical cropping techniques adapted to their own situation, but whose principles may inspire other farmers or agricultural R&D actors (Salembier *et al.*, 2016; Verret *et al.*, 2020). Drawing on these innovations to stimulate and fuel system design by other farmers in other situations presupposes a systemic agronomic analysis of these innovations, thereby enabling varied contributions to design (Salembier *et al.*, 2021): identifying and sharing creative anomalies; shedding light on little-known systemic biological and agronomic processes that can be utilised in design processes on other farms; stimulating design on issues or in orphan areas of innovation; sharing and circulating innovation concepts and knowledge that facilitate creativity; linking designers with each other. These contributions are also based on efforts to formalise the knowledge produced, which, while retaining its systemic logic, should enable empirical local knowledge to be made generic, specifically by hybridising expert and scientific knowledge (Girard and Magda, 2020). Numerous farmers' innovation tracking studies have already been performed on issues relating to the reduction of pesticide use (managing plant health in protected market gardening systems while minimising pesticide use, managing thistles in field crops without pesticides, managing lentil and faba bean weevils without pesticides, managing vineyard systems without pesticides etc.), and such other studies are to be deployed more widely to enhance and share farmers' technical innovations. Their deployment raises the question of how to share the knowledge produced with as many people as possible and to feed into the design of agricultural systems. To this end, digital tools are being developed, such as GECO [6]. This tool is derived from the AgroPeps prototype, designed by a collective of actors from the SdCi RMT (Guichard *et al.*, 2015) and comprising both producers of knowledge and technical innovations, and users of this knowledge to support design among other farmers. Research focusing on the formalisation and open sharing of cognitive and operational resources, making the most of digital assets, is still in its infancy (Prost *et al.*, 2018) and is essential to support the design and development of pesticide-free farming systems.

Multi-criteria assessment of complex systems

Removing pesticides is not the only challenge agriculture faces: reducing greenhouse gas emissions, promoting biodiversity and reducing pressure on non-renewable resources (e.g. fossil fuels) while maintaining economic profitability are also key issues in the transformation of agricultural systems. This enlarging diversity of criteria enhanced works on the development of multi-criteria assessment tools (Sadok *et al.*, 2008). They enable complex innovations to be assessed not only in terms of their intended target, but also in terms of other components of agricultural system sustainability (Colnenne-David *et al.*, 2017). To broaden assessment and avoid deferring negative externalities upstream or downstream of production, life cycle assessment (LCA) tools have been performed to evaluate cropping systems less dependent on pesticides (Deytieux *et al.*, 2012; Renaud-Gentié *et al.*, 2020; Alaphilippe *et al.*, 2013), or those favouring crop diversification (Nemecek *et al.*, 2008). However, it should be noted that LCA is not well adapted to consider the effects of agricultural practices on biodiversity.

Studies on multi-criteria assessment tools have sought to standardise evaluation criteria and the parameter bases used to calculate them in order to facilitate comparisons (Sadok *et al.*, 2009; AGRIBALYSE® program). The standardisation of evaluation criteria has facilitated the comparison of prototype innovative

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[6] https://geco.ecophytopic.fr

systems, both *ex ante* and *ex post* their implementation. However, during innovative design processes aimed at developing disruptive systems, new evaluation criteria frequently emerge not foreseen by the designers. In fact, farmers' criteria, which are often different from those of agronomists, rarely have a place in the standardised tools developed by research (Salembier *et al.*, 2013, 2016; Verret *et al.*, 2020). In this context, standardised multi-criteria assessment tools can prove ill-suited, as they are too cumbersome to implement or take insufficient account of certain aspects deemed essential by their users. For example, while the question of the relationship between farming practices and health is increasingly central, particularly for systems designed to eliminate pesticides, tools that take these aspects into account are still frustratingly limited. Progress is therefore expected in the coming years to provide such evaluation criteria, which are essential for working at the scale of food systems (Duru and Le Bras, 2020).

Step-by-step change management: stimulating learning

The transition from pesticide-based to pesticide-free systems cannot happen overnight. Knowledge on the biological processes to be enhanced is insufficient, the systems to be designed are complex (numerous interactions between techniques, and between these and environmental conditions, dependence on available resources etc.), and the expected effects of certain alternatives are uncertain. As a result, until now, researchers have been mainly focused on showing that it is possible to design *ex nihilo,* and then test in experiments complete systems that achieve the expected performance (Vereijken, 1997; Debaeke *et al.*, 2009; Chikowo *et al.*, 2009; Colnenne-David *et al.*, 2015, 2017; Simon *et al.*, 2017; Lefèvre *et al.*, 2020). However, the change in cropping or production systems by farmers themselves is generally much more gradual. This is known as step-by-step design (Mischler *et al.*, 2009; Meynard *et al.*, 2012; Coquil *et al.*, 2014). Based on observations made on the evolving system, technical changes are suggested and implemented to improve the results, encouraging genuine design loops (diagnosis — exploration — implementation — evaluation and new diagnosis etc.). Putting system evolutions into action is a source of learning, the content of which farmers often share with other farmers undergoing change (Bakker *et al.*, 2021): research studies on step-by-step design and adaptive management of practices should be strengthened. To reduce risks, farmers sometimes first experiment, on a small part of their farm, the technical solutions they have imagined, before extrapolating solutions deemed satisfactory to a larger scale (Catalogna *et al.*, 2018). Encouraging this type of experimentation and supporting their analysis with suitable tools is a major challenge for the large-scale transition to pesticide-free systems. In particular, the capacities of stakeholders and the tools enabling relevant diagnosis to be conducted on systems under construction should be widely developed to enable precise and relevant identification of system elements for improvements in subsequent design loops. Work is also needed to stimulate the development of indicators for managing complex systems under uncertainty. Learning can also focus on the formalisation of the system's target, the outlines of which are refined as the process progresses, and on the conditions for implementation, leading to new shareable knowledge (Meynard *et al.*, 2019).

Key messages

In order to control pests without pesticides, farming systems and their spatial organisations need to be both highly innovative and adapted to the diversity of local specificities. This requires farmers and other stakeholders to rethink and adapt their management practices. Agronomists have made major changes to their working methods in order to support stakeholders in these endeavours. Over the past decade, this has led to a major renewal in research work, which is set to intensify in the years ahead. The transformation of activities to support stakeholders in these profound transformations also affects advisers, who will no longer be able to disseminate generic techniques to be applied, but will have to support the gradual transformation of systems, adapting them to individual and collective objectives, and to the means available.

⏩ Conclusion

If we hope to contribute to the emergence and deployment of pesticide-free systems, we need to review not only the knowledge produced, but also the activities and organisation of R&D actors. Identifying and prioritising the new knowledge to be produced, from the design process, is a real challenge in a research world accustomed to self-determining its priorities through "scientific states of the art" (Toffolini *et al.*, 2020). A radically different kind of organisation (Midler, 1998) needs to be established. Spreading innovative design approaches that mobilise the diversity of upstream and downstream actors presupposes both an increase in research work formalising the necessary methods and tools, and a profound change in the activities and skills of the actors in charge of supporting design processes (Cardona *et al.*, 2021). The large-scale deployment of innovative production methods, developed by researchers (often in participative research), or identified by pioneering farmers, is a prerequisite for a drastic reduction in the use of pesticides by farmers. This means developing R&D activities under real conditions and with farmers (tracking, co-design, participatory evaluation etc.) in systemic approaches that take into account the diversity of farmers' objectives and resources. However, the deployment of such activities to build diversified systems is hampered by the historical, and still very top-down, structure of R&D, as well as by a habit of focusing work on analytical solutions. As a result, systems agronomy has not been given prominence in public policies aimed at a major reduction in pesticide use (Aulagnier *et al.*, 2017; Aulagnier, 2021). The culture of open innovation has yet to be widely transmitted, developed and implemented. Both within the industry and in research, the separation of professions, linked to their specialisation, is currently a real obstacle to the coordination of innovations, which is essential for the transition to more sustainable food systems (Meynard *et al.*, 2017). Similarly, the segmentation of agricultural R&D by value chain severely constrains work and hampers the transition to very low-input, highly diversified and, by nature, multi-chain agroecological systems and farms. To develop pesticide-free systems, we urgently need to revisit these organisations, gain recognition for the innovations and knowledge produced from practitioners (farmer groups and innovative pioneering farmers), sources of radical and systemic innovation, and design digital tools to stimulate the sharing of knowledge and innovations by mobilising their future users.

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Chapter 4

Biocontrol(s) from a pesticide-free agricultural perspective

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⏩ Biocontrol: a single term for a variety of crop protection methods

Overview of biocontrol methods

The French term “biocontrôle” is a neologism, frequently used from 2010 in France and recorded in the country’s 2014-1170 law on the future of agriculture, food and forestry (Herth and Le Maire, 2011). It is defined as “Agents and products using natural mechanisms as part of integrated pest management. They include in particular: (i) macroorganisms; (ii) phytopharmaceutical products comprising microorganisms, semiochemicals such as pheromones and kairomones, and natural substances of plant, animal or mineral origin”. The definition on the French Ministry of Agriculture and Food’s website presents it as a set of plant protection methods based on the use of natural mechanisms (Ministry of Agriculture and Food, 2021).

“Biocontrôle” is not simply a French translation of the English term “biocontrol”. The scope it defines has hardly been formalized with respect to international references. However, if we place the methods developed by the French scientific and technical community within the terminological framework proposed by Eilenberg et al. (2001), “biocontrôle” encompasses:

– The four types of biocontrol: classical biocontrol, inundation biocontrol, inoculation biocontrol and conservation biocontrol,
– Autocidal control (sterile insect technique),
– Some biorational chemical agents.

The scope designated by this apparently simple term is, in fact, vast. First, it includes the direct and indirect use of living organisms (arthropods, viruses, bacteria, fungi etc.). In terms of direct use, we speak of biological control through inundation when the introduction of beneficial organisms (often in large quantities) is aimed at short-term control of the pest by the released organisms themselves. Biological control through inoculation is used when the introduction (often more targeted and in smaller quantities) is aimed at control over a few generations or seasons, and therefore an at least temporary establishment of the organism's population. When biocontrol organisms are exotic (when they are initially absent from the geographical area considered), and the aim is their permanent establishment with a view to long-term control of the pest, this is classical biological control (also known as establishment biological control). The indirect use of living organisms already present in the geographical area under consideration is conservation biological control. This type of control includes all practices (planting of grass strips, hedges, floral mixes, introduction of additional resources such as sugars and pollens, etc.) and even landscape configurations designed to encourage the growth of populations of organisms that are natural enemies of pests. Also implicitly included in "biocontrôle" is autocidal control. This involves using individuals of the pest's own species, that field introduction will cause a reduction in the density of the natural population. The classic example is the mass introduction of previously sterilised males, which compete with the males of the natural target population and disrupt reproduction.

Besides, the French term "biocontrôle" covers a wide range of methods based on the use of substances or molecules of plant, animal or mineral origin, in a form existing in the natural environment (if the molecule used has undergone any chemical modification making it different from its natural counterpart, then we no longer speak of it as "biocontrôle"). These molecules and substances can be extracted from living organisms or synthesised chemically (provided, once again, that they remain strictly identical to the molecules naturally present in the environment). These "natural substances" include plant oils, plant and animal metabolites, toxins, semiochemicals and so on. Another specificity of "biocontrôle" within the meaning of French law is the inclusion among these substances of minerals (sulphur and ferric phosphate, for example), which strongly differentiates the French "biocontrôle" from all international definitions close to "biocontrol".

Another dimension to consider for each of these categories, whether macro- or microorganisms, substances of natural origin or semiochemicals, is that they use very diverse modes of action. Many are designed to act directly on pests but by different means: parasitism (macro- or microorganisms), antibiosis (microorganisms), nutritional competition (microorganisms), toxicity (natural substances), physical barrier (natural substances), sexual confusion (semiochemicals), trapping (using semiochemicals) and so on. Others, called PRI or plant resistance inducers (microorganisms and natural substances), are designed to act on the target crop to activate its immunity and ensure its own protection by establishing physical and chemical barriers. Finally, some biocontrol products combine several modes of action, for example, antibiosis and PRI for some microorganisms, and toxicity and a PRI effect for some natural substances.

A final subtlety of the term is conferred by the method used to create the French national list of plant protection products recognised as "biocontrôle" in France. To establish this list, 19 hazard statements (for health, for the environment etc.) are used as exclusion criteria for candidate substances. Some organisms or substances considered as biological control in other countries may therefore not be "biocontrôle" in France.

It should be noted that methods not based on the use of natural organisms or substances, but which have similar direct (toxic) or indirect (induction of immunity) effects, such as special-spectrum light treatments or mechanical stress, are not currently included in the scope of "biocontrôle".

French term "biocontrôle" implicitly oriented towards products

In French law and in communications from public authorities and most private actors alike, biocontrol is explicitly presented as a set of four product categories (macroorganisms, microorganisms, semiochemicals and natural substances). Government action plans and funding programmes also emphasise the development of new products and the growth of the biocontrol industry (in the sense of product developers and marketers). Implicitly, biocontrol methods are thus currently presented as inputs, with a tendency to consider them as substitutes for synthetic chemical products. Biocontrol is positioned as an industrial sector whose role is similar to that of agrochemistry (creating and marketing inputs for a maximum number of uses) but it differs in the nature of the inputs marketed. Many industrial biocontrol operators are also involved in the agrochemical industry.

This way of presenting biocontrol is not without significance in terms of its impacts. First, it does question current cropping systems and value chain organisations. Second, this product-focused vision marginalises other forms of biocontrol based on services and on more or less long-term regulatory actions: conservation biological control, classical and autocidal control in particular. It is interesting to note, for example, that after a decade of use in everyday language, biocontrol has been assimilated by a large part of the research and innovation community to a logic of substitution of one polluting practice by another that is more virtuous (biocontrol is referred to in this way in this book, in Box 7.5).

Remarkable biocontrol successes go beyond the success of a single product

This communication focused on biocontrol products is not devoid of interest for the promotion of biocontrol and it highlights an industry that is small in size (around €100m to €150m in annual sales) but very active, as attested by the rates of increase in market share for biocontrol products (more than 10% every year over the 2010's).

The promotion of products is also reflected in practice with, for example, more than a third of the action sheets in the French plant protection product savings certificates CEPP scheme (Box 1.11) involving biocontrol products ^{7}.

However, this focus on products overlooks many original and spectacular successes, which often seem to correspond to the implementation of strategies that go beyond the use of a high-performance product, or involve approaches that do not use a commercial product. Over the past two decades in Europe, three emblematic examples can be cited: the rise of biocontrol in greenhouses in most European countries, classical biological control programmes that have enthused entire value chains and collective successes in implementing conservation biological control.

Box 4.1. Biocontrol offers extremely attractive cost/benefit/risk ratios

Since the 1990s, scientific studies have repeatedly documented that biocontrol displays lower development costs, higher development success rates and equal or higher cost-benefit ratios when compared to chemical pesticides (Bale *et al.*, 2008). For biological control by inundation and inoculation (i.e. biocontrol products), cost-benefit ratios are evaluated as close to that of insecticides (between 1: 2 and 1: 5) and reaches 1: 250 for classical biological control. Furthermore, biocontrol methods present a low risk of resistance developing in pests, and much lower impacts on biodiversity and health.

The successful integration of biocontrol into integrated protection systems for greenhouse-grown crops is an emblematic example. This success is often presented as the commercial success of biocontrol products thanks to high value-added production and the ease of control in confined environments. While these two factors obviously favour the use of biocontrol, it is remarkable to observe the extent to which this integration is in fact based on combinations of resistant varieties,prophylaxis (in particular through climate control) and biocontrol (combining inundation, inoculation and conservation). This integration is also associated with growing farmer expertise in the use of living organisms and a strong propensity on the part of biocontrol industrial actors to tacitly support their products with personalised advisory services. The development of biocontrol in greenhouses has also been accelerated by health scandals linked to the use of pesticides in confined environments and the presence of pesticide residues in fruit and vegetables. These events came as a shock to all those involved, and led to a cessation of pesticide use, whether voluntary or imposed by law. They led to massive changes in practices, sometimes over short periods of time, and motivated strong R&D investment. This was observed, for example, in protected crops in southern Spain, where the area under biocontrol increased from 1,400 hectares in 2007 to 26,000 hectares in 2014, following a scandal after the detection of residues of a pesticide banned in Europe in various vegetables in 2006 (Glass, 2012; Sanchez *et al.*, 2014).

The second example is the potential of classical biological control in sectors where the crop protection options offered by chemical pesticides are sparse. This strategy

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[7] https://alim.agriculture.gouv.fr/cepp/content/ap_fiches_action

differs greatly from the practice of using inputs in the form of products. While an input requires a major initial R&D investment, followed by recurrent commercial use (remunerating the biocontrol company and representing a recurrent cost for the farmer), classical biological control involves a more modest initial R&D investment which, once the introduced beneficial insect has become established, gives way to a perennial service, free of charge for the farmer. This approach can extend to the regulation of the targeted pest, dispensing with the need for any plant protection practice in the long term. A recent example of such a success in France is the establishment of the Asian parasitoid *Torymus sinensis* against the chestnut gall wasp, an invasive species threatening the entire industry in Europe. Reported in France in 2007 and affecting key areas of chestnut production from 2010 onwards, this biological invasion was the subject of a classical biocontrol programme launched in 2011. In just a few years, the programme, which has strongly mobilised stakeholders in the sectors concerned, has enabled the introduced beneficial insect to become established in 80% of its release sites and has drastically reduced pest infestations (Borowiec *et al.*, 2018). Another major difference compared to conventional input use is the structure of the risk taken by stakeholders. What is expected from a conventional input is repeated efficacy that is as constant as possible over time, with a recurring but moderate risk. In contrast, classical biological control is characterised by high initial risk-taking as the probability of satisfactory pest control after classical biocontrol is only 10% (Kenis *et al.*, 2017), but this 10% often provides significant success stories for entire agricultural sectors.

The third example is a proof of concept of the potential of implementing collective conservation biological control strategies. In the southern Netherlands, near the city of Rotterdam, a project was initiated in 2004 by a group of farmers working with research teams to set up flower strips and evaluate their impact over an area of around 325 km^2 (Alebeek and Clevering, 2005; Paulin *et al.*, 2020). A 90% reduction in insecticide use in potato and wheat crops was achieved and maintained. In some crops (e.g. field beans), yield benefits were also recorded. Once the five-year project was completed, the participating farmers continued and expanded the initiative by founding a cooperative called Coöperatie Collectief Hoeksche Waard (CCHW). To date, 84 farmers have joined the cooperative and set up 500 km of flower strips. The initiative also involves local authorities and the tourist board, who use the flower strips to promote the region (notably by creating cycle paths close to the strips). This example represents a major success on a geographical scale, albeit local, but significant in terms of the areas involved and their economic importance. Yet, this success story is not widely advertised at the international level — the results are mentioned in the scientific literature (Steingröver *et al.*, 2010; Paulin *et al.*, 2020) and the initial project was reported in Dutch (Alebeek and Clevering, 2005) — and is unlikely to have been widely used as a proof of concept at the European scale. This example illustrates both the potential and the difficulties of disseminating conservation biological control. Initiatives using these strategies are not necessarily named and promoted as such. They are often initiated by a diversity of local actors and their geographical extrapolation is rarely an initial objective or taken up by other initiatives.

⏩ Dominant agricultural models influence biocontrol practices and research

Dominant cropping systems are unfavourable to biocontrol

As explained in Chapter 1, the dominant agricultural models are the result of decades of investment in optimising simplified cropping systems that robustness is based mainly on high-yield varieties and broad-spectrum pesticides. This, and the fact that biocontrol is currently mainly seen as a substitute for or a complement to pesticides, lock biocontrol into a framework directly inherited from agrochemistry. In most cases, public authorities, private investors and users formulate, explicitly or implicitly, expectations corresponding to chemical references. In this agrochemistry-like vision, a dynamic, job-creating upstream industry should develop and market inputs, that distribution and advice could be organised by existing players. These inputs should be available for the control of the pests that could pose a problem, be used independently of each other and have a visible curative efficacy in a relatively short space of time. Their cost should be as close as possible to that of chemical pesticides, and preferably be usable in the field with agricultural equipment originally designed for chemical applications. However, these expectations are incompatible with most biocontrol methods.

First, several types of methods are not recurrently marketed inputs available from distributors (such as classical and conservation biological control), which induces a genuine marginalisation of these methods. Indeed, despite the highly favourable cost-benefit ratio of classical biocontrol programmes (median ratio of 1: 63 according to Naranjo *et al.* (2019) for arthropod control) and the per-hectare benefit levels of conservation biocontrol (median benefit of $86 per hectare according to Naranjo *et al.* (2019)), these strategies are the subject of little public and private investment. This is probably due to the criteria currently used to assess the relevance of investments: sales linked to a product, creation of wealth and jobs in the industrial sector developing and marketing the product, short-term effectiveness of the product against a particular pest etc. Moreover, as we shall see in the next section, these strategies are not, or only to a limited extent, the subject of adapted stakeholder organisations and business models.

Second, certain methods differ profoundly from chemical inputs in terms of their conditions of use, even if they involve organisms or substances repeatedly introduced into the target agrosystem (and can thus be considered as inputs). This is the case, for example, with the use of semiochemicals for mating disruption, or the use of sterile males for autocidal control. Both methods require the coordination of a number of farms in the geographical area hosting most of the pest population, otherwise their effectiveness will be drastically reduced. Indeed, these methods are based on the disruption of reproduction (in the first case, male pests can no longer find their way to females, and in the second they are sterile and cannot fertilise the females with which they mate). If only part of the population is controlled, and females of the target species are sufficiently mobile, then females mated in uncovered areas may disperse to covered areas and infest crops there. Effective use of these methods therefore requires coordination and management of pest populations over entire areas and over several seasons. However, such service is little or not at all requested, offered or provided by the various actors in current dominant agricultural systems that use chemical inputs. Another example is the use of PRI, whether microorganisms or natural substances. Dominant agricultural models using chemical pesticides have essentially considered plants as passive partners in crop protection. By contrast, PRI use plants as central and active players, but the environment — whether climate or certain cultural practices (fertilisation, biostimulation, growth regulators and irrigation) — acts on the plant's physiological state and may condition the success of inducing immunity. The efficacy of PRI will therefore remain disappointing and their use marginal as long as these various interactions are not clearly understood and taken into account in the practical application of this biocontrol method.

At another level, the incompatibility between expectations influenced by dominant systems and biocontrol can also be observed for most biocontrol methods based on relatively conventional use in the form of inputs (substances or organisms). A major advantage of these methods is their harmlessness, or their extremely low impact on the environment and health. These properties, which positively differentiate them from chemical pesticides, are often based on the fact that these organisms or substances are less biocidal and toxic for living beings and are also less persistent in the environment. However, high biocidal activity and persistence are the expected key properties of inputs in our dominant agricultural systems. This is what enables them to control a broad spectrum of pests over a relatively long period (so much so that, despite their curative vocation, these inputs are used as a preventive measure). From both a technical and financial point of view, a single broad-spectrum product with persistent activity cannot be replaced by a multitude of methods, each controlling one or more pests and requiring repeated use over time. The use of biocontrol's modes of action therefore requires the use of prophylactic methods (resistant varieties and agronomic practices) to reduce the number of pest problems to be managed simultaneously, and a level of natural biological regulation that is high enough to ensure the use of highly curative inputs is not essential. However, the use of chemical pesticides in a system, unless it is highly targeted (which is generally not the case in today's dominant systems of high-input agriculture), these two conditions for success are often invalidated either directly (the presence of residual biocides destroys or unbalances the communities responsible for the biological regulation of pests) or indirectly (the use of chemical pesticides makes the choice of resistant varieties or prophylactic agronomic practices a low priority). For these same reasons, strategies promoting the use of biocontrol as a complement to chemical pesticides (for example to reduce doses or avoid residues at the end of the season) only marginally support (and even tends to block) the use of biocontrol in agricultural systems, as it strengthens agricultural systems that are mostly incompatible with the use of biocontrol and other agroecological methods.

The characteristics and organisation of actors in the value chain also create a lock-in effect. Solid expertise, know-how and experience with chemical inputs are established among actors in logistics, distribution and advisory services. Current expectations, in the frame of the "product" vision of biocontrol, implicitly force biocontrol to conform to the logistics, distribution and advisory standards in pesticide-based systems. As a result, biocontrol is clearly at a disadvantage, as it requires different organisations, services, knowledge and equipment (which vary according to the type of biocontrol and its mode of action). In practice, this translates into higher biocontrol costs and a perception of lower efficacy, leading current advisory and distribution actors to offer biocontrol methods only marginally, preferring previously available substances recently reclassified as biocontrol products under French law (Villemaine *et al.*, 2021).

The aforementioned factors are probably the source of the ceiling that biocontrol methods are unable to break through in terms of the area of use or market size. In France, for example, apart from sulphur, which is a very special case (it is a historically widely used input which, internationally, is not considered as biological control, but is a "biocontrôle" product under the French law), the best-known biocontrol methods (e.g. the use of *Trichogramma brassicae* against the European corn borer (*Ostrinia nubilalis*), sexual confusion against the European grapevine moth (*Lobesia botrana*) and codling moth (*Cydia pomonella*), or *Cydia pomonella* granulovirus against the latter pest) are capped at around 100,000 hectares (according to data released in 2019 by biocontrol manufacturers[8].

Research and innovation inhibited and guided by the framework imposed by pesticide-using systems

This ceiling, observed both in France and abroad (Barratt *et al.*, 2018; van Lenteren, 2012; van Lenteren *et al.*, 2018), is symptomatic of the fact that dominant systems are locking in the boom in biocontrol. From a technical point of view, investment in research and innovation should help overcome this by improving the scientific and technical state of the art on a series of key needs (e.g. improved formulations or characteristics of substances or organisms, introduction or field application methods, expertise and tools to position them in time and space, tools to coordinate actors in the use of semiochemicals and the sterile insect technique etc.). However, this substantial investment is not forthcoming for logical economic reasons. The likelihood of private investment depends on the presence of markets and therefore of unsatisfied needs. However, in systems based on chemical pesticides, unsatisfied needs are uncertain: they are often formulated in anticipation of the withdrawal of an active substance (the decision to withdraw is, moreover, often conditional on the existence of alternative solutions, the development of which is itself inhibited by the dominant position of the active substance facing withdrawal). Moreover, when the unsatisfied need is real, the agricultural surface concerned, and the corresponding markets seem in most cases to be capped at relatively limited levels. As for public investment in innovation, this has often been set in proportion to private investment, for example *via* financing systems such as research tax credits, the public investment bank, public-private partnerships etc. In addition, the structure of the public sector has often been based on the principle that public investment in innovation is proportional to private investment. Furthermore, market structure (predominance of needs expressed in terms of products based on the chemical model) and

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[8] https://www.ibmafrance.com/ibma-france/

financing methods steer investment towards the industrial development of input-type products and their corresponding business models.

The current logic of biocontrol support, based on the industrial development of products, therefore has intrinsic limits, as it is locked into a vicious circle: small markets limit investment, and insufficient investment limits product development and use capacities, which in turn limits the use of biocontrol products and caps the market size etc. The problems spontaneously expressed by actors developing products — the lack of financial support for R&D on the one hand (which has led, for example, to a request for an increase in research tax credits for R&D in biocontrol[9]), and the length and cost of marketing authorisation procedures on the other — are certainly legitimate and constitute short-term barriers. Above all, though, they reflect the effects of dominant agricultural systems that cap market sizes and investment. Indeed, if market prospects were much more attractive, investment would be higher, allowing for more ambitious R&D projects that would include the costs of marketing authorisation.

Without wishing to disparage the current biocontrol industry, which is at the origin of new solutions useful to farmers and which should continue to be supported by existing measures, it also seems appropriate and important to diversify the approach to ensure the growth of biocontrol and, in particular, to find ways of taking advantage of biocontrol strategies which do not yet benefit from appropriate support measures and are not yet stabilised in terms of business models.

Key messages

Our current dominant agricultural systems are built around pesticides and are unfavourable to the development of biocontrol for several reasons. They impose expectations that are incompatible with the characteristics of most biocontrol strategies: (i) actors are organised to produce, distribute and use inputs, whereas several biocontrol approaches do not correspond to input use (conservation or classical biological control), (ii) the logistics and agricultural equipment optimised for pesticides and through which biocontrol products must transit are not adapted to the characteristics of the latter (living organisms, different formulations, volatile substances, etc.), (iii) the weakness of the methods used to ensure prophylaxis and natural pest regulation makes almost essential the use of methods with strong biocidal power, acting on a broad spectrum of targets, with strong persistence. Furthermore, current biocontrol actors, as well as the public authorities, are today reinforcing the locking of biocontrol use despite themselves by promoting and supporting the growth of a biocontrol industry which develops and markets products very much along the lines of the pesticide model (R&D, R&D funding, production, distribution, advice, etc.). However, this pessimistic assessment needs to be counterbalanced by the many positive prospects currently emerging. On the one hand, the many scientific and technical possibilities (formulations, agricultural equipment, diagnostic and predictive tools for positioning interventions, etc.) may enable biocontrol products to be better developed and positioned. On the other hand, inventing new organisations

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[9] https://www.assemblee-nationale.fr/dyn/15/amendements_alt/3360C/AN/429

and business sectors could make it possible to fully exploit the potential of biocontrol strategies, which are currently at the origin of many success stories in the area of biocontrol (conservation and classical biological control, collective deployment of semiochemicals and autocidal control, etc.), but private and public investment is very low and under-utilised. In this context, setting a pesticide-free framework would appear to be an excellent way of stimulating innovation (technical and organisational), leading to greater diversification and deployment of biocontrol.

⏩ Which research and innovation priorities will be encouraged by the aim for pesticide-free agriculture?

In addition to the potential redirection of human and financial efforts from the chemical industry to agroecological levers, the ambition to be pesticide-free provides the opportunity to think about the organisation of value chains, territories and cropping systems that are more favourable to biocontrol, opening up a diversity of business models that make the most of the full range of strategies based on natural mechanisms.

We can distinguish two main types of research and innovation priorities that should be strengthened: upstream research and first proofs of concept in emerging and promising fields, and research into techniques or concepts that are already relatively mature, but whose efficacy and deployment can be greatly improved.

Studying and managing the microbiome: a major avenue for innovation

A particularly promising field for the application of biocontrol is the understanding and management of plant microbiomes. Plants host a wide variety of microorganisms (archaea, filamentous fungi, eubacteria, oomycetes, protists and viruses) within or on their surfaces (roots, leaves, flowers, fruits, seeds etc.). These microorganisms interact with each other and with their environment and can have a direct or indirect impact on plants modifying their responses to biotic and abiotic stress and by acting on pests (Barret *et al.*, 2020). The possibilities for biocontrol applications in microbiome research have been cited in the scientific literature for several years (Massart *et al.*, 2015). They cause a stir because they open up a whole range of avenues, from the identification of pest antagonists (likely to become products used in the form of biological control by inoculation or inundation), to strategies for managing a beneficial microbiome *via* different means (agronomic practices, choice of cultivated and non-cultivated species, i.e. a form of conservation biological control using microorganisms). In France, two recent projects bear witness to this interest. In 2019, the public-private research-development-innovation consortium on biocontrol spurred the launch of the BCMicrobiome[10] project, aimed at designing and using inferential methods on the interaction networks of microorganisms based on two major

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[10] www.consortium-biocontrole.fr

pathogens (downy mildew in grapevines and septoria in wheat). The aim is to identify organisms that influence these pathogens directly or indirectly. The Priority Research Programme “Growing and Protecting Crops Differently” has also strongly supported research in this area through two large-scale projects. The first, DEEP IMPACT (Box 4.2), proposes a global approach to characterise the role of microbiota in the pest resistance of oilseed rape and wheat.

Box 4.2. The DEEP IMPACT research project: analysis of plant-microbiota interactions to promote plant pest defences (2020/2026, financed in the frame of the Priority Research Programme “Growing and Protecting Crops Differently”)

Promising results have shown that the untapped diversity of soil microbiota can influence plant tolerance/resistance to pests. Modern agriculture is facing the challenge of designing a new generation of agroecological solutions to increase plant resistance to biotic stresses, making the most of plant-microbiota interactions. However, the design of plant-specific synthetic microbiota requires a better understanding of the mechanisms underlying plant-microbiota interactions in a realistic ecological context. The DEEP IMPACT project aims to combine ecology, biology, plant genetics and biostatistics to identify, characterise and validate microbial communities, plant communities and agricultural practices modulating the resistance of oilseed rape and wheat to several pests. Ultimately, a combination of microbial and soil species correlated with improved crop resistance to pests will be identified. DEEP IMPACT will also study the potential role of beneficial plant species in modulating crop resistance to pests by acting indirectly on soil microbiota. This work will enable the implementation of sustainable agricultural practices based on plant microbiota to reduce pesticide use in farming (INRAE, 2024).

The second project, SUCSEED, focuses on plant protection strategies *via* seed management (Box 5.7) and explores the specific case of seed microbiota management. The seed microbiota is in fact the primary source of the future plant’s microbiota and is likely to influence its development and health (Shade *et al.*, 2017). As such, seeds are both targets for biocontrol, but also vectors for delivering beneficial substances and organisms to the agrosystem (Buitink *et al.*, 2020).

Optimising and deploying strategies already in use: a challenge for research

As mentioned above, another type of research challenge that can be promoted by the ambition to be pesticide-free is to improve and deploy methods that are already in use but are not achieving their full potential. Although more applied and not such a breakthrough as a research focus on plant microbiomes, this challenge is nonetheless key to the development of biocontrol, as it is linked to knowledge fronts and calls on a diversity of disciplines. For example, improving and deploying a strategy based on the use of a living organism requires (i) its study (from its genome to the dynamics of its populations in various environments), (ii) technological and engineering research to develop efficient rearing and field-release methods (automation of production processes, artificial feeding, new packaging that preserves the biocontrol performance of the agent, application devices and aids for temporal and spatial positioning in the agrosystem, etc.) and (iii) research on innovation management to facilitate the implementation of business models and stakeholder organisations fostering the use of biocontrol methods.

The list of biocontrol methods that could be considered mature for wider deployment is potentially long as many methods in all biocontrol categories are currently being used below their potential. However, case studies could focus primarily on emblematic cases, i.e. methods that represent a success within the field of biocontrol but remain affected by the aforementioned glass ceiling: their use, while effective and satisfactory locally, tops out at around 10-20% of the possible area in which they could be used (these figures vary according to sources, years and countries, but are generally of this order, whichever method is considered).

So what research and innovation activities could move these approaches from chronic under-use to widespread use for the benefit of farmers? Here we suggest discussing the case of each biocontrol category, citing if possible emblematic situations likely to constitute case studies for research and innovation on biocontrol deployment.

First and foremost, the problem of deployment obviously concerns organisms used in the form of products for biological control by inundation and inoculation, and natural substances. While their use may at first glance resemble that of synthetic pesticides, they are characterised by specific constraints. Their transport and storage often require conditions that are different to those of pesticides, particularly for living organisms. Some substances or organisms can be used with relatively standard agricultural equipment, provided they are not damaged by the pressure of spray nozzles, for example. Others, such as macroorganisms or pheromones, require dedicated equipment. Moreover, because their action is less persistent their positioning often requires greater precision. Current pesticide distributors are not always equipped to support and advise farmers on biocontrol use.

Among the products available in France, we can cite four emblematic examples that could serve as case studies of the actions and infrastructure that need to be developed to boost deployment. The first, historically, is the use of the micro-wasp *Trichogramma brassicae* against European corn borers. This is an interesting case study insofar as successive innovations (conditioning for field release, planning of the successive releases of adults from a single posing of diffusers in the field, choice of strains with higher parasitism in the field, automated agricultural equipment for releases etc.) have enabled this biocontrol product to be used for around 20% of the areas affected by corn borers. The use of *Bacillus thuringiensis*, known as Bt, is another emblematic and widespread example. More recently, microorganisms of the genera *Bacillus*, *Trichoderma* and *Coniothyrium*, marketed by several manufacturers, have seen a boom in use, without dominating the market. As such, they are also good candidates for case studies. In the category of inorganic substances, ferric phosphate, used for slug control, is also a product that has become significantly used and illustrates both the technical and organisational challenges involved.

The challenge of deployment is probably even more relevant in the case of conservation and classical biocontrol and autocidal control. These strategies offer highly advantageous benefit/cost ratios and have been the source of frequent success stories for several decades. However, they remain largely underused.

Classical biocontrol is, in essence, a service as it involves introducing a (non indigenous) beneficial organism, ideally only once, to establish it on the long run. In France, this service is largely financed by the State, *via* research institute staff and research subsidies, supported by agricultural technical institutes and industry stakeholders. In other countries these services have been financed in a more balanced way between public research and the industry as in New Zealand's programme to introduce the parasitoid micro-wasp *Mastrus ridens* (Charles *et al.*, 2019). The question of how to organise this activity and how it could be co-financed by the various stakeholders involved is a topical issue. Optimising these strategies also requires fundamental and applied research in population biology and evolutionary ecology. Indeed, it is necessary to optimise population establishment success rates according to the population characteristics of the beneficial organism, the target pest, the rearing environment and the release environment. Unintended risks to native biodiversity must be minimised if classical biocontrol is to take place. There are potentially many possible study cases in this category, some of which are unpredictable as biological control programmes through classical biocontrol are typically launched following a biological invasion. However, current programmes (against codling moth and *Drosophila suzukii*) are highly relevant case studies for working on the technical and organisational innovations needed to deploy this method.

Conservation biocontrol is more diversified than classical biocontrol in its methods. It involves encouraging the action of beneficial organisms by a range of means. These may involve adapting agronomic practices, redesigning fields and landscapes, or planting certain cultivated or non-cultivated species to create refuges or additional resources for beneficials. Methods are also based on the addition of resources in the field (sugars, pollens, sterilised eggs of beneficials' prey, habitat for beneficials, etc.). The form of this biological control can therefore be both a service (advice or a service for the implementation of conservation biological control measures), combined or not with products (resources such as sugars or pollens can be made available in the form of commercial products by the industry). The organisation of the implementation of this type of strategy raises questions as well, and this is clearly not stabilised in France or abroad. This is borne out, for example, by the absence of a plant protection product savings certificates CEPP action sheet (Box 1.11) on conservation biological control, despite the fact that more than 30 action sheets use biocontrol. The widespread use of conservation biological control raises at least two categories of research activities. The first concerns the theoretical and empirical study of how communities are functioning in agrosystems (community ecology, trophic network ecology, functional ecology and understanding of natural regulation factors). It forms the basis of all conservation biological control strategies and can also lead to farm and landscape management measures that maximise the probability of increasing the level of pest regulation by beneficial organisms (Muneret *et al.*, 2020). The second concerns the way of designing and implementing targeted conservation biological control techniques in a certain sociotechnical environment (e.g. the use of flower strips adapted and evaluated in the Hoeksche Waard area of the Netherlands). Such research activities mobilise a large range of disciplines: biological sciences and digital sciences related to the biotechnical innovations considered but also economic and social sciences to understand which organisational, institutional and social innovations may enable the implementation of the conservation biocontrol practices by the actors in their area. Closer to development and shared with industry stakeholders and local authorities, targeted conservation biocontrol programmes are also currently seeking ways of organising and co-financing them, like classical biological control.

Autocidal control is also a method that can be used in a variety of ways. It includes the use of sterile males (which mate with natural females and thereby interfere with their reproduction), the use of incompatible or avirulent individuals (whose mating with natural individuals will, again, produce sterile or avirulent offspring) and the replacement of natural populations by populations causing less damage to crops (Gould, 2008). The application of these methods has recently been revisited thanks to new capacities for genome editing and gene drive, based on the use of genetic material that can be transmitted and disseminated on a major scale in target populations from generation to generation. This opens powerful pest control possibilities, but also raises concerns about their impacts and complex ethical debates (Legros *et al.*, 2021). Autocidal pest control can therefore consist of launching time-limited eradication programmes to achieve long-term control, as in the case of the eradication of New World screw-worm flies (*Cochliomyia hominivorax*) in several North and Central American countries during the second half of the 20th century (Pérez-Staples *et al.*, 2021). It can also take the form of recurrent releases of mass-produced individuals under industrial conditions to restrict the target pest population to very low densities. An emblematic example of this strategy is the successful regulation of codling moth populations in British Columbia, Canada, whose populations are regulated through a collective programme of sterile male releases across an entire production valley (Thistlewood and Judd, 2019). The research and innovation challenges for autocidal control are both short and long term. In the short term, the challenge is to put in place the organisations and infrastructure to take advantage of the technologies already developed, because despite repeated successes abroad, Integrated Pest Management (IPM) programmes have been largely ignored in France. The reasons for this lack of activity on the sterile insect technique (SIT) have not been scientifically studied and objectified. However, it seems that the problem is organisational: the business models of current actors in the private biocontrol sector are geared towards the production and sale of products. Integrating a territorial coordination activity and services associated with the sale of sterile insects is undoubtedly seen as complex and costly by these actors. Furthermore, in some countries, governments have taken on the bulk of the investment needed to launch large-scale SIT programmes, but the French government has not stepped in so far. We therefore need to look at what needs to be done to produce proofs of concept and include this method in the range of tools available to French actors. This short-term objective calls for research in innovation management, sociology and biology to optimise and adapt production and release methods to the French context. Among the case studies of mature methods, SIT programmes against codling moth and the Mediterranean fruit fly (*Ceratitis capitata*) have produced excellent results abroad. In Canada, the OKSIR programme in British Columbia, for example, kept 80% to 95% of orchards below damage thresholds, while reducing insecticide use by a factor of five between 1998 and 2004 (Bloem *et al.*, 2007). In the longer term, autocidal control also opens a set of new research questions. It is best known in France in the form of releases of insects sterilised by X-ray, but autocidal control can also rely on other technologies based on knowledge of pest biology and genomics (macroorganisms as well as microorganisms). Recent projects have focused on the possibilities of using hybridisation between populations with varying degrees of phytopathogenicity and the use of endosymbionts as incompatibility factors between individuals to drive target populations towards extinction vortexes.

Semiochemicals (for the moment mainly sex pheromones used to disorient or attract and trap pests), currently used as conventional commercial products, also deserve mention here as a pressing challenge for deployment in pesticide-free systems. Indeed, although they can be used as inputs at the field scale, they only reach their full potential when used in a coordinated way across an entire geographical area. This calls for tools and measures to encourage collective action, as well as technologies to facilitate their optimal use (placing them in the right location at the right time and in the right quantities for optimum efficiency). Most semiochemicals are currently sex pheromones (most often female) designed to attract or disorientate males, but future research will help to expand the range of techniques available: the use of kairomones (odours originating from species other than the target species), volatile molecules blocking odour perception systems in target organisms etc. Pheromones for mating disruption in codling moth (*Cydia pomonella*) and European grapevine moth (*Lobesia botrana*) are two emblematic examples of deployment in this category and are recognised for their efficacy. The deployment rate of these methods varies greatly among contexts. For example, while mating disruption against *L. botrana* is used in approximately 10% of vine acreage in France, it is worth noting that it is sometimes much more widespread. In Chile, for example, following the recent biological invasion by *L. botrana*, the State, *via* the *Servicio Agricola y Ganadero* (SAG), has been organising compulsory monitoring and control of this pest since 2016 as part of a national plan. In practice, SAG shares the cost of purchasing pheromone dispensers with farmers and supports them over an area of around 115,000 hectares, i.e. around 50% of the surface area of the crops concerned (mainly vines, but also plums and blueberries)[11].

Methods designed to induce immunity (e.g. PRI) also need to be researched to systematise their efficacy and to optimise their deployment. First and foremost, their use must take into account the environment at the field scale (climate and cultivation practices), as they act on a plant's ability to establish its defences (Walters *et al.*, 2013). A better understanding of the influence of climatic conditions would enable us to better recommend applications and avoid treatments that are doomed to failure. Similarly, it is essential to assess interactions, either positive or negative, with other cropping practices acting on crop physiology within the PRI use window, to avoid sending contradictory messages to the plant. This undoubtedly requires finding a compromise between immunity and productivity, as the race for the latter sometimes favours pests so much that any attempt to induce a plant's defences will remain doomed (see, for example, the ambivalent role of nitrogen in Mur *et al.*, 2017). A second area of research, linked to plant immunity management through biocontrol is genetics. Breeding has undoubtedly progressively reduced the arsenal

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[11] Sources: www.sag.gob.cl, www.odepa.gob.cl

of physical and chemical barriers in cultivated species as sources of negative traits, for example, in terms of taste or digestibility (Alseekh *et al.*, 2021). Reintroducing metabolic diversity into cultivated varieties while maintaining acceptable agricultural and food product quality is another compromise to be sought to improve crop immunity through genetic selection. An innovative avenue of research would be to direct this selection towards varieties that are more responsive to PRI treatments. This could be achieved by improving the perception mechanisms of these PRI-related exogenous stimuli, provided they are known, but also by diversifying the defences that a plant can induce. The transient nature of this induction could be the solution to the necessary compromise mentioned above. Optimising a crop's immunity in practice therefore requires a highly integrated and necessary approach to promote biological interactions within the plant itself and goes far beyond simply replacing pesticides with PRI products. This is the concept of agroecological immunology borrowed from the animal sector (Sadd and Schmid-Hempel, 2009). It aims to understand and promote positive interactions to optimise the immune response, by mobilising practices, methods, tools and products of different natures, all of them ecological. Research into this concept is supported in France by two recently initiated projects: the RMT Bestim[12], a network funded by France's Ministry of Agriculture and bringing together actors in research, development and education across all sectors, and the Priority Research Programme "Growing and Protecting Crops Differently" CAP ZERO PHYTO project, which focuses on apple and tomato (Box 5.8). With regard to possible case studies for the deployment of currently mature methods based on plant immunity management, there are several PRI products (microorganisms and natural substances such as phosphonates) currently in use and the subject of action sheets in the plant protection product savings certificates CEPP scheme (Box 1.11) for several crops in France.

Key messages

Redirecting attention, resources and research and innovation priorities towards the levers for agroecological crop protection, setting research on course to be pesticide-free, causes three types of challenge in the field of biocontrol. The first is fundamental investment in areas of research that are still exploratory and have great potential, such as the study of the functioning of plant microbiota with a view to their management for plant health. The second is the production of knowledge and tools for optimising and deploying biocontrol strategies, a particularly multidisciplinary challenge (involving research in the fields of biology, digital technology, robotics, innovation management etc.). To meet this challenge, it seems important to take advantage of the growth of chains involved in developing pesticide-free production, representing areas of co-innovation where the constraints implicit in pesticide use are relaxed (pesticide-based cropping systems, networks of actors adapted to input use, agricultural equipment etc.). The third, stemming from the realisation that the withdrawal of broad-spectrum chemical inputs will require farmers to rely on combinations of methods, involves research and innovation that will have to revisit

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[12] https://www.gis-relance-agronomique.fr/GIS-UMT-RMT/Les-RMT/BESTIM

conceptual frameworks and approaches to integrating different types of biocontrol and other levers. We have cited here the example of the concept of agroecological immunity, which places the cultivated plant at the centre of the crop protection system and considers immunity in its broadest sense.

⏩ The importance of diversifying business models in the biocontrol sector

Achieving pesticide-free cropping systems involves not only changing cropping practices, but also rethinking the socio-economic systems that have accompanied the development of synthetic pesticides. Intensification of agricultural production and the advent of productivism based on hybrid seeds and use of pesticides were made possible by the creation of stakeholders' networks enabling the development, improvement, test and availability of these inputs. A point raised earlier is that the current socio-economic organisation, in which inputs are products with global rather than localised specificities, and with generic rather than crop — or disease-specific effects —, can evolve. Transforming practices therefore requires to thinking changes in the socio-economic organisation of crop protection, which may involve developing different not only products but also services. These changes entail the transformation of associated actors' networks and the elaboration of innovative business models, ultimately leading to changes in value chains.

Agriculture: a link in a global value chain

Innovation in agriculture is currently viewed within a framework that dates to the 1950s, a period that saw the creation of today's structures and stakeholders, whose common criterion is yield growth. The construction of the French system is well described by Mendras (1992). It dates to the 1930s, with the creation of the network of chambers of Agriculture and of the profession of agricultural adviser. This movement intensified after the Second World War, as the food crisis called to increase agricultural production. Improving productivity required to introduce new techniques (Chapter 1). Large-scale trials were possible through the creation, in 1946, of the National Institute of Agronomical Research (Institut National de la Recherche Agronomique — INRA), while rapid, uniform dissemination was facilitated by the creation, also in 1946, of the National Federation of Farming Union (Fédération Nationale des Syndicats d'Exploitants Agricoles — FNSEA), followed by the creation of agricultural technical institutes — one by cropping sector so far — and of a network of agricultural high schools. This movement was to the detriment of farmers' knowledge and the territorialisation of agricultural activities. The first regulation governing the marketing of pesticides were introduced in the 50's. This shows that the current form of the system is the result of a deliberate construction and public policy, contributing to the establishment of a complex value chain in which the quantity produced, and the yield are the main coordinating criteria of actors (Porter, 2008).

Over the course of the second half of the 20th century, agriculture evolved from a constellation of territorial activities to a global activity with embedded elements following product standardisation, yield optimisation, and cost reduction. This global value chain is characterised by global pricing and a division of labour by country (Gibbon, 2001). This concept — developed from the observation of agribusiness —defines what agricultural innovation should be as well as the mode coordination of associated stakeholders, including agrifood. The interplay between the different levels of the value chain is illustrated by seed research. The introduction of genetic modification offers a promise to "reducing agricultural production costs or improving crop yields", while at the same time improving quality to suit the supply chain, in particular food industry actors (Vanhaverbeke and Cloodt, 2006). Innovation and research in this field therefore integrate economic constraints and not just agronomic ones. This view of production systems and innovation is typical of dominant nations, and it is restrictive when it comes to considering the sustainable impact of organisations (Boons and Lüdeke-Freund, 2013). Yet it remains central to the way we think about food production. Biocontrol products and techniques, which properties are systemic, enable us to rethink the articulation of systems at different scales, by transforming the business models at play.

Biocontrol business models: levers for Change

The agricultural sector is complex and integrated, and current business models are the sum of many trade-offs, this makes the current challenge of rethinking these modes of coordination all the more difficult. To highlight an initial avenue of transformation, we introduced the concept of a "global value chain". Until the 20th century, agriculture was extremely dependent on soil and climate, whereas the Green Revolution has partially detached from the latter (Box 1.4). Agriculture is organised in such a way that stakeholders are grouped within cropping sectors. Knowledge is specialised and built up to optimise the production of each crop. Yet, biological regulation raises issues such as the monitoring of pest populations linked to a specific geographical area and sometimes across several crops. Then, the management of biological regulation requires territorial coordination which structure does not exist yet. There is a need for organisational innovation, which is even more difficult today given that the parameters on which agriculture is based are those of conventional farming.

To overcome this limitation, we introduce the notion of business model. As Schaltegger *et al.* (2016, p.5) point out, research on business models has the potential to open up new perspectives on ecological transition since it "highlights the value creation logic of an organization and its effects and potentially allows (and calls) for new governance forms such as cooperatives, public-private partnerships, or social businesses, thus helping transcend narrow for-profit and profit-maximizing models."

This concept allows us to lift strong hypotheses about how organisations work (Massa *et al.*, 2017) and constitutes a means of supporting change through organisational innovation (Demil *et al.*, 2018). Business models is a pluralistic concept, it can be considered as a representation of the way an organisation creates and distributes value, and it is also seen as a tool for thinking about associated organisational system (Massa *et al.*, 2017). Business model is therefore a valuable concept for studying innovative biocontrol companies and for supporting the sustainable organisational transformations of a complex value chain, which is central to the agroecological transition that biocontrol techniques and products can accompany. The business model concept is closely linked to that of value chain. It allows us to look at different dimensions and inquire into interactions and mechanisms at work within and between the parts of a system when innovations are introduced, rather than analysing innovations as independent from their context. Solutions such as IPM and biological control, like biocontrol products and techniques, are like biocontrol products and techniques, are systemic innovations and involve thinking holistically about change. Hence the need to rethink collaborations and scales that are conducive to the smooth operation of cultivation methods that will enable us to achieve the zero-pesticide objective.

Among the theoretical frameworks for thinking business model, the RCOV approach (Demil and Lecocq, 2010) involves four components: available resources (R) and competencies (C), the organisational structure (O), encompassing the business process (ie. value chain) and the value network (characterisation of the relationships with stakeholders), and finally the value proposition (V) delivered to a wide range of users (including consumers, suppliers and competitors), which is all the greater as the value chains are more complex.

The case of biocontrol is very special, since pure players in this industry claim a value proposition modeled on that of chemical pesticides and based on their properties (Boutet & Parmentier-Cajaiba, 2021). Hence, the value network claimed remains the same at that defined by the existing industrial system. No organisational innovation[13] is seriously considered when it comes to thinking about the modes of valuation (value proposition) and their articulation with external stakeholders (value network) for disseminating biocontrol techniques and products to a wider public. The examples given in Box 4.3 acknowledge a diversity of possible business models when it comes to biological control, relatedly to the value proposition and its value network.

Box 4.3. Diverse business models for developing biological control

Different business models, linked to different value chains, have been theoretically envisioned to develop biological control on a larger scale.

Classical biological control

This is not a highly attractive business model for a for-profit company, since it seeks the long-term installation of beneficials without needing support to users. The successful regulation of chestnut gall wasps identifies the markers of a generic classical biological control business model (Borowiec *et al.*, 2018).

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[13] An organisational innovation is a transformation in the way an activity is carried out. As an example, DELL innovated in its field by proposing to make computers corresponding to the precise demands of individual consumers, rather than offering standard PC. This was made possible by introducing and organisational innovation involving the reorganisation of the supply chain, combined with the introduction of a powerful integrated management system.

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The value proposition is straightforward: that cynips presence should be limited to ensure the continuation of the activity without substantial loss of income, and to avert the threat of growers' reconversion. The value network brings together private and public actors, ensuring coordination at several levels. These actors come from (i) research in several countries to monitor the introduction and its consequences; and (ii) support and coordination by professional organisations, such as the technical centres and the territorial federations to controlling pests present in each French administrative territory (Fédérations départementales de lutte contre les organismes nuisibles — FREDON). The impact of the project has not only permitted us to realise the value proposition, but also to generate new knowledge about the implementation of classical biocontrol and to launch coordination networks and new ways of doing things.

Autocidal control (Sterile Insect Technique — SIT)

The CeraTIS project (Ecophyto 2020-2023 funding) is experimenting with SIT to control the *Ceratitis Capitata* flies affecting fruit production in Corsica's Vescovato valley. The value proposition aims to control pests that persist from one season to the next, since fly reservoirs remain from one fruit crop to another. Growers and distributors are among those primarily concerned. The initial value network was based on technical and research institutes, as well as the local experimental station. However, for long-term implementation of the technique, the project aims to mobilise political and public stakeholders whose may have an interest in reducing pesticide use: residents associations, environmental groups, hotels and tourist offices and so on. In this case, the island's tourist-centred character may be a lever for supporting the establishment of a territorial biocontrol business model.

Inundative biological control

The BIDIME project (funded by the French National Research Agency (ANR) — 2020-2023 Écophyto Maturation program) is an experiment to release several species of *Trichogramma* micro-wasps in greenhouses for perfume, aromatic and medicinal plants (PPAM) production in France's Grasse area. The value proposition here is to provide a means of pest control for a high-value-added niche sector for which few, if any, solutions are available. The value network here is loosely structured around a very active growers' association (Les Fleurs d'Exception du Pays de Grasse), which has been developing research and lobbying activities for 20 years. The idea here is to involve more stakeholders. On a local scale, the aim is to mobilise public authorities to promote agroecology as a territorial brand and explore the issue of potential employment through local production of beneficial insects. At a national scale, the project aims to involve stakeholders downstream in the value chain, in particular luxury brands whose are buyers of production-derived absolutes[14]. In this case, brand image and production quality are relevant levers.

Addressing the issue in terms of business model therefore leads not only to rethinking the coordination between agricultural actors, but also to a broader consideration of the stakeholders involved, including those outside of the agricultural perimeter. These examples show that, ultimately, the value produced lies not only in biological regulation, which limits economic losses, but also in the creation of knowledge and the discovery of multi-actor and territorial modes of coordination. There are ways

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[14] Absolute is a natural perfume concentrate extracted from a flower or other plant part.

of generating environmental and social benefits through local action. However, it is essential to bring together all the stakeholders — both private and public — who are potentially interested in these aspects.

Two examples of SIT show that several configurations are possible for the deployment of the same technique. The introduction of SIT to control codling moth in British Columbia, Canada (OKSIR project), has made it possible to largely limit the use of pesticides on a regional scale and develop an eco-friendlier regional identity. This was achieved by involving a wide range of public and private stakeholders, particularly citizens, and by creating a common interest in the issue of agroecological transformation (SIR, 2021). As well in Canada but in Quebec, a private consortium offers first, identification services of pest, this service was followed by the deployment of SIT later (PRISME, 2021) for controlling the onion fly. Here, the activity relies on a network of private (technical centres, members of farming community & media), hence members of Prisme (producer organisations) benefit from various services according to their needs (research and development, implementation and monitoring).

In both cases, the distribution of biocontrol products and techniques needs to be tailored to the territorial characteristics, crop sectors involved, and available networks. This becomes the responsibility of networks of collaborative actors, rather than that of isolated, omnipotent economic actors. These two examples show that there are different ways of deploying zero-pesticide strategies based on a same technique. The business models implemented express this diversity: in the first case, the territory is the driving force, and local organisations have been involved. In the second, an *adhoc* structure addresses several territories and makes the most of partnerships. This diversity is also reflected by the different forms of governance, in which decision-making is involved in a variety of ways. Public policy support to increase the diversity of business models could include the fostering of organisational structures that enable this diversity; some already exist, such as cooperatives, but new forms of structure could also be developed.

Key messages

Since the Green Revolution, a production model has been established that implicitly relies on the use of chemical inputs. A zero-pesticide objective requires rethinking current agricultural business models. To support this necessary effort of organisational innovation, we focus on three essential dimensions: (i) relevant scales for monitoring bio-agressor populations needs to be thought beyond the field or the farm; (ii) coordination with new stakeholders, who are not identified as "agricultural actors", needs to be introduced, including upstream and downstream stakeholders in the supply chain, but also environmental and civic associations, and even local and national public authorities; (iii) criteria other than productive efficiency alone need to be developed, such as biodiversity gains as well as soil quality and landscape value. For this, research needs to be carried out more collaboratively, to build measures and indicators, that are both objective and shared, thus broadening the scope of what is understood as having value.

⏩ Diagnostic, forecasting and decision support services at the heart of future strategies and biocontrol business models?

Diagnosis and decision support are obviously key to the development of biocontrol

Earlier in this chapter and in this book, we have highlighted two key points when considering the future of biocontrol. The first is that the dominant cropping systems, which optimise the use of pesticides, give relatively low priority to the management of biological balances, the close monitoring of pest and beneficial populations and the prediction of their dynamics. Preventive, calendar-based chemical treatments, the use of relatively coarse trigger thresholds and the massive curative power and persistence of pesticides generally control pest outbreaks. The second observation is that biocontrol requires strong diagnostic and forecasting skills, both to ensure, that it is applied in the right place at the right time and in the right way[15], and that the cropping system is resilient to pests (and therefore not primarily dependent on inputs with high curative power and long-lasting effects in the environment).

As we shall see in Chapter 7, this need for diagnosis and management is common to most agroecological levers, and many promising avenues are currently being explored at the farm scale. Here, we would like to focus on the requirements related to specific features of biocontrol-related innovations, which broad scope — ranging from efficient input use to landscape management, *via* a wide variety of modes of action — makes it particularly important to combine and coordinate different methods, and even to consider entire area-wide agroecological systems. We shall also raise the issue of how to pinpoint the very needs of operators in the field, as well as the organizational modes that can be used to meet these needs, through the provision of tools for different actors at different scales.

Managing biological regulation and using biocontrol inputs efficiently ideally requires a set of diagnostic and predictive tools for:
- Monitoring and predicting pest population densities.
- Monitoring and predicting beneficial population densities.
- Understanding the state of the plant (and more generally the phytobiome, i.e. the plant, its microbiota and their interactions) in its specific environment.
- Determining, based on the above information, when and where specific management actions are necessary.

While these statements may seem obvious, translating them into innovation and deployment priorities is proving complex. First, many tools, whether diagnostic methods or Decision Support Systems (DSS), have been developed over the years, but they are mainly designed for use at the field scale and specifically for a precise objective (for the use of a particular input). The diversity of modes of action in biocontrol products, the recognition of a plant as an active partner in its protection and the

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[15] The issue of positioning is not unique to biocontrol, since it has been a major focus of innovation for pesticides, but it is even more significant for biocontrol inputs.

development of other agroecological methods or levers (prophylactic methods, but also mixtures of species, including service plants etc.) highlight the need to think about the construction of more global DSS. These tools should make it possible to manage the necessary trade-offs between pests and plant species, between biocontrol methods (in the broadest sense) and between productivity and protection. They should also make it possible to position interventions (of all kinds) in relation to each other during periods where there is a risk of pest outbreaks. More specifically, interventions to stimulate plant defences must target a receptive physiological state, conditioned by numerous factors. This means DSS should integrate indicators of plant physiological state, to direct biocontrol treatments towards PRI applications or, on the contrary, towards other methods with more direct action on pests, depending on the crop's receptivity status. The other challenge is to integrate a spatial dimension into DSS, so that they can be used to make decisions at the landscape scale, comprising a variety of farms, crops and non-cultivated landscape elements.

The challenge of developing and deploying biocontrol tools is not just a technological one

It is likely that technological advance will enable to develop a variety of tools relatively quickly (see Box 6.2 on olfactory sensors, for example), there are several thorny questions regarding their development and use. How one can organise the spatial deployment of diagnostic tools? As with weather forecasting which takes into consideration numerous interacting factors, is it possible to design epidemiological and biological regulation forecasts with high reliability on a relevant term (from one season to the next, for example) to be applied in practice? Is integrating so many types of information and predictions into DSS realistic? How one can combine analyses conducted at different scales (epidemiological on a national scale, population dynamics at a landscape or field Scale, etc.) to produce forecasts that are relevant to field workers?

Another key factor for deployment is the identification of the real needs of actors about these tools and how these needs are met. Faced with the expected explosion in the number of tools available, whether simple monitoring methods or complex DSS integrating numerous parameters, how will current and future actors in the agricultural world position themselves? How to choose them (and with which partners), and what priority should be given to research and innovation aimed at developing and combining them? Many of the tools available are little or not used on a regular basis (or remain closer to researchers rather than practitioners). This reminds that a technological invention appearing relevant *a priori* a does not necessarily meet an actual unsatisfied need of stakeholders. This may be due to a cost-benefit ratio that is incompatible with expectations, or to a complexity that is out of step with the interest expressed by potential users. Co-innovation between research and actors in the field has been mentioned for years as essential in most calls for research and innovation projects. We must however remember that identification and characterisation of needs, combined with co-innovation of actors committed to agroecological strategies, shall be essential to the success of biocontrol and the tools accompanying its deployment.

Once needs have been identified, the next key questions concern the way in which these tools will be made available and used to support the integration of biocontrol into agroecological systems. In what form will they be available (services, products etc.) and how will they be integrated by actors into their business models? By way of example, four non-mutually exclusive scenarios can be considered:

– The first scenario corresponds to historical biocontrol companies marketing biocontrol inputs, organisms in particular, which have naturally integrated monitoring and direct support services for producers over time. However, these services are most often directly linked to the use of their product: for example, the use of traps to monitor pest populations and to decide on the best time to use biocontrol inputs. These services have recently been extended to include increasingly sophisticated devices, e.g. automated, programmed sprays or connected sensors to optimise the use of mating disruption. Other companies have integrated online monitoring and pest dynamic mapping into their offer as a package [16]. Such tools are likely to be increasingly integrated within the range of activities delivered by biocontrol companies.

– The second scenario is the development of new companies, specialised in digital technologies (Internet of Things, DSS, remote sensing, monitoring etc.) and close to producer groups, which provide packages of tools in the form of services. These companies are already common for optimising sowing and irrigation systems but may develop with the rise of sustainable crop protection strategies.

– A third scenario is the massive appropriation of these tools by cooperative and collective players (producers' associations, agricultural cooperatives, cooperatives for the use of agricultural equipment, collective interest cooperatives etc.). Currently, this scenario seems to be relatively underdeveloped in France, but these stakeholders could play a key role in coordinating actors on the scale of more or less vast geographical zones, depending on their area of influence.

– Finally, many tools can be made available to actors *via* public services. While this form of tool provision seems logical and legitimate because many of these tools are designed to facilitate the coordination of a variety of actors and to manage a common good, its adoption depends heavily on the doctrines of States and local authorities in terms of public support for private actors. In France, the State's position on this does not seem entirely clear-cut. State services are present locally in agricultural areas and play an active role in biological monitoring, but their role in the operation or use of diagnostic and decision support tools and services seems relatively unstable. One example of this instability concerns the "Bulletins de Santé des Végétaux" (BSV, plant health updates), created in 2009. These BSV display great potential for coordinating actors on a territorial scale and could integrate data from a wide range of actors and diagnostic tools. However, the development dynamics and the very sustainability of the BSV are recurrently a subject of debate within public authorities, focused on funding modalities and the will to diversify them.

Key messages

Like all agroecology strategies, successful use of biocontrol methods is highly dependent on tools that enable or facilitate (i) the detection and quantification of pest and beneficial population densities, (ii) the prediction of their spatio-temporal

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[16] https://colbics.eu/main-results/decisions-support-tools-for-the-monitoring-of-arthropod-pests-in-chile

dynamics, and (iii) decision support for the management of natural regulation or field interventions.

The development and appropriate parsimonious use of these tools naturally represent a considerable technical challenge in terms of detection technology, modelling, automation, data integration and analysis. Because the state of the art still in its infancy, investment in research required to develop such tools is considerable, particularly in terms of predictive capacity within complex systems on timeframes compatible with the requirements of field operators in terms of planning. Another challenge lies in the capacity to link together data obtained at different scales (from plants to biogeographical zones larger than a country etc.).

The challenge of supporting different types of biocontrol with diagnostic and decision-making tools is not just a technical or a technological issue. Faced with the possible profusion of tools, a challenge for research and innovation is also to look ahead to future agroecological systems, future geographical areas and future stakeholders, to realistically characterise the needs in terms of tools and to propose suitable modes of organisation.

⏩ Conclusion

The pesticide-free paradigm proposed in this book is expected to provide a strong stimulus to the diversification of biocontrol methods through greater investment from the public and private sectors, and the acceleration of research on scientific fronts such as the study of the phytobiome. This paradigm shift could speed up the diversification of biocontrol methods currently deployed in agricultural chains, acting as a catalyst for the development of new infrastructure, stakeholder organisation, business models, diagnostic tools and decision support systems adapted to biocontrol and its combination with other agroecological levers. This expected expansion should increase the number of biocontrol methods available and deployed. This expansion could also rebalance methods made available to actors in the form of products (which currently represent the majority of methods offered to farmers) and methods made available in the form of services (integrating tools for predicting and managing natural regulation) (Figure 4.1).

In practical terms, we make the following recommendations to support the research and innovation fronts mentioned in this chapter: (i) set up support mechanisms and research and innovation actions on the most under-developed strategies (deviating from traditional product logics) and rebalance efforts between products and services; (ii) study needs, prioritise actions and develop biocontrol strategies in sustainable cropping systems and sustainable commodity chains that already use few or no pesticides. This will help to develop methods and tools in systems that are the most free of implicit constraints set by the infrastructure inherited from agrochemistry; (iii) continue to support fundamental research that opens up prospects for new modes of action and deployment, as has been done in the French Priority Research Programme "Growing and Protecting Crops Differently". These three types of action are intended to complement existing private R&D support schemes.

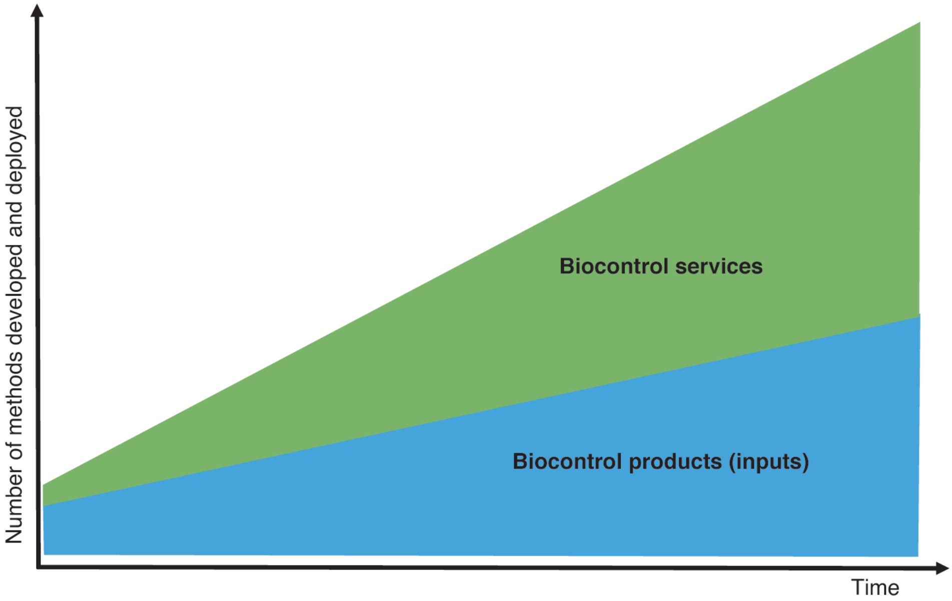

Figure 4.1. Expected effects of the pesticide-free paradigm on the evolution of research and innovation enabling the use of biocontrol to flourish: increase in the number of methods available and deployed, private and public investment, political and public support, diversity of biological mechanisms involved etc.

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Chapter 5

Developing species and varieties enabling the redesign of cropping systems

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⏩ Introduction

From domestication to cultivated crops

Today's cultivated plant species are mostly the result of human domestication of so-called wild ancestors during the Neolithic period. Domestication consists of fixing a certain number of genes involved in the control of traits that favour human use and cultivation (increasing grain size, limiting dehiscence to facilitate harvesting, limiting the number of branches for more grouped flowering and ripening etc.). This initial selection process, during which humans influence the dispersal and reproduction of a species, is accompanied by a drastic drop in genetic diversity for the newly domesticated species, notably due to the speed of the process (domestication syndrome). In fact, as only a limited number of wild individuals are at the origin of cultivated species, this domestication is accompanied by a sharp reduction in the genetic diversity present in the cultivated compartment compared to that found in the wild compartment. Since Neolithic times, a relatively small number of cultivated species have emerged and spread through intercontinental migrations and/or intercontinental exchanges, for example, when the first farmers migrated out of the Fertile Crescent, or when Christopher Columbus discovered the New World, bringing tomatoes, beans, maize etc. to Europe. After an initial reduction linked to domestication, the genetic base of cultivated populations then tends to re-enrich itself over the passage of time, with the appearance of spontaneous mutations (the natural mutation frequency of a gene is around 10^{-6} per generation), flows between plant populations and, finally, the diversity of the agroecosystems in which they evolve, linked to historical exchanges and movements. The discovery of Mendelian genetics in the 19th century (rediscovery of Mendel's laws in 1900 by Hugo de Vries, Carl Correns and Erich von Tschermak-Seysenegg), followed by the discovery of the structure of DNA (Watson and Crick, 1953), then accelerated genetic progress, defined as the gain for a given trait in the selected population compared to the average of the initial population.

The term variety is most often used in agriculture to define, within a plant species, an artificial population made up of genetically close individuals with defined common agronomic characteristics and that can be reproduced stably. These varieties are registered in an official catalogue, which enables them to be marketed. The aim of plant breeding is to create new varieties adapted to the needs of farmers, agrifood industry and consumers. Practiced since the earliest days of agriculture, breeding techniques and schemes have consistently been improved, accelerating the creation of new varieties and genetic progress. Among cultivated plants, common wheat (*Triticum aestivum*) is a textbook case (Venske *et al.*, 2019). The first varieties sown by farmers, or "local varieties", corresponded to populations of individuals with common characteristics (e.g. earliness) but with genetic diversity within these populations (corresponding to today's definition of a variety population). These varieties were maintained by farmers, because part of the harvest served as seeds for the following crop. From around 1850 onwards, plant breeders began to specialise and these varieties were gradually replaced by so-called "pure line" varieties in which all individuals are genetically identical and whose characteristics are preserved from one generation to the next (the first wheat variety to emerge from controlled cross-breeding was Dattel, registered in 1884). From 1945 onwards, new genitors were used to obtain high-yielding varieties widely distributed throughout the world as part of the Green Revolution. These were more resistant to lodging thanks to the incorporation of dwarfing and photoperiod sensitivity modification genes (for which Norman Borlaug was awarded the Nobel Peace Prize in 1970 for his work in combatting world hunger). Since then, high-potential varieties, grown in monospecific stands, have become widespread, to the detriment of the genetic diversity of cultivated areas, combined with a specialisation of territories that reduces the number of species present in the crop rotation. Gradually, new ecological and environmental challenges have led to the introduction of new selection criteria, in particular to reduce the use of fertilisers and pesticides, by focusing on pest resistance and tolerance.

With regard to disease control, the search for resistance genes in plants initially focused on pathogen recognition mechanisms (R genes). These total resistance genes were then introduced into varieties to limit pesticide use (Gururani *et al.*, 2012). However, these varieties were soon confronted with a problem as pathogens overcame their resistance (Box 5.1), diminishing their effectiveness. The durability of resistance genes and the diversification of resistance mechanisms remain major challenges for plant breeding today.

Box 5.1. Avoiding loss of resistance: a key concept for pesticide-free agriculture

Pathogens establish intimate and complex relationships with host plants to obtain the nutrients they need for growth and development. The evolution of plants has therefore been accompanied by the evolution of microorganisms and other organisms, both beneficial and pathogenic. In return, plants have developed a set of processes that give them the ability to resist infection.

Over the past 80 years or so, the creation of new resistant varieties to improve yields has been a priority, through the selection of varieties with one or more major resistance genes (R genes). The presence of resistant individuals in a population limits reproduction of the pathogen targeted by the new variety's gene(s). In turn, the presence of these resistant individuals exerts selection pressure on pathogen populations, encouraging the emergence of new pathogen variants that can bypass the plant's resistance gene(s). This arms race, or "red queen hypothesis" (van Valen, 1973), is one of the theories available to explain why an organism constantly evolves with its environment. These evolutionary processes, such as mutualism between plants and beneficial organisms, can also be at the origin of defence mechanisms. The speed with which resistance conferred by R genes is overcome is often rapid. Generally, in two to five years, a variety R gene resistance is overcome (Gasselin and Clément, 2006).

As early as 1995, Michel Griffon laid the foundations for a new approach to agriculture aimed at a "doubly green" revolution, which provided a new framework for plant breeding and which has since evolved with the progress of agroecological practices. Varietal selection is a major lever for contributing to this. From this moment on, breeding must be multifactorial, integrating environmental, economic and socially just sustainability objectives, in particular by taking into account the ecological processes of species and the environments in which they are grown. This represents a profound change in plant breeding, requiring to consider plant's adaptation mechanisms and interactions with its biotic and abiotic environment. Historically, various criteria were integrated into a single genotype but other possibilities need to be considered to meet these new challenges. Diversification through species or variety mixtures is a promising avenue for the development of agroecological systems, but requires adapted varieties with good behaviour in mixtures (adaptability in a context of plant/plant competition) (Finckh, 2008). For the time being, these latter criteria are only rarely addressed by breeding programmes, although the seed industry sector is now actively working with national research organisations, including INRAE, on this objective.

Variety selection in pesticide-free cropping systems

Achieving the production objectives of a cropping system depends in part on the different varieties available to farmers (Box 5.2). Indeed, the first step in a given cropping system is the choice of variety for a given species, on which many subsequent technical choices will depend, particularly as plants differ in their ability to use environmental resources or to defend themselves against pests. Choosing the best variety per species is therefore crucial, and requires anticipation and risk-taking on the part of farmers, who integrates into their decision-making process criteria dictated by characteristics specific to their production system: the biophysical environment of the farm, the crop's place in the rotation, the markets for the crop produced etc. In pest control, the genetic lever is obviously not limited to the choice of variety. It also concerns the choice of species sown and the way in which they are combined over time (such as the succession of species on the same plot) and space (such as the combination of species).

As presented in this book, the goal of pesticide-free agriculture requires the identification of the best combinations of existing levers at different agricultural scales and contexts. Plant breeding is one of the keys to achieving this goal, but it is also one of the current obstacles, as it requires not only disciplinary research but also interdisciplinary dialogue to integrate the complex mechanisms of interactions between plant communities and their biotic and abiotic environments. The goal of pesticide-free agriculture also calls into question: (i) the evaluation criteria for species and varieties registered in the official catalogue, and (ii) the adaptation of the processing chain to take into account these new varieties. It is therefore essential to strengthen interdisciplinary and inter-organisational dialogue during the various stages of varietal creation (see part "Avenues for new breeding programmes").

Box 5.2. What is an official catalogue?

Since 1932, an official state-created catalogue of species and varieties has listed the characteristics of each variety, enabling end-users to choose the most suitable one for their needs. By law, any person or organisation can register a new variety. However, to be recognised as a new variety, a set of criteria must be met. These are the DUS tests (Distinctness, Uniformity, Stability), plus the tests known as VATE in France (agronomic, technological and environmental value) for field, forage and turf species. VATE tests make it possible to compare the different varieties that are candidates for registration in terms of characteristics such as yield, resistance to pests and diseases, and the quality of the final product.

The aim of the catalogue is therefore to provide seed users with a guarantee of a seed's characteristics, particularly with regard to its distinctive qualities. As an example, in France, all entries must be approved by the French government, on the basis of an advisory opinion issued by the Permanent Technical Committee on Breeding. There are several lists in the catalogue, both for varieties intended for commercial agricultural use and for vegetable varieties threatened by genetic erosion or with no intrinsic commercial value (such as traditional varieties). The criteria for inclusion in the catalogue are not set in stone, but evolve over time. For example, the "Grenelle de l'environnement" summit in 2007 made it possible to introduce environmental criteria and to prepare for the inclusion of varieties suitable for organic farming, enabling public authorities to guide genetic progress. Varieties registered in the national catalogue are included in the European catalogue and can now be grown throughout Europe. DUS characteristics are also used to ensure the intellectual protection of the variety through the granting of a plant variety protection certificate ("Certificat d'Obtention Végétale" — COV), a *sui generis* right established by the 1961 Paris Convention, which excludes the protection of plant varieties by patent.

⏩ What are the challenges for plant breeding in a pesticide-free agricultural context?

Making the most of the genetic diversity of varieties and plant-plant interactions as a lever against pathogens, insect pests and weeds

The development of pesticide-free agriculture means rethinking cropping systems and crop management approaches, and therefore the role or expected contribution of future varieties. In this new context, the regulation of pest populations relies primarily on the management and optimisation of biological and ecological regulation at different spatial scales (plot, farm or territory), which are themselves largely dependent on the level of diversity present in the field. Consequently, the choice of variety is a lever for influencing genetic diversity within a plot and/or farm. These varieties must therefore be designed to fit into an agroecological framework, i.e. to exploit biological interactions, including plant-plant interactions. At present, the majority of crops are monospecific and monovarietal, based on homogeneous varieties (pure lines, clones and F1 hybrids). This needs to be reconsidered, as tomorrow's varieties will be grown in systems that optimise genetic diversity, i.e. in mixtures, either with other species (such as cereal-legume intercropping or, as is already largely the case, mixtures in temporary grasslands) or in varietal mixtures on an intraspecific scale. In both cases, the varieties selected must have interesting intrinsic characteristics (e.g. good levels of resistance to pests and diseases), as well as good suitability for mixing.

First, let us look at the intraspecific scale. At this scale, it is reasonable to think that in a context of uncertain pest and disease assemblages, it is unlikely that a single variety will be able to display all the favourable adaptive traits. Varietal mixtures therefore appear to be a promising solution for combining different favourable traits within a single stand. In varietal mixtures, the presence of several varieties can increase resistance to pathogens. Indeed, each variety provides different resistance genes, reducing selection pressure against pathogenic strains at the scale of the cultivated plot. In addition, mixing varieties also makes it possible to cumulate effects modifying pathogen population dynamics by limiting spore dispersal through the splash effect (Vidal *et al.*, 2018), with different plant heights, for example, or by modifying the microclimate. In soft wheat, in the absence of fungal protection, the cultivation of varieties in a mixture has proved to perform better than the average of the varieties making up the mixture taken individually. In oilseed rape, a 95/5 varietal mix, with only 5% of a very early variety, provides effective control of damage caused by pollen beetles. Crop combinations are also an important means of adapting to pesticide-free agriculture, notably to limit and regulate insect or slug damage, and weed and disease development, through dilution or barrier effects. In addition, crop combinations, which are more heterogeneous in time and space, favour the establishment of associated biodiversity in the cultivated plot, enabling the provision of several ecosystem services. For example, 25% of France's organic oilseed rape acreage is planted with a legume (mainly to combat insect damage in autumn), and 12% of wheat acreage was planted with a mixture in 2020.

The challenge for breeders therefore lies in the ability to evaluate and select future varieties not only for their value in their own right, but also for their ability to be mixed and optimise interactions between neighbouring plants within the field (Annicchiarico *et al.*, 2019). Initially, empirical approaches may be implemented, but in the long term, detailed knowledge of the genetic and ecological processes involved will make it possible to target new selective traits, corresponding to complementary and optimised services in new component varieties offered for mixtures. In increasingly uncertain environments, it is becoming increasingly difficult to predict which variety will be the best, just as it is complicated to be able to cumulate all favourable traits in a single variety, due to the trade-offs between traits involved in adaptation. The local adaptation of planting material will, in part, lie in the positive interactions between different varieties and/or species planted simultaneously in the same plot. The type of plant-plant interaction over space and time, *via* niche partitioning (complementarity) or facilitation, concerns, for example, access to mineral and water resources (exploration of the soil by root systems, recruitment of rhizosphere microbiota, nutrient utilisation efficiency for nitrogen, phosphorus etc.), the plant's resistance or tolerance to different pathogens and its use of light resources (Díaz and Cabido, 2001; Hinsinger *et al.*, 2011). However, plant-plant interactions are context-dependent, i.e. strongly conditioned by the level of resources (water, nitrogen etc.) defining a level of perceived abiotic stress. This modification of plant-plant interactions is theorised by the stress gradient hypothesis (Stefan *et al.*, 2021). Nevertheless, the complementarity sought remains determined by the genetic diversity of the mixtures. Building an optimised mix therefore involves targeting the main traits for the production system in question, then identifying the components (varieties or species) with different and complementary traits (for example, by exploiting vigor, rooting depth, disease-resistance mechanisms, aerial architecture etc.). The aim here is also to promote selection for heterogeneity (increasing variance) (Litrico and Violle, 2015). The challenge is also a technical one, since we need to be able to describe and phenotype these complex traits for a large number of genotypes, while reporting on behaviour in the field and in mixtures. These questions correspond to emerging and promising research themes, seeking to optimise aptitude for specific or interspecific mixtures, as in the MOBIDIV research project for soft wheat (Box 5.3), or the SPECIFICS research project for legumes (Box 3.2). The projects are also exploring new functional traits, such as the interaction between a plant and its root microbiota, notably to improve the resistance of oilseed rape and wheat to biotic stress (DEEP IMPACT research project, Box 4.2).

Box 5.3. The MOBIDIV research project: mobilising and selecting intra- and interspecific crop diversity for systemic change towards pesticide-free agriculture (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

Intra-plot diversity is a major lever for achieving pesticide-free agriculture because it enables unique and essential regulation through plant-plant interactions. However, the causal mechanisms of plant-plant interactions are still poorly understood. Furthermore, the selection of mixtures of varieties and species entails a major change in the methods and organisation of the seed industry. Given this context, MOBIDIV aims to produce and disseminate scientific knowledge for plant breeding dedicated to intra-plot diversification.

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The project's first objective is to identify diversification dynamics in France and their technical and socio-economic determinants, and to study intra-plot diversification practices among selected farmers. Second, the mechanisms of plant-plant interactions favouring pest control are being studied using functional ecology and genetic approaches coupled with modelling. These mechanisms are being used in field trials to design gradients of genetic and functional diversity and assess their impact on pest incidence and adaptation, as well as on ecosystem services. Third, innovative genetic and statistical methods are being used to build selection and mixture evaluation schemes. In parallel, participatory approaches are being used to co-design and select a wide range of mixtures, varieties and populations, and to assess their adaptation to local contexts. Finally, scenarios are being developed for adapting market standards, as well as the organisation and funding of agricultural research and advice, with a view to crop diversification (INRAE, 2024a).

The durability of resistance based on knowledge of pest biology

The knowledge acquired over recent decades on the molecular basis of pathogenesis and plant-pathogen interactions has contributed to the development of breeding strategies aimed at improving disease resistance in cultivated species. Breeders have long relied on the use of single-gene resistances, due to their strong effects and ease of use in breeding. These resistances are based on the presence of resistance genes called R genes, which generally code for immune receptors that directly or indirectly recognise pathogen molecules, triggering strong and rapid defence responses in plants (Box 5.4). However, mutations and changes in the virulence of pathogen populations make the efficacy of these R genes — specific to one strain of pathogen — short-lived. In contrast to the high level of resistance conferred by R genes, resistance controlled by minor-effect quantitative trait loci (QTL) is considered more durable and is generally not strain-specific. However, because of their weaker effect, to achieve a high level of resistance it is necessary to accumulate several QTLs within the same genotype, or to combine them with monogenic resistances controlled by R genes. Pyramiding (combining R genes and/or QTL within the same variety), with complementary resistance spectra or modes of action, can produce additive and synergistic effects on the level and spectrum of resistance. Although the combination of R genes and QTL in the same gene pool is effective for disease control, the integration of these two types of resistance in an elite cultivar is technically difficult, notably due to a lack of knowledge of the genes underlying QTL and their interactions with the gene pool and environment.

Box 5.4. Two types of plant defence: constitutive and induced

Plants have a defensive arsenal at their disposal to protect themselves against pests. There are two types of defence strategy: passive or constitutive, and active or induced in response to the presence of a pest. Constitutive resistance corresponds to the plant's passive barrier-type defences, such as cell wall thickness or waxy cuticles. Induced resistance arises when, under the influence of the inducing stimulus produced by recognition of a pest, a mobile signal is generated and transported to other parts of the plant, where it reinforces the mechanisms that normally function to limit the infection, growth, multiplication and spread of fungi, bacteria and viruses.

So, when pyramiding R genes and/or QTL, an R gene can mask the effects of other resistance loci and the genetic background of varieties can affect the resistance phenotype. The effects of combinations of different R genes and QTLs are therefore not predictable and need to be tested in different genetic backgrounds before being used in breeding programmes. Further studies of the mechanisms underlying the synergistic or antagonistic effects of different combinations of resistance genes or QTL and genetic backgrounds would provide essential new information for the selection of sustainable broad-spectrum resistances. Other avenues of research are also being explored, such as identifying resistance genes that "balance" the trade-off between resistance and yields (Deng *et al.*, 2017; Wang *et al.*, 2018), or limit the negative effect of defence proteins on plant growth (Xu *et al.*, 2017).

Furthermore, the interaction between plants and pathogenic microorganisms is strongly influenced by multiple environmental factors such as temperature, humidity, light and nutrients. Nutritional stress caused by nutrient excesses or deficiencies (nitrogen, phosphate, iron, copper etc.) can affect a plant's response to infection by a pathogen and therefore modify the outcome of the interaction. The plant stage and presence of reproductive organs that consume a lot of nutrients can therefore modify the interaction between plants and pathogenic microorganisms. The impact of nutritional stress on disease resistance is difficult to predict, as results differ greatly depending on the identity of the interacting partners (host and pathogen). From the point of view of the host plant, the complexity of the interaction between nutrition and disease development is linked to the different combinations of resistance loci present in each plant genotype and to the reactivity of each resistance loci (R or QTL) to stress. For example, nitrogen availability has an effect on a plant's primary and secondary metabolism, which in turn can affect host defence responses. While promoting plant growth, a high nitrogen supply can lead to a decrease in lignin formation and a reduction in the thickness of secondary cell walls, which form a plant's physical barrier to pathogen infection. An oilseed rape genotype susceptible to clubroot disease under non-limiting conditions can therefore prove resistant under a reduced nitrogen availability (Laperche *et al.*, 2017). From the point of view of the pathogen, the pathogenicity of fungi, for example, can be affected by nitrogen availability. Nitrogen-induced susceptibility to rice blast is associated with the induction of rice genes involved in nitrogen recycling and increased pathogenicity of *Magnaporthe oryzae* (Huang *et al.*, 2017). In contrast to what is observed in rice, nitrogen fertilisation reduces the severity of diseases caused by *Verticillium* spp. in *Solanum* species, indicating that no generic model can describe the role of nitrogen in a given interaction (Veresoglou *et al.*, 2013). With regard to phosphate nutrition, emerging evidence supports the existence of interference between the signalling mechanism of phosphate deprivation and immune responses in plants. However, our knowledge of the interactions between plant adaptation mechanisms to phosphate excesses and immunity is still limited. The genetic determinism controlling disease resistance can therefore be strongly modified as a function of cultural practices. And yet, even though particular attention is now paid to a variety's adaptation to environmental and growing conditions, in particular its water and nitrogen efficiency (VATE evaluation), the selection of resistant varieties is still mainly carried out in non-limiting growing conditions which are not those expected in agroecological systems.

With regard to insect pests, research into plant resistance to them has so far focused on identifying the main resistance genes (R genes) and simple gene-for-gene interactions, whereas in reality it is likely to be polygenic and involve multiple genes or pathways, similar to what is observed for pathogen resistance. Although defence through morphological traits (increased number of trichomes, sclerophyll, latex deposition etc.) is mainly used by plants against insect pests, biochemical defence is considered more effective as it directly affects insect growth and development. However, resistance induced in response to herbivorous insect attacks renders host plants phenotypically plastic with less nutritious plant tissues, making them a less attractive and virtually tasteless food choice for insect pests. Nevertheless, various insects can tolerate or detoxify certain plant secondary metabolites, and some insect species use plant secondary compounds as necessary indicators for feeding or oviposition (Schoonhoven *et al.*, 2005). Furthermore, there is ample evidence that many phytophagous insects have co-evolved with the secondary metabolite profile of their host plants (Futuyma and Agrawal, 2009), complicating the design and management of crop resistance based on secondary metabolite chemistry.

Many cultivated species have much lower secondary metabolite synthesis and animal toxicity than their wild relatives. For example, domestication of tomato plants (*Lycopersicon esculentum*) was accompanied by the loss of two genes (zFPP and ShZIS) encoding enzymes that synthesise sesquiterpene 7-epizingiberene. Cultivated tomato plants offers better protection against three insect species, following the introgression of these genes from a wild tomato species. However, some plant taxa have retained their toxicity following domestication. For example, potato tubers are rich in glycoalkaloids, cassava tubers contain cyanogenic glycosides and many legume species contain alkaloids. It has been suggested that the domestication of certain crops included selection for toxicity, i.e. toxins confer protection against predators, including insects, but are inactivated by cooking and other treatments prior to human consumption (McKey *et al.*, 2010).

Furthermore, while the interaction between legumes and rhizobia has been understood and used for many centuries, there is now irrefutable evidence that the nutrition, immune function and general well-being of plants and animals depend on the activities of microbial communities present on their surfaces and in their tissues, in all species (Box 5.8). The interaction with microorganisms is of particular importance for plant-insect interactions, as there is evidence that plant microbial communities, including fungal endophytes and mycorrhizal fungi, can influence herbivory and that the host plant range of some insects is shaped by their microbiome (Casteel and Hansen, 2014). Although most research to date has focused almost exclusively on the foundations of microbial impact on plant-insect interactions, crop protection possibilities are increasingly being considered. Recent work shows that soil microbiota modulate the expression of cruciferous clubroot in oilseed rape, *via* regulation of the transcriptomes of the host plant and pests simultaneously (Daval *et al.*, 2020).

Breeding with long-term impacts in mind

Integrating societal or environmental objectives into plant breeding requires the integration of ecosystem services other than production, such as erosion reduction, carbon storage and water quality (Brummer *et al.*, 2011). To this end, it is necessary to integrate ecological concepts of plant-environment interactions modulated by microorganisms (Gopal and Gupta, 2016). By way of example, plant breeding can be employed to help maintain a microbiome in the soil from which plants can recruit organisms enabling them to better defend themselves against pathogens or insect pests, but also to improve their nutrition (Hunter *et al.*, 2014). The functioning of the rhizosphere, the soil zone subjected to root activity, is a major interface between a plant and its environment (Carof *et al.*, 2018) and the ability of plants to recruit and maintain themselves in this environment is crucial for pesticide-free agriculture (Box 5.5).

Box 5.5. The challenge of multi-objective varietal selection integrating productivity and maintenance of ecosystem services *via* associated and cultivated biodiversity

The choice of species and genotype has a significant impact on the functioning of an agroecosystem. The multiple expectations of society and the environment mean that several selection criteria need to be considered, calling into question the principle of a single genotype covering all the objectives assigned to a cultivated species. Agricultural practices and adaptation to the local environment must therefore be characterised at the appropriate scales for their effects on the establishment of plant-organism relationships in order to rationalise selection efforts. Other criteria for evaluating species grown under limiting conditions also need to be introduced into breeding programmes, as resistance to pests is also associated with plant nutritional status. Consequently, the potential of plant-microbiome relationships (DEEP IMPACT research project, Box 4.2) should be encouraged.

Recent research has shown that a group of mutualistic rhizosphere microorganisms can induce plant defence mechanisms. Induced resistance is a generic term covering a range of biological and chemical mechanisms that protect plants from possible pest attacks. More broadly, a reflection on the feedback loops between plants and soil could provide a new framework for the criteria to be introduced into plant breeding. These feedback loops are partly modulated by soil microbial communities. Soil microbial communities react to plant species and genotype in two main ways. The first is induced directly by root systems through rhizodeposition[17], and more broadly by root system-induced modifications. The second pathway is induced by the effects of litter and crop residues. It means plants can induce changes in soil functioning through microbial communities *via* these two pathways. Once the causal plants have disappeared, the induced effect can persist for a long time in the soil, affecting pathogen communities. This "ecological legacy" effect is therefore linked to plant functional traits. These determine the ability of plants not only to modify soil resources and therefore the dynamics of soil microbial communities, but also to respond to these changes (Baxendale *et al.*, 2014). Taking these interactions into account should be part of a rationale for defining crop succession rules in order to act synergistically with the diversification of crop production (Peralta *et al.*, 2018; Carof *et al.*, 2022). Consequently, it would be interesting to integrate these multi-annual dynamics into breeding schemes in order to influence the soil microbiome in such a way as to obtain positive feedback effects. Close to the concept of agronomic

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[17] Rhizodeposition is the secretion of organic compounds directly into the soil by plant roots.

rotation, these feedback loops cannot ignore the effect of agricultural practices such as tillage in maintaining a soil microbiome, as the risk of a single event critically modifying it is possible (Kraut-Cohen *et al.*, 2020). Increased dialogue between geneticists, agronomists and ecologists is essential to integrate in the longer term a broader reflection on the weight of plant species choice in rotations.

Key messages

In light of the new criteria set by pesticide-free agriculture, it is essential to rethink varieties and how they are bred. However, other objectives, such as promoting soil biodiversity or limiting nitrogen leaching through efficient use, must also be kept in mind in plant breeding programmes. Fundamental research into resistance mechanisms and the links between plant diversity and resource dynamics, as well as the stability of agroecosystems, are therefore a challenge for breeders, as they multiply the objectives assigned to cultivated species.

⏩ Avenues for new breeding programmes

Genetic resources as a reservoir of resistance and adaptation genes

Whatever the technological means available to the breeder (molecular biology tools, genomic selection etc.), genetic progress and the success of a breeding programme, particularly in the long term, always depend on the available genetic diversity (the universal breeder's equation). In addition to being an issue in its own right, managing genetic diversity is also key to genetic progress and varietal innovation. Maintaining and conserving the genetic diversity of cultivated species means maintaining a reservoir of genes and alleles that can be used to improve future breeding programmes. This diversity is present in genetic resource collections. For a given crop species, genetic resources comprise "plant material containing functional units of heredity and having actual or potential value" (Convention on Biological Diversity, Rio Summit, 1992). They include traditional varieties, wild-appearing species and accessions present in all geographical zones where a species is cultivated on a global scale. As early as 1926, Russian biologist Nikolai Vavilov had established the link between the geographical distribution of genetic diversity and the evolutionary history of cultivated plants (Harris, 1990). He was able to identify various centres of origin where genetic diversity was greatest and where domestication of cultivated species from their wild ancestors had taken place. These observations underlined the interest of these high diversity regions, particularly as a reservoir of genes involved in adaptation. These include central Mexico (maize, and beans), the Middle East (wheat, rye and melon) and the Mediterranean (cabbage). Collecting, maintaining and characterising these genetic resources is vital if we are to maintain our capacity for innovation and offer new varieties adapted to a wide range of constraints, some of which are already known (e.g. resistance to a range of diseases and insect pests), and some of which are still partially unknown (e.g. the impact of climate change).

Two main forms of conservation exist for these resources. *Ex situ* management, where plants/seeds are conserved outside their original habitat, and *in situ* management, where plants are maintained in their (agro-)ecosystem. *Ex situ* collections exist for most species. These generally consist of seed lots stored in freezers and regenerated every 10 to 20 years to maintain a high germination rate. The best-known example of such gene banks is the Svalbard global seed reserve in Norway, but similar collections exist in most countries. In France, they are managed by networked biological resource centres. To optimise the use of these resources, we need to be able to characterise and organise them. *In situ* management is more cumbersome to establish, as it requires maintaining the (agro-)ecosystems in which the target species evolve. However, it also has advantages, since whether on farms or in natural ecosystems (for forest genetic resources or wild relatives of cultivated species), accessions maintained *in situ* continue to co-evolve with their biotic and abiotic environment and maintain their adaptive potential (adaptation to new abiotic and/or biotic constraints). The underlying scientific hypothesis is that by maintaining evolutionary pressure on these genetic resources, we maintain interesting adaptation genes to enrich future breeding programmes.

This hypothesis has been used in dynamic management programs where heterogeneous varieties are maintained in the field and evolve without the strong pressure of human selection over the generations and environments in which they are established. This enables these heterogeneous varieties, or “evolving populations”, to evolve according to the local context (impact on alleles with earliness genes, cold requirements etc.) (Rhoné *et al.*, 2008). In wheat, this concept of dynamic management was then developed within the framework of participatory breeding programmes, where evolving varieties were shown to be more stable over time (between climatic seasons) and between environments than commercial varieties (Goldringer *et al.*, 2020; van Frank *et al.*, 2020). This dynamic management of genetic diversity therefore makes it possible both to conserve adaptive genes in the population and to maintain genetic diversity in the field in connection with the production of ecosystem services.

The improvement of a cultivated species relies first and foremost on the exploration and use of natural diversity within the species. In addition to this intraspecific variability, which is more or less large depending on the species, the breeder can also enrich the reservoir of favourable alleles by making crosses with related species. Although interspecific hybridisations, classically carried out in many cultivated species, make it possible to enrich the genetic diversity exploitable in breeding by homologous recombination, they are sometimes restricted by problems of incompatibility between species or simply by the absence of diversity in related species for the trait of interest. In addition to the rescue of embryonic plants, new avenues are currently being explored to remove reproductive barriers between species. For example, it is possible to remove the mechanisms establishing hybridisation barriers in the endosperm during interspecific crosses by manipulating the plant’s epigenetic mechanisms (Schatlowski *et al.*, 2014). Finally, faced with the absence of intra- and inter-species genetic diversity, breeders have genome-editing biotechnologies at their disposal to generate new genetic diversity, such as “classic” non-targeted mutagenesis (chemical or physical radiation), and more recently directed mutagenesis (using site-directed nuclease (SDN) of the CRISPR/Cas9 (clustered regularly interspaced palindromic repeats / CRISPR associated protein 9) type, for example).

Tools and methods to take these new challenges into account in breeding programmes

In view of the various challenges presented above, designing tomorrow’s varieties means providing farmers with:
– A strong potential for adaptation, which is now even more important since the environments in which they will evolve will be increasingly constrained and fluctuating.
– The production of several ecosystem services in addition to food production (maintaining biological diversity, soil quality and pollinating insect populations, managing pest populations etc.).
– Cultivation in complex stands (combined crops, varietal mixtures, agroforestry systems etc.).

Identifying the genes controlling the traits of interest mentioned above requires suitable phenotyping tools to target the traits of interest and adapted genetic analysis methods. Finally, new genome-editing techniques open up new avenues for plant breeding, the potential implications of which need to be examined.

Better knowledge and characterisation of the environment and plants/crop stands to target traits of interest

The response of plants to stresses (biotic and abiotic), alone or in combination, is a major challenge for plant breeding. Being able to characterise this response in a reliable, resolutive and high-throughput way is a real challenge. Indeed, to optimise their choices, researchers and breeders need to be able to target traits precisely, to highlight small differences between genotypes (especially when compared with the differences between species most often studied), for a large number of plants and in a reproducible way. The challenges are therefore twofold. First, we need to be able to control stresses in such a way as to reproduce the same evaluation conditions (control of fertilisation, water supply, light and temperature conditions, disease pressure etc.). Second, to be able to access traits through the phenotype being considered for a large number of individuals. The past decade has seen the development of numerous high-throughput phenotyping platforms, thanks to the development of digital technologies and the availability of numerous sensors that have enabled the automation and control of experimental conditions in greenhouses. Examples include the Phenome project’s PhénoArch platform in Montpellier, which can be used to fine-tune water conditions and imitate different stress scenarios in which plants can be evaluated. Access to individual plants (and their organs) obtained under these highly controlled conditions then enables them to be finely characterised, using both variables describing the functioning of the whole plant and variables providing access to phenotypes at the organ or cell level, thanks to high-throughput profiling tools. These tools include metabolomics, proteomics and the fine characterisation of fluxes (such as gas exchanges or metabolic fluxes in the plant, see Blein-Nicolas *et al.* (2020) for example). These platforms also enable plants to be phenotyped during the course of stress (and not just an end state, for example), but also to access all plant compartments, including roots (Dijon 4PMI platform, Jeudy *et al.*, 2016). These platforms are essential for accessing the entire root system and its architecture, as the type, morphology and descriptive variables of root architecture are particularly important for the adaptation of varieties to very low-input or pesticide-free growing conditions, as they are linked to the absorption of water and nutrients by the root system and the recruitment of beneficial organisms, particularly through the exudation process. The culturomics approach, which aims to isolate and identify the various microorganisms in a sample, completes this description, as it could be used to screen genotypes for their ability to interact with the rhizosphere microbiota in a controlled manner (DEEP IMPACT research project, Box 4.2).

It is essential to combine these fine-tuned descriptions of plant behaviour in interaction with their biotic and abiotic environment with actual behaviour observed in the field or in high-throughput phenotyping. The development of sensors (multispectral sensors, RGB cameras, LiDAR etc.) and different vectors (drones, phenotyping robots, portable systems etc.), as well as the development of probes and sensors (temperature, water status and solar radiation) are complementary, as field phenotyping must combine both the crop stand and the environment. Soil sampling and the corresponding chemical and physical analyses (soil texture, quantity of nitrogen in the different horizons etc.) are still necessary to provide a detailed description of the environment.

Understanding the genetic determinism of traits of interest

Previously, we emphasised the interest of new traits which currently do not receive much consideration for plant improvement programmes. Integrating them more easily into breeding programmes often depends on the ability to link them to biomarkers that are easily accessible during high-throughput and reliable whatever the environmental conditions. The biomarkers most often used are molecular markers, such as SNP (single-nucleotide polymorphism) markers or, more recently, spectral data (NIRS spectrum, near-infrared spectroscopy). In addition, genomic resources are now widely available for a large number of cultivated species and are no longer restricted to only the major ones. This easier access to the genome and associated endophenotypes (transcriptome, proteome, metabolome etc.) has led to greater precision in the analysis of genomic regions involved in the control of traits of interest. As a result, it is now possible to gain finer-grained access to the genetic determinism of complex traits (controlled by a large number of genes or QTL with weak effects), whose expression fluctuates as a function of the environment or genetic background. The methodology for identifying genomic regions of interest through association genetics has benefited greatly from these advances, since it proves highly effective when a large number of genotypes (several hundred) can be phenotyped and genotyped at high throughputs. Having biomarkers close to the genomic regions of interest is therefore a valuable tool for breeders, since the plant material for these programmes can then be screened at very early stages (as soon as the first leaves appear), thereby reducing the time between generations. It is also possible to increase the number of individuals screened. These association genetics approaches have also been coupled with environmental characterisation methodologies (notably within large experimental networks) to be able to target the genetic determinants involved in adaptation, stability and genotype-environment interactions (Bustos-Korts *et al.*, 2019), traits whose relevance for agroecological systems we highlighted above.

Adapting/changing selection schemes

Selection schemes and methods need to be rethought in order to consider the rapid evolution of methods and tools (phenotyping and genomics) as well as the range of plant species considered. The diversification of cropping systems is likely to result in an increase in the number of species cultivated in order to optimise various services (control of telluric diseases and insect pests, enhancement of the value of certain species in push-pull strategies, interest in perennial species for agroforestry systems, inducing beneficial feedback loops between plants and soil etc.). For a given species, the cultivation of mixed species or varieties, as well as the interest in maintaining a certain genetic diversity within varieties, raises the question of how to manage and maintain genetic diversity both during the breeding process (creative selection) and during the multiplication of seeds or seedlings distributed to growers (conservative selection). Current breeding programmes are mainly based on varietal types with little genetic heterogeneity (pure lines, F1 hybrids and clones). However, plant populations subjected solely to natural selection, with no steering of the genetic progress, will not be able to meet the challenges. Indeed, there is a significant risk that natural selection will favour genotypes with better fitness, to the detriment of their agronomic values. It is therefore necessary to classify the avenues for adapting breeding programmes. These include: (i) the role and the management of the genetic variability and pre-breeding, (ii) the definition of selection criteria and the new traits to be considered, (iii) the tools available, and (iv) aspects linked to registration, post-registration and seed and plant multiplication.

Genetic resources represent an important reservoir of adaptation and resistance genes, but their use in breeding programmes can be complex, due notably to the distance between these genotypes and breeders' elite varieties. Introducing them effectively into breeding programmes (pre-breeding) requires consideration of the interaction of these genes with the gene pool (will the effect of these genes be maintained or identical when transferred to an elite gene pool?), as well as the possibility of introducing these genes in a targeted manner by optimising genetic recombination, so as not to concomitantly introduce unfavourable traits. These steps are crucial, all the more so as selection schemes for agroecology will have to manage a higher level of genetic diversity than today's programmes, both at the start of crossing plans and throughout the selection process.

Agroecology is also challenging selection criteria. Proposing new varieties can no longer be based solely on the choice of genotypes with the best average performance in homogeneous stands. Criteria have therefore been proposed for estimating mixing aptitude, based on the combination of aptitude traits used in selection schemes for F1 hybrid varieties (Forst, 2018). However, estimating these abilities relies on carrying out a large number of mixture combinations and may be a limitation to the use of this criterion. Other criteria have also been proposed to optimise the combinations of the different components of a mixture, notably based on the complementarity of the ranges of variances explored by each component of the mixture. The ultimate aim is to propose an optimised adaptation potential within the mixture (Litrico and Violle, 2015). Finally, it is also important to consider selection for multiple objectives, which must consider several traits simultaneously and in a hierarchical manner. Some trade-offs between target traits can be limited by using varietal mixtures (Barot *et al.*, 2017), but the construction of ideotypes will still have to be rethought in terms of combinations of target traits according to expectations in terms of the ecosystem services to be maximised and the disservices to be limited. The nature of the selection traits themselves is likely to evolve. Indeed, in breeding programmes it is important to be able to consider functional traits that guarantee the niche complementarity of the different components of the variety or mixture (see the issues relating to phenotyping, p. 164), with the difficulty of taking traits into account in a simultaneous manner and considering the correlations (positive or negative) between these traits.

Breeders have tools at their disposal to speed up selection cycles and reduce costs. Genomic and phenomic selection, whose aim is to predict the phenotypic value of the targeted trait(s) using high-throughput genotyping (or spectral) data, are particularly interesting as they can predict the phenotype of traits whose genetic determinism is complex (Meuwissen *et al.*, 2001; Rincent *et al.*, 2018). Furthermore, these methods are currently being developed to take better account of genotype-environment interactions, as well as several traits simultaneously, which is in line with the thinking on the evolution of selection criteria (Gillberg *et al.*, 2019; Moeinizade *et al.*, 2020).

Genome editing offers new possibilities for overcoming the limitations of conventional breeding (Box 5.6). In addition to generating new alleles for the target gene, the latter can be directly modified in elite varieties, thereby greatly shortening selection times by avoiding the generations of backcrossing traditionally carried out after hybridisation between the donor genotype and the elite variety. Beyond the creation of new alleles conferring resistance to pests, CRISPR/Cas9 technology can also be useful in the process of pyramiding resistance genes (Borrelli *et al.*, 2018). In addition, CRISPR/Cas9 technology makes it possible to avoid the local loss of diversity linked to linkage drag, which can have potentially negative impacts on agronomic performance. Furthermore, by targeting the homologues of so-called domestication genes, it is now possible to rapidly introduce orphan species (semi-domesticated and wild, for example) into cropping systems (Wolter *et al.*, 2019), contributing to their diversification. The genetic diversity present in wild species or uncultivated varieties can then be used as a source of alleles and thereby expand the pool of genetic diversity available for species of interest. However, genome editing cannot be conducted without excellent characterisation of the gene(s) controlling the trait of interest and of the species genome. Finally, while the use of this biotechnology may be interesting for traits under oligo- or monogenic control, it seems more difficult to implement for complex traits under polygenic control or in polyploid species.

Box 5.6. New genomic techniques (NGT)

In 2007, a working group commissioned by the European Commission identified eight plant breeding techniques known as NGT (new genomic techniques), whose inclusion or not within the scope of European Directive 2001/18/EC of March 12, 2001, on the deliberate release into the environment of GMOs, had not yet been clearly defined. What these eight biotechnologies (Lusser *et al.*, 2012) have in common is the ability to overcome certain limitations in conventional breeding, in order to produce plants with the desired characteristics more quickly and precisely. Some of these techniques are older, but others are more recent, such as those linked to CRISPR/Cas9 technology, which belong to the SDN family of directed nuclease techniques. Four families of directed nucleases are, or have been, in use: meganucleases, ZFN (zinc finger nuclease), TALEN (transcription activator-like effector nuclease) and, more recently, CRISPR/Cas9-type nucleases. SDN-directed nucleases, the most extensively studied NGT at present, involve nuclease enzymes with the ability to cut both strands of DNA at a predefined region. The cut, detected by the endogenous cell monitoring system, is repaired by the non-homologous end joining (NHEJ) recombination system. This system is subject to error, so nucleotides can be added, not replaced or even deleted (from one to several dozen nucleotides), generating insertions/deletions and therefore mutations in the target sequence. The result is an imperfectly repaired (and therefore mutated) sequence that differs from the initial sequence. The HDR (homology-directed repair) system of homologous recombination can also repair this DNA cut by inserting another sequence (another allele) with homologous motifs at the cleavage site.

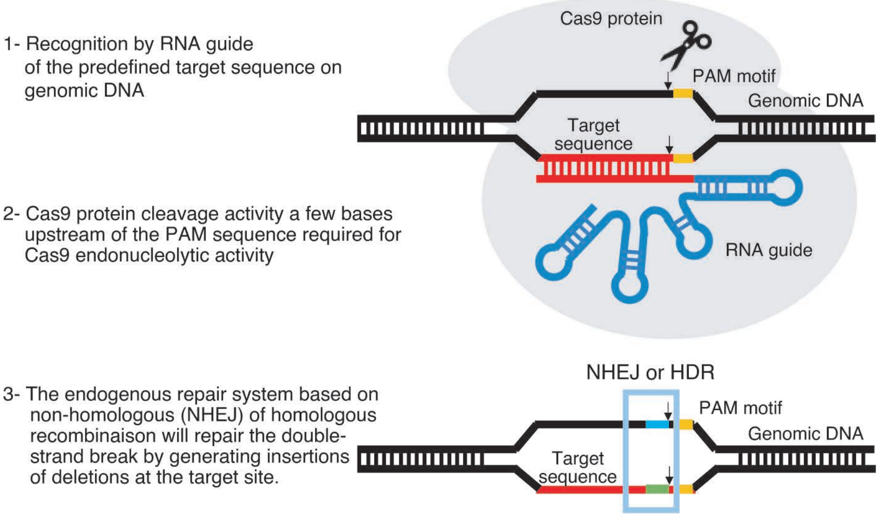

Figure 5.1. How the CRISPR/Cas9 system works for genome editing.

CRISPR/Cas9-type nucleases, which are natural enzymes of the bacterial immune system to combat viral infections, are currently the most widely used. They consist of a Cas9-type protein nuclease and an RNA guide. Directed nucleases, notably CRISPR, can be adapted for molecular applications other than genome editing *stricto sensu*. The nuclease activity of SDNs can thereby be suppressed or replaced by another enzymatic activity to enable targeted actions on genomes.

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Modified SDNs can therefore be used to modulate gene expression by inactivating or activating transcription, or by modifying epigenetic marks and thus chromatin structure at the target site. The European Commission has proposed a new regulation in July 2023 on plants obtained by specific new genomic techniques, as CRISPR— Cas technology, which is now subject to discussion in the legislative process. NGT plants deemed to occur naturally or through conventional breeding techniques ("category 1 NGT plants"), could be treated similarly to naturally occurring or conventionally bred plants. after a verification procedure for their equivalence.

Finally, the process of evaluating, registering and disseminating varietal innovation is also challenged by the demand for pesticide-free agriculture. Evaluation, both during registration and in post-registration networks, considers criteria such as environmental impact and resistance to major diseases. The service plants section of France's Comité Technique Permanent de la Sélection (a breeding technical committee) also allows the registration of varieties that are evaluated for services other than production and that use biological regulation to provide different services. This section, which initially focused on nitrate-trap intermediate crops (known as CIPAN in France), then opened up to other services and crops such as companion species, and is the place where demand for these new services is being formalised. Furthermore, in the case of agricultural species, future varieties are being evaluated using low-input or organic farming techniques. However, the idea of local adaptation is still poorly appreciated and therefore is not really taken into account in registration decisions. One of the challenges of registration and multiplication therefore lies in the possibility of describing, multiplying and offering farmers varieties with a higher level of genetic diversity. Changes in European regulations (EU regulation n°2018/848) allowed the marketing of "heterogeneous organic material" for organic production from January 2022, which should partly meet the demand from some producers. Finally, we must not underestimate the impact of these new selection schemes on the seed multiplication phase. The local adaptation of varieties and their potential heterogeneity, accompanied by a much greater number of varieties, will have repercussions on the conditions for multiplication, intellectual protection of innovation and the associated business model. It is partly in response to these questions that participatory breeding networks have emerged (Box 5.9). In the long term, this complementary vision could also provide food for thought on the evolution of more "conventional" breeding schemes.

Finally, the adaptation of varieties also depends on the "seed" as a vector for innovation, and we must not forget to think about the variety as a complement to the innovations that can be brought about by the seed itself. So, the development of seed technologies and the idea of beneficial microbiota to be combined with seeds are also important avenues to explore, particularly to combat damping-off of seedlings (Box 5.7).

Box 5.7. The SUCSEED research project: ending the use of pesticides on seeds and proposing alternative solutions (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

Seeds play a central role in our agricultural system: they are at the heart of our food production and are sold in an increasingly globalised market. Given this context, guaranteeing the high sanitary quality of seeds is crucial to preventing disease emergence and to secure food production. The SUCSEED project is based on the need to identify and develop innovative seed protection solutions using natural, effective and eco-friendly approaches. The project aims to make seeds a central player in plant health management by focusing on two major plant health problems: pathogens transmitted to and by seeds, and damping-off which can see seed fail to germinate or emerge due to pathogens. The research is being carried out on four plant species of agronomic interest: wheat, tomato, common bean and oilseed rape, and their respective major pathogens. To identify alternative solutions to pesticides, SUCSEED proposes three levers for action: improving seed defences, controlling seed microbiota and modifying the microenvironment of germinating seeds. The innovative solutions obtained *via* these three levers will be formulated using technological approaches adapted to seeds and deployed over a wide range of genotypes and environmental conditions in order to validate their potential efficacy and commercialisation (INRAE, 2024b).

Key messages

Varietal creation and selection are at the crossroads of various challenges. Tools and methods to support the adaptation of varietal breeding programmes to multiple objectives are one of these challenges. The preservation of genetic resources is also at the heart of this dynamic. A new dynamic is at work, with interdependencies (development of tools and selection, for example) requiring human and financial investment throughout the entire varietal creation and selection process.

⏩ Integrating new varieties into cropping systems

As a preamble to this section, it should be remembered that varietal choice and the resulting management approaches are made by farmers according to their production objectives. Since it takes around 10 years to create a new variety in current breeding programmes, it is essential to start thinking about transformation of agricultural future systems now, in order to suggest criteria for breeders to include in their selection plans. To this end, the use of field indicators could help define selection criteria (see section "Adapting/changing selection schemes"). These indicators are easily interpretable data that breeders and farmers in particular will be able to use to understand the interaction between plants and their environment. For example, there are now numerous indicators of the physical, biological and chemical quality of soils, which can be used to provide a detailed description of soil functioning not influenced by zones of intense biological activity such as the rhizosphere. The soil-plant interface (the rhizosphere) is one of the entry points for soil-borne pathogens and pests, but also the site for the recruitment of beneficial organisms that can induce immune responses in plants. Although great strides have been made in characterising how the rhizosphere functions, the dynamics and diversity of the processes involved, as well as the dependence on genotype, make it tricky to establish a causal link between the variety introduced into the cropping system and plant performance in a given environment. In fact, the recruitment of organisms depends on the soil microbiome, which itself evolves under the influence of agricultural practices, soil type, climate and the plant species introduced during cropping successions. Furthermore, if causal relationships can be estimated at all, obtaining a rhizosphere sample under field conditions remains very difficult, since it depends on the type of soil, its humidity at the time of sampling and the roots from which it is obtained (Mira *et al.*, 2022). As a result, it is possible to observe differences in performance without it being possible to distinguish between what is specific to the variety and the effects of agricultural practices, which in turn influence rhizosphere processes linked to plant health. The lack of information on this compartment is therefore a possible brake on the adoption of new varieties, limiting decision-making, but also on the design of cropping systems enabling the full potential of these new varieties to be expressed. As an example, INRAE's ResDur programme (resistance to the main fungal diseases in grapevines) has led to the creation of four new varieties (Artaban, Floreal, Vidoc and Voltis). However, these new varieties have yet to find their place in winegrowing systems where the notion of terroir stems from traditional knowledge. One way of getting around this hurdle is to bring together breeders who can explain the mechanisms involved in optimising practices, in workshops for co-designing cropping systems, enabling growers to benefit from breeders' expertise on the new varieties planned as part of the agenda for pesticide-free agriculture.

Box 5.8. The CAP ZERO PHYTO research project: adapting the concept of ecological immunity to crop protection (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

The ability of plants to use their own immune systems to fight against pests and diseases is at the heart of the CAP ZERO PHYTO project. The aim is to propose new crop protection strategies based on the combined use of immunity levers designed to modulate crop defence mechanisms. The concept of ecological immunity, defined for animals, will be adapted: the physio-molecular bases of immune responses are being considered in a broader context of ecology and adaptation, by characterising interactions between immunity levers and studying sources of variability. Six immunity levers are being explored singly and in combination: genetic resistance, companion plants, biocontrol solutions with PRI action, UV-C flashes, mechanical stress and nitrogen application. For this, apple and tomato and their main pests are initially being used as model crops due to their high treatment frequency indicators (TFI) (see Box 1.6). The project is being carried out in close interaction with professional stakeholders to ensure the relevance and feasibility of the proposed strategies. A specific task is dedicated to disseminating the results in academic training courses in order to train the next generation in sustainable and ecological agricultural practices (INRAE, 2024c).

More broadly, the introduction of new varieties also requires new references (on fertilisation, tillage, suitability for mixtures etc.) for the technical management of new varieties and demonstrations of their implementation to facilitate their adoption. Plant-soil feedback loops also need to be integrated into crop successions and so there is a long-term dimension (see section “Breeding with long-term impacts in mind”) and therefore ecologists are involved. Participatory approaches that include end-users (Box 5.9) are inspiring from this point of view. New decision-making criteria in the choice of species and varieties can also be envisaged. Faced with the risk of disease, resistance may become a more important criterion than productivity, as the latter is more uncertain in the absence of treatment solutions. In addition, the new varieties could per se enrich crop diversification by enabling the introduction of new species into successions and rotations, if, for example, a reduction in the number of degree days is envisaged in these new breeding programmes.

Box 5.9. The role of participatory approaches in innovative breeding for pesticide-free agriculture

Participatory approaches make it possible to encourage the adoption of new technologies, particularly in under-represented environments. Participatory breeding is defined as an approach to varietal creation in which farmers and researchers create varieties based on needs expressed by farmers that have not been met by conventionally produced seeds. In this way, varietal creation involving committed farmers encourages the adoption of new varieties. Participatory approaches require a rigorous methodology shared by all those involved in breeding and varietal creation programmes. The success of these methods therefore hinges on communication between the various actors and on the definition of rigorous protocols. As the breeding process is highly dependent on the environment (pedoclimatic and economic), a decentralised approach is essential to ensure that the criteria of yield, stability and the preferences of end-users, i.e. farmers, are considered. In addition, the exchange of seeds, the maintenance of traditional varieties and the adoption of a greater number of varieties by farmers help to preserve cultivated biodiversity and can contribute to preserving the genetic resources *in situ*. Like this, participatory approaches can contribute to innovative breeding for pesticide-free agriculture.

Key messages

Introducing new varieties to meet the challenge of pesticide-free agriculture calls for a more global approach to cropping systems and crop management approaches, requiring successful communication between the various actors involved in the varietal creation process, ecologists and end-users during co-design workshops.

⏩ Conclusion

Varietal improvement is essential for pesticide-free agriculture because the varieties currently available have not been bred for this approach to crop management. This chapter has highlighted the scale of the challenge involved in developing new varieties adapted to pesticide-free cropping systems. However, these challenges cannot be seen in isolation from climate change, which imposes abiotic stresses and is likely to influence pathogen and pest genes, and even the emergence of new pathogen and pest genes. So how do we approach plant breeding when faced with these multiple challenges? It is crucial to promote genetic research aimed at defining and integrating new criteria in order to achieve the ambitious goal of pesticide-free agriculture, which involves all actors in the seed industry. However, it is not just one industry that needs to be involved, but all agricultural stakeholders, since crop management also needs to be rethought in terms of the expectations placed on varieties. In this sense, breeding strategies integrating participatory approaches can be complementary to other approaches, but it is the whole range of approaches that must be mobilised to meet the challenge of pesticide-free agriculture. Indeed, the most recent advances in fundamental research have revolutionised plant breeding by providing access to information that is essential for characterising plant responses to their biotic and abiotic environment, and for identifying the best candidates. However, all actors in the seed industry need to be mobilised, in particular to preserve genetic resources. However, the time-scale of plant breeding (around 10 years with current methods) also raises the question of how to train breeders to deal with these complex issues.

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Chapter 6

Mobilising agricultural equipment and digital technology for pesticide-free cropping systems

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Agricultural equipment and digital technology are essential levers for developing pesticide-free cropping systems. Innovations in equipment precision and adaptability are expected. Simultaneously, the development of sensors will make it possible to improve the monitoring of pests and diseases, as well as that of the entire crop system and its environment. Sensors combined with new information technologies could also contribute to the emergence of pesticide-free supply chains, facilitating traceability from field to fork. Questions will nevertheless arise as to the use of the extensive data collected and the potentially high cost of new equipment.

⏩ Precision, autonomy and adaptability: key themes for agricultural equipment in pesticide-free cropping systems

What are the requirements for pesticide-free cropping systems?

Agricultural equipment refers to machinery used in agricultural production. For crop production, a wide range of agricultural equipment is available, ranging from tractors through to harvesting and handling equipment, including soil-working and irrigation tools. In France, the highly dynamic agricultural sector invests between

€6 billion and €7 billion each year in agricultural equipment for animal and plant production (Axema, 2020). The design of this equipment and its use in the field represent an important dimension of the transition towards ending pesticide use, in particular by supporting crop diversification and the in-depth transformation of practices towards greater use of natural processes. Various pesticide-free cropping systems are currently being tested in experimental schemes such as CA-SYS[18] and Res0Pest[19]. In the latter, experimenters have designed crop successions in cooperation with local partners (technical institutes, researchers, agricultural advisers, farmers etc.) around a common set of specifications. Weed control soon proved to be the main recurring concern for experimenters and to tackle these innovations in agricultural equipment are a major lever, with the development of broad-width hoes with laser or camera guidance. Both of these features speed up work rates. Such equipment is now commonplace on wide-spaced crops such as maize, sunflower, beet and even oilseed rape, and could soon be extended to narrow-spaced crops such as cereals in order to replace chemical by mechanical weeding. Another significant innovation has been the development of wheels or stars that act on the row while protecting the young seedlings of the cash crop. New needs have arisen for more efficient tools for close hoeing (15 centimetres) in cereals, as well as for under-row weeding in viticulture and arboriculture. Added to this are constraints specific to mechanical weeding, such as the sometimes very narrow intervention possibilities linked to climatic conditions and soil type, as well as the need for low-cost solutions for low value-added production, as is currently the case for some forage legumes. Some robots are able to work over 24 hours and 7 days a week.

Another problem encountered concerns cover crop management, particularly for those which cohabit with the main crop without competing with it and which must be controlled mechanically. Highly innovative techniques are currently being studied, such as an inter-row shredder developed jointly by Arvalis - Institut du Végétal and the Eco-Mulch company (Figure 6.1) or Bionalan new machines. By shredding without damaging wheat (Eco-Mulch and Arvalis, 2019), this tool facilitates the management of living permanent cover crops, such as alfalfa or clover in wheat inter-rows.

Figure 6.1. Detail of an Eco-Mulch inter-row shredder (Eco-Mulch and Arvalis, 2019) (photo: C. Huyghe).

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[18] https://www6.inrae.fr/plateforme-casys/

[19] https://www6.inrae.fr/reseau-pic/Projets/Res0Pest

Another well-identified need concerns sowing operations, in particular for combinations of species (at least two species grown simultaneously in the same field), as they are of great interest in pesticide-free cropping systems. Drawing on farmers' experiences with simplified cultivation techniques, many manufacturers have developed seeding machines combining several seed hoppers for precision seeding of different species, at precise densities and depth for each species. This equipment can also be used to apply fertiliser in the seed furrow. The ability to apply fertiliser locally on the seed furrow ensures the crop gets off to a fast start, which is a key to its competitive success over weeds. The latest machines also enable seeds of different species to be precisely positioned at different depths in a single pass of the drill, which is what experimenters had been waiting for, as highlighted by Labreuche *et al.* (2017). Furthermore, when conditions favourable to plant growth are short, it may become necessary to install a cover crop within a crop already in place using a relay cropping approach, which requires numerous adjustments to the seed drill so as not to hinder the crop which has already developed (Lamichhane *et al.*, 2023). A growing number of agricultural equipment companies are now marketing multi-hopper seeders to meet these needs. Alongside sowing, innovations are also needed to simultaneously harvest seeds from combined crops, as well as to sort them, as seed mixtures generally cannot be marketed as such, particularly for human consumption. Several avenues can be explored to facilitate this stage, such as investing in more efficient sorting equipment that can combine several principles (honeycomb sorter, densimetric tables and optical sorter), bearing in mind that the cost of sorting must be put into perspective with the value of the marketed products. Optical sorters, initially reserved for sorting vegetable seeds, are now widely used to remove impurities from industrial vegetable harvests and to separate seeds of mixed crop species. One solution for reducing investment costs is to pool these tools, either at the storage facility or across several farms, enabling larger volumes or a greater diversity of mixtures to be sorted. Last but not least, digital and sensor-based agricultural equipment will continue to develop, notably for autonomous weed control and early weed detection (see section "More precise and autonomous agricultural equipment").

As far as biocontrol is concerned, innovations are needed so that biocontrol organisms and substances can be deployed simply alongside other actions (fertilisation, irrigation, weed control, etc.) and, if possible, used flexibly and targeted according to need. First of all, equipment needs to be developed to ensure that the application of such products is no longer a primarily manual task, as is currently the case. For example, drones are now capable of depositing capsules containing *Trichogramma* to control European corn borers, which can be particularly useful when plants are too developed to be protected with a tractor without seriously damaging the crop. The use of chemical mediators, also highly dependent on manual interventions, could be facilitated by the introduction of dedicated diffusers connected to sensors. Finally, some organisms and substances used in biocontrol appear to be considerably impacted by conventional sprayers: the joint development of biocontrol products and equipment adapted to their application therefore appears necessary. Coupling sensors to diffusers is a clever way to reduce the cost of the biocontrol solution by optimizing the amount of substance used to protect a given area according to favourable wind directions only.

Adaptability and self-building of agricultural equipment

Most of the agricultural equipment currently available has been designed concomitantly and consistently with the evolution of cropping systems, varieties, farm structures and landscapes leading to higher pesticide use (Jepsen *et al.*, 2015). This means today's machines are adapted to large fields and have been designed to minimise labour requirements and optimise pesticide use through, for example, precision application and high speeds to intervene at optimal times. However, in order to benefit from biological regulations that are more effective in small fields and heterogeneous landscapes (notably the regulation of insects by beneficial organisms coming from the field hedge), pesticide-free agriculture will require a reduction in field size. This will require new machinery that is adapted to small fields and can deal with crops that are more or less intertwined (multispecies combinations, for example), adapted to local soil and climate conditions. The key challenge for agricultural equipment is to offer tools that can adapt to a multitude of environments. This flexibility can be addressed in different ways, each of which can coexist with the others. The first is to reconcile an industrial agricultural equipment production chain that limits the cost of equipment with customisation according to the needs expressed by buyers, which can be contradictory but easily delt with by the supply chain when using digital information. The result would be a single production line for different products. A second axis concerns self-building, with agricultural equipment offered in kit form ready to be self-built (Joly, 2017). Self-building enables farmers to manufacture their equipment in order to best adapt it to their cropping systems and local context (Salembier *et al.*, 2020). Very much in line with the rise of Fab Labs, these open assembly or repair workshops can be of particular interest to cooperative structures, including cooperatives for sharing agricultural equipment (known as Cumas in France), which will have an important role to play (Box 6.1). Finally, intelligent machines equipped with integrated sensors also represent a solution for facilitating the adaptation of agricultural equipment, in particular by managing navigation, speed and precision of actions (Berducat *et al.*, 2009). In the near future, such digitized machines will be able to provide further self-adjustments to guarantee results and maintain performance in a changing context.

Box 6.1. Atelier Paysan: a cooperative organisation promoting the self-building of agricultural equipment

Atelier Paysan is an agricultural and rural development organisation that supports farmers in the design and manufacture of machinery and buildings adapted to agroecological practices. Its aim is to re-mobilise farmers around the technical choices they need to make about their work tools, in order to collectively regain a sense of "technical sovereignty and autonomy through the reappropriation of knowledge and know-how" (Gaillard, 2021). Operating as a cooperative, Atelier Paysan has set itself two main missions: (i) participatory research and development, which includes activities such as the production of technical drawing of equipment, and (ii) the dissemination of skills and knowledge to farmers through training courses or the provision of free-access plans for the self-building of agricultural equipment (Salembier *et al.*, 2020).

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Figure 6.2. Hoeing star designed at Atelier Paysan for mechanical weeding in vine rows; (a) model of a hoeing star that can be easily adapted to different mounts; (b) stars being made during a training session at Atelier Paysan (L'Atelier paysan, 2021).

More precise and autonomous agricultural equipment

Progress in the field of agricultural equipment will stem from the development of sensors which can acquire various signals in real time and enable increasingly precise and automatic curative or preventive actions. First, sensors coupled to agricultural equipment can be used to ensure optimum adjustments in all circumstances. In the context of pesticide or biocontrol product application, this currently makes it possible to adjust spraying to the presence or volume of a target to be treated, in the interests of efficiency and reduced use (Maillot *et al.*, 2020). This is especially important to make affordable, biocontrol solutions often considered as expensive. Devices that provide this modulation are commercially available and can be adapted to a wide range of existing sprayers. Farmers committed to the transition towards pesticide-free cropping systems will also be able to benefit from sensors to increase the precision of mechanical weeding, for example by weeding under the row in arboriculture or viticulture. Furthermore, advances in artificial intelligence mean that prototypes of autonomous robots can now be proposed which, depending on the information provided by their sensors, can suppress certain weeds, prune a branch and therefore intervene precisely (Jacquet *et al.*, 2018). The development of robotics of this kind makes up for a common obstacle to the use of autonomous agricultural equipment, namely its slowness. Indeed, if the aim of the robot is to contain pest pressure by weeding or eliminating only contaminated plant parts, then high speed is not indispensable. However, if this type of technology is to become more widespread, there are still improvements to be made to the robot's ability to locate itself in space, as plots are likely to become more complex than at present (e.g. mixtures of varieties or species).

The development of mechanised prophylaxis remains limited at present, no doubt due to the short-term economic advantages of chemical control. A better connection between agricultural equipment and digital technology will accelerate progress by integrating external data, such as the weather, and more generally data that can be used to make decisions about the interventions to be conducted. It will undoubtedly be possible to introduce and deploy autonomous systems integrating various sensors, robots and algorithms to limit the presence of insect pests on cultivated plants. For example, when insect pests are detected, the risk of damage to plants could be limited by releasing repellent pheromones in the right place and at the right frequency, according to the local context of the plot or plant.

Autonomous equipment also opens up the possibility of breakthroughs in the way farming systems are designed and managed. This is illustrated by the FarmDroid robot from Danish company FarmDroid ApS, winner of the 2021 Sima Innovation Awards (Stecomat, 2021). This robot is dedicated to mechanical sowing and weeding in crops such as sugar beet. During sowing, it records the position of each seed sown. It can then carry out mechanical weeding throughout the vegetative cycle, not only between rows, but also between sown seeds, whether or not these have led to a growing plant. A single robot is able to manage 20 hectares in total autonomy as it is equipped with large solar panels. Another illustration is the ability to imagine new forms of cooperation between machines and humans, by entrusting the machine with repetitive and arduous tasks which are frequently the source of musculoskeletal disorders. Such cooperation has been suggested by Israeli research teams (Bechar *et al.*, 2000; Vasconez *et al.*, 2019) for melon harvesting, where the human marks ripe harvestable melons, and the machine then quickly picks them. To the best of our knowledge, there is no similar cooperation on crop protection topics to date. But the human-machine cooperation topic is evolving fast (Vasconez et al. 2019; Benos et al. 2020; Lytridis et al. 2021).

The development and marketing of high-tech agricultural equipment, based on digital technology and sensors, is hampered by their costs, which are still high at present due to the emerging nature of the sector, but which should fall once prototypes or small series are no longer involved. Proactive policies to support companies that offer them, often start-ups, combined with purchase subsidies for farmers or a commitment to a value-added chain, could be necessary for their widespread use. But the solution also lies in the development of joint purchasing and use of new and costly (including maintenance) agricultural equipment, as well as in self-building and mutual aid for the creation of specific tools adapted to individual needs (Box 6.1).

Key messages

Innovations in agricultural equipment will be essential for developing pesticide-free cropping systems, both for producing and harvesting diversification crops and for cultivating plants in other ways, such as the combination of crops. Thanks to sensors, curative or preventive actions can be conducted very precisely and automatically. At the same time, the adaptability of agricultural equipment will be a crucial lever for implementing diversified cropping systems adapted to local soil and climate conditions. This adaptability could involve the use of sensors, facilitating *in situ* adjustment of agricultural equipment, as well as its self-construction by farmers' collectives. Once the technological approaches have been mastered, it will be easier to grow several species in the same plot, sow them at different times and harvest each one when ripe. By making it easier to spread risk, the new association cropping methods facilitated by technology will speed up the emergence of pesticide-free systems (Vasconez *et al.*, 2019; Benos *et al.*, 2020; Lytridis *et al.*, 2021). All these innovations in machinery will, of course, have to be developed in a coherent way, taking into account agronomic innovations and varietal choice, while limiting the associated costs (Maurel and Huyghe, 2017).

⏩ Digital technology for extended epidemiological surveillance

The aim of plant health epidemiological surveillance is to monitor the development of pests and diseases so that preventive action can be evaluated at their real benefit or curative action can be taken in good time. To be effective, four elements need to be monitored: hosts, pests, beneficial organisms and the environment. Can digital technology reinforce this epidemiological surveillance? Several examples in human, animal and plant health suggest that the answer is yes, and that a turning point has already been reached.

Digital technology to enhance the acquisition of monitoring data

Digital technology in its broadest sense is first and foremost a means of significantly increasing the acquisition of epidemiological surveillance data, for example *via* sensor networks (Reboud *et al.*, 2021). In addition to their use in conjunction with agricultural equipment, sensors can also be used to monitor the health of cultivated plants and their environment, in order to anticipate the presence of pests. The use of sensors for epidemiological surveillance in agriculture is not new and has already helped to improve the monitoring of certain key parameters such as the weather or animal surveillance (Hutchison *et al.*, 2019), but they are increasingly being used to track:

– Cultivated and uncultivated vegetation. Non-destructive monitoring of the latter, in particular the aerial parts, has developed in recent years and has made it possible to estimate plant biomass, describe the three-dimensional structure of the plant cover and even quantify certain physiological responses under stress, such as wilting due to a lack of water (Araus and Cairns, 2014; Yang *et al.*, 2021).

– The abiotic environment. As climate monitoring is of prime importance in agriculture, numerous solutions are already available for measuring the main climatic variables in air, soil and water (e.g. temperature, humidity and solar radiation for photosynthetic activities). Sensors are also available to measure the physico-chemical properties of environments (pH and electrical conductance, in particular) or quantify chemical compounds of biological or anthropogenic origin (such as CO_2, O_2 and N_2O), including on large scales *via* satellites (European Copernicus programme).

– The biotic environment. Monitoring this component of the agroecosystem, other than vegetation, is certainly both the most eagerly awaited and the most complicated. Prototypes of various technological solutions are already available (Reboud *et al.* 2021), such as those capable of automatically identifying species on the basis of their images (Lürig *et al.*, 2021), the sound they produce (Lima *et al.*, 2020), the odours they emit (such as pheromones), or a molecular trace that is specific to them

(Cesewski and Johnson, 2020). The latter technology enables monitoring to be extended to microorganisms.

Sensor development is constantly evolving, drawing on both technological and biological advances (Box 6.2). However, research into automatic detection technologies still needs to be conducted, in particular to improve the location and recognition of organisms present, whether pests or beneficial organisms, whether this be in the air, soil or water (Cubero *et al.*, 2020; Cui *et al.*, 2018). For example, sensors based on insect pheromone receptors hold promise for providing early warning of invasive insect pests (Tewari *et al.*, 2014; He *et al.*, 2023). Other types of sensors, including molecular analysis such as lab-on-a-chip, could be a promising option for efficiently detecting and analysing diseases caused by microorganisms (Kashyap *et al.*, 2017). In addition to monitoring different organisms, progress remains to be made in monitoring the nitrogen nutrition status of crops, which represents a key factor in understanding pest attacks.

Box 6.2. The PheroSensor research project: olfactory sensors using pheromone receptors for early detection of insect pests (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

Monitoring insects remains a major challenge for epidemiological surveillance. By detecting them at an early stage, we can implement appropriate measures to avoid excessive infestations. The methods currently available for this type of detection rely on pheromone-based insect traps (chemical compounds emitted by insects to attract conspecifics). However, these methods sometimes lack efficacy and require frequent human intervention to count and identify captures. These molecules also need to be actively released into the environment, which means knowing how to produce them beforehand. An innovative way of detecting insects would be to detect their pheromones directly, even though these compounds are emitted in small quantities. The PheroSensor project aims to meet this challenge by developing bio-inspired sensors based on the pheromone receptors of three insect species. First, the major compound of these receptors will be characterised in order to develop biological sensors on sentinel flies with a limited lifespan. From there, pheromonal receptors will be grafted onto diamond transducers to create physical sensors. When used in the field, these sensors will track not only pheromone emissions, but also the presence of compounds emitted by host plants. They could prove to be a highly refined "nose" for opening up the world of odours and integrating this information into action programmes to avoid major damage to crops (INRAE, 2024a).

Alongside advances in sensors, significant progress has been made in wireless communication and sensor networking (Ojha *et al.*, 2015). So, sensors, which were once linked to wired central recording units, are now wirelessly connected objects that can perform part of the calculations. "Cloud computing" transmits relevant information to a server, which in turn transmits it to the user. The development of the Internet of Things and of low-frequency (LoRaWAN and SigFox, for example) and cellular (3-5G) network infrastructure is therefore now as important as the sensors themselves in moving from data recording to geo-localised monitoring devices, enabling in particular the reproduction of mapped information

(Fuentes-Peñailillo *et al.*, 2021). This growing contribution of network infrastructure to the digitalisation of agriculture illustrates the arrival of new actors jostling up against the institutional actors in machinery and agricultural meteorological forecasting (Lakhwani *et al.*, 2019).

Participatory, citizen or collaborative sciences are sources of scientific data and knowledge production through non-professionals who have an interest in monitoring plant and agroecosystem health (Houllier and Merilhou-Goudard, 2016). Obviously, it is easier to mobilise citizen participation in some subjects more than others, and the appeal of crop pests does not spontaneously mobilise many volunteers. The data collected may be fairly basic, but their number and regularity make it possible to identify the first signals of a species in a territory, detect invasive pests and ensure the monitoring of their development (Ryan *et al.*, 2018). Digital technology plays a central role in networking the actors involved in this surveillance, centralising and reproducing the data collected, and also in providing identification tools, particularly image recognition. Participatory science initiatives focusing on plant health, for example by monitoring invasive species, have already been launched, but remain relatively limited (Streito *et al.*, 2021). Increasing the power of agroecosystem monitoring in this way will require continued efforts to educate citizens (such as agricultural stakeholders and naturalists) on how and why to identify species, as well as a surge in data sharing that can then be used to improve species recognition using machine learning algorithms (Nugent, 2018; Di Cecco *et al.*, 2021). Here, too, an economic model for data sharing may need to be invented, to ensure that this "common good" data becomes massively available, while remaining freely accessible.

Mobilising data to understand, model, predict and guide

The availability of data and its use to guide decision making currently remain the main obstacles to extensive monitoring of pests and agroecosystems to inform prophylactic practices. Digital technology is one way of overcoming this hurdle and considerably increasing the mass of data available relating to the development of cultivated plants and their biotic and abiotic environment. The aim is not only to gather information on pests and diseases, but also on the agronomic practices used, so that they can be connected. The combination of information from fixed sensors, on-board sensors (e.g. satellites, drones and vehicles), participatory science and text mining makes it theoretically possible to finely monitor many components of plant health, practices and agroecosystems over time and space. If we add to this the growing power of sequencing data and, more broadly, of all genomic data, we should have multiple, dense and high-quality sources of information in the medium term. This would represent enormous potential for extending our understanding of ecological processes and their determinants, and then guiding corrective actions to maintain favourable conditions that limit interventions in crops. This is where process — and data — driven modelling work needs to step in to take advantage of monitoring data. The use of mechanistic models has the advantage of providing a qualitative understanding of the system under study by mathematically describing the major processes. In principle, therefore, they can be used to test prophylactic practices *ex ante* through simulation (Rimbaud *et al.*, 2021; Thompson and Brooks-Pollock, 2019). However, they have the disadvantage of being very demanding in terms of detailed knowledge of processes and few are currently capable of dealing adequately with the impact of pests. So, with the quantitative and qualitative increases in data, statistical approaches are gaining in importance. Among these, machine learning methods, such as deep learning, are the most popular for their predictive capabilities, particularly for processing massive data such as images (Jung *et al.*, 2021; Kirkeby *et al.*, 2021). But they, too, have their limitations, notably that of not being able to account for practices that are not yet widespread. As all models have advantages and weaknesses, it is generally worthwhile combining them, for example to jointly integrate physical and biological processes (Allen-Sader *et al.*, 2019) or to reduce uncertainties in predictions (Skelsey, 2021; Viboud *et al.*, 2018). In epidemiological surveillance, these models are currently used to identify risk factors (Martinetti and Soubeyrand, 2019), but much work remains to be done to assess the effectiveness of measures implemented to directly or indirectly reduce the risk of epidemics.

We can see a gradual shift in the focus of monitoring, from an approach concentrating on pests with a view to eliminating them with pesticide treatments, to a more systemic approach, in which the pest is still observed but within the network of biotic interactions to which it contributes, in a fluctuating and uncertain abiotic environment. Ultimately, it is the agroecosystem in its entirety, and in part its regulatory function, that becomes the focus of study. The aim is to ensure good crop health *via* the health and regulatory capacities of the agrosystem, and to provide the means to monitor its evolution.

Towards intelligent epidemiological surveillance as part of the *One Health* concept

Beyond data acquisition and processing, digital technology can also make plant health monitoring more intelligent.

The development of digital epidemiological surveillance can initially take place under the paradigm of massive data: recording as much information as possible with a limited *a priori*, storing the data and employing statistical and computational methods to extract relevant information. However, this approach still poses problems of storage, data sovereignty and energy consumption, increasing the digital environmental footprint (Weersink *et al.*, 2018). Data collection can be made smarter and more frugal by mobilising different complementary strategies such as ubiquitous computing, which enables sensor networks to automatically adapt to local conditions to acquire data only when relevant, or the use of statistical methods to define the optimal positioning of insect traps in a territory, offering efficient monitoring while minimising costs (Bourhis *et al.*, 2021; Parisey *et al.*, 2022). In the near future, it is reasonable to envisage autonomous digital push-pull systems combining automatic pest detection with volatile molecule delivery systems to attract pests out of crops and, conversely, beneficial organisms into crops.

Finally, epidemiological monitoring is still limited in terms of space, time and target, as it relies primarily on direct, relatively short-term observation of pests in or near cultivated fields. However, for pesticide-free agriculture, epidemiological monitoring should include a wide range of organisms, from parasites to beneficial organisms, to provide information on potential large-scale natural regulation. This could help predict contamination risks over an entire territory (Allen-Sader *et al.*, 2019; Leyronas *et al.*, 2018), integrating regulations within interaction networks, or even rationalising about large-scale management measures such as the spatial organisation of species and varieties in the landscape (Rimbaud *et al.*, 2021). Furthermore, the recent One Health concept asserts that most new animal and human diseases originate from disturbed natural environments that act as reservoirs and sustain disease vectors (Cunningham *et al.*, 2017). Extending this concept to plant production means that any type of epidemic invasion is indicative of more or less profound, even irreversible, disturbances. To achieve this, it will be necessary to monitor the risk factors for pest proliferation, by including non-agricultural areas in epidemiological surveillance (Morris *et al.*, 2021) and thereby optimising the preventive approach required for prophylaxis (Box 6.3). In addition, it would be interesting for the epidemiological monitoring of plants, animals and humans to share at least some of the technology and data to compare results and improve prevention and forecasting capacities at appropriate embeded scales (Davis *et al.*, 2017). Efficiently integrating the many indicators that can be calculated from monitoring derived from smart sensors, social networks, digital maps and remote sensing would pave the way to the development of the next generation of epidemiological models and the creation of innovative decision support tools, not only at the service of farmers as is currently the case, but also at the service of the environment and other stakeholders.

Box 6.3. Beyond research project: towards enhanced epidemiological surveillance (2020-2026, financed in the frame of the Priority Research Programme "Growing and Protecting Crops Differently")

The current paradigm for epidemiological surveillance (in grey in Figure 6.3) consists of direct observation of pests and relies on specific data from relatively short-term events in the vicinity of cultivated fields. The Beyond project aims to develop a new paradigm (blue in Figure 6.3) by encompassing broader space-time scales, such as non-agricultural areas and integrating data from indirect observations of pest populations. This includes opportunistic data (e.g. satellite images) obtained from existing monitoring systems developed in non-agricultural contexts and therefore not requiring investment. Other types of data, such as data from experts, could also be integrated to maximise the opportunities for prophylaxis.

To achieve this goal of "augmented" epidemiological surveillance, the Beyond research project is based on interdisciplinary research. A comparative analysis of augmented epidemiological surveillance strategies is being conducted for some 15 agricultural systems representing a range of crops (arboriculture, market gardening and grapevines), pests (fungi, bacteria and viruses) and dissemination routes (insects, wind and trade). This change in scope is accompanied by new concepts on the factors influencing pest emergence and evolution, as well as a new decision-making rationale for implementing effective prophylaxis (INRAE, 2024b).

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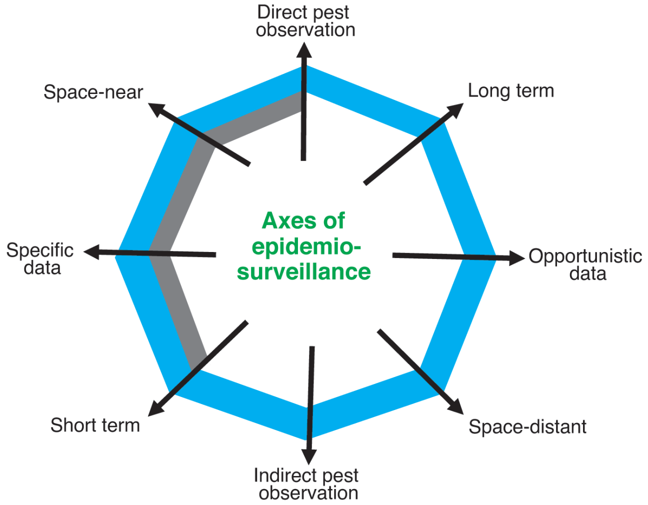

Figure 6.3. The axes from current epidemiological surveillance (grey) to extended epidemiological surveillance (blue) (INRAE, 2024b).

Key messages

Digital technology will increase data acquisition for monitoring crops, pests, diseases and beneficial organisms by integrating the whole biotic and abiotic environment. This will require technical innovations such as bio-inspired sensors, which can detect the presence of certain insects based on their pheromones. In addition to sensors, participatory science supported by digital tools also represents a promising lever for collecting information. These various sources of increasingly massive data will feed modelling approaches, including those based on artificial intelligence, to provide farmers with indicators to guide prophylaxis. A change of scale is also necessary, as epidemiological surveillance cannot be confined to monitoring pests and diseases within crop systems alone. Indeed, it is all agroecosystems, and even non-agricultural ecosystems, that need to be monitored in order to limit the risks of pest proliferation or assess the functionality of ecological processes. So, based on the One Health concept, plant health is part of a wider scheme, in which all organisms, both animal and plant, and ecosystems, whether agricultural, urban or natural, have a role to play. Epidemiological surveillance of this kind involves a large number of stakeholders, going far beyond just farmers.

⏩ Digital technology for sharing, traceability and value enhancement of agricultural production

The development of certain fixed and on-board technologies, combined with advances in data processing, whether massive or not, is making it possible to improve the transparency and traceability of agricultural production processes (Fielke *et al.*, 2020). For example, thanks to sensors positioned on implements and a GPS plotter in the cab, farmers will be able to record work carried out on a plot in real time. As cultivation operations are recorded automatically, the farmer's work will be simplified. Furthermore, the latest digital innovations, such as blockchain[20] technologies, can help improve farm data management, while opening up the possibility of certifying production and its associated cultivation practices for industry stakeholders. Of course, in return, the energy cost of the traceability technology must be factored into the balance sheet (Pincheira *et al.*, 2022). With regard to pesticide-free systems, this traceability can have two types of advantage. First, it can make it easier for public authorities to monitor the inputs used, limiting the costs and duration of inspections, both for farmers and authorities (OECD, 2019). This could also encourage the introduction of subsidies based on very low input use. Going a step further, fixed sensors in or around plots could report on the state of the agroecosystem and, in particular, biodiversity to allow farmers to be remunerated for the ecosystem services they produce (Zhao *et al.*, 2019; Reboud et al. 2021).

The second advantage of such traceability is that it facilitates the implementation of specifications linked to labelling. Dedicated channels, promoting production methods with little or no pesticide use will be able to develop more easily because it will be easier to verify management programmes, certify production and, ultimately, offer attractive remuneration to producers (Choe *et al.*, 2009), provided that specific investments linked to the organisation of traceability are reduced, which is a major challenge for digital technology. For example, a producer committed to insecticide-free management under contract to a food processing company that promotes this production method in its marketed products will not need to incur additional costs for certification if all treatments are monitored by integrated sensors. Taking this a step further, the development of sensors for real-time analysis could make it possible to measure results (no pesticide residues, biodiversity score etc.) in addition to the means used to achieve them (pesticide-free practices). This could help boost consumer confidence and open up new market segments. Finally, digital technology should make it easier for farmers to organise themselves to meet the same requirements. Following the example of the consumer brand "C'est qui le Patron?!", it becomes possible to propose an inverted model for setting the price and specifications of agricultural products based on consumer wishes (Renault, 2019). Farmers could then commit to producing goods according to precise criteria, with, in return, a selling price that is known in advance, relying on digital technology to limit monitoring costs.

Finally, digital technology can be used to share observations, knowledge and know-how between farmers. Collaborative tools such as GECO (ÉcophytoPIC, 2021) are now available to facilitate the sharing of innovative techniques and rare know-how: their widespread use will be an effective means of democratising pesticide-free practices. Furthermore, by using epidemiological surveillance and practice monitoring tools specific to each farm, it is possible to determine the trigger threshold for a given alternative practice within the management plan. This becomes particularly interesting if the information produced in real time is shared between

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[20] Blockchain is a technology for storing and transmitting information without a controlling body, enabling its users - connected in a network - to share data without intermediaries.

farmers, who can then decide whether or not to adjust their own approaches. This means the increased sharing of information thanks to digital technology makes it possible to mobilise pest management levers beyond the farm, by facilitating the identification of technical solutions that work on other farms and promoting their coordinated implementation over a landscape scale. Nevertheless, these promising advances need to be weighed against two issues: the high cost of this new equipment and the feelings generated by the loss of a farmer's decision-making autonomy once the equipment is directly linked to sensors.

⏩ Conclusion

In many respects, agricultural equipment and digital technology appear to be extremely relevant ways for monitoring and improving the health of agroecosystems. The development of agricultural machinery specifically dedicated to pesticide-free farming is still in its infancy. It offers major prospects, all the more so as it is associated and co-constructed with changes in cropping systems. Nevertheless, the costs associated with the development of the various technologies described here are currently considered to be a major obstacle. On the one hand, agricultural equipment companies need to change their technological orientation in order to limit costs, adapt production lines and even pool investments to democratise access to cutting-edge technologies. Group dynamics that encourage the self-building of equipment also represent a definite opportunity: they can be used to pool investments while sharing skills, thereby stimulating innovation. On the other hand, the potential additional costs associated with the use of these technologies, which help to drastically reduce pesticide use and impact, will need to be taken into account in the value chain, in particular through the creation of dedicated value chains promoting the positive externalities of such technologies and/or support through public policies. Beyond the economic aspects, the biggest challenge for the equipment and digital sector will undoubtedly be to move on from epidemiological surveillance centred on pests to a much more complex monitoring of the state of the health of agroecosystems, geared towards the mobilisation of prophylaxis. This extension of epidemiological surveillance can lead to the inclusion of interstitial spaces and natural areas, and to the mobilisation of other actors such as veterinary and public health services. However, this raises the question of the impact of potential interventions in natural areas, which may be carried out for prophylactic purposes, but which may also have the effect of increasing our stranglehold on the environment.

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Chapter 7

Political and organisational levers

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The preceding chapters have shown that knowledge and know-how now exist to transform agricultural systems and develop new ways of protecting crops against pests. New avenues of research have also been identified with a view to completing the road to pesticide-free agriculture. But technical solutions alone are not enough and, if they are to be adopted by as many farmers as possible, they need to be supported by both political and organisational solutions. Political solutions refer to all the means available to public authorities to support transition efforts. In contrast, organisational solutions, include private initiatives which, while not in opposition to public initiatives, emanate directly from local actors involved in transitions.

Of course, the consequences of possible actions are difficult to anticipate and assess in advance (*ex ante*), because they depend on numerous exogenous factors, such as the balance between crop and livestock production on a national and global scale, and the impact of climate change on production and pests. Taking into account the influence of these different factors requires a detailed analysis of possible dynamics and the construction of different scenarios. This is the purpose of a foresight study carried out in the frame of the Priority Research Programme "Growing and Protecting Crops Differently" which identified the effects of the transition to pesticide-free agriculture in different possible futures (Box 7.1).

In recent years, several types of action have been taken to reduce pesticide use in France: bans on the use of certain plant protection products, agri-environmental subsidies of the Common Agricultural Policy (CAP) and demonstration and technical assistance programmes under the Écophyto plan to develop cropping systems which are parsimonious in their pesticide use. Today, however, it has to be said that these actions have failed to achieve the desired environmental objectives set by public authorities. However, there are many other levers, or combinations of levers, never before used in France, that could trigger a large-scale transition to pesticide-free agriculture.

This chapter analyses why, despite the efforts made by public authorities to encourage farmers to reduce pesticide use, the instruments mobilised have not achieved the desired goal. It also presents the political and organisational innovations likely to be used in the near future to correct the ineffectiveness of past policies, and to devise new ones. The solutions proposed in this chapter are developed on the basis of five recommendations:
- Greater transparency in the options offered to farmers, who are the primary actors in the transition.
- Fairer distribution of the cost of switching to pesticide-free agriculture.
- Greater flexibility in support policies to take account of the uncertainty associated with changing production systems.
- More coordination between farmers to integrate spatial issues.
- More consultation between stakeholders to encourage the development of a shared conception of the transition to pesticide-free agriculture.

Box 7.1. 2050 foresight study: Pesticide-Free European Agriculture

The Pesticide-Free European Agriculture in 2050 foresight study is an approach designed to anticipate future changes in order to define transition trajectories that consider the relationships between cropping systems, commodity chains, ecosystems and food consumption, as well as major uncertainties (such as the impact of climate change and the evolution of international markets). It was launched to build pesticide-free agricultural scenarios for the European Union in 2050 by answering two questions:
- What different forms of pesticide-free agriculture might be possible in 2050, with what consequences for production, land use, trade and biodiversity?
- Which different trajectories could lead towards these forms of pesticide-free agriculture?

To achieve this, the foresight study took a systemic approach linking the emergence of pesticide-free agricultural systems to the future of food systems, land, biodiversity, public policies and the consequences of climate change. This foresight involved various stages, from the definition of the study system, through scenario modelling and simulation, to scenario debate (INRAE, 2024a).

⏩ Agricultural development and training policies: how to provide farmers with the keys to alternative approaches?

The development of pesticide-free systems presupposes the development of a coherent set of agroecological practices that make the most of natural regulations. This complex objective means that actors in the agricultural world have the skills and abilities to respond to the problems they face at different scales. So, farmers and their advisers must learn to manage new, increasingly complex cropping systems, where the unexpected and variability are the norm (Girard and Magda, 2018). This evolution requires an increase in farmers' skills, through (i) initial and continuous training, (ii) peer support facilitating situation-based learning and (iii) an evolution in farm advisory services.

Initial and continuous training

Currently, farmers are trained by a variety of agricultural technical schools and, in rarer cases, by engineering schools. What these different training courses have in common is that they are based on a range of monodisciplinary teaching (in disciplines such as plant sciences, zootechnics and economics). In 2018, activities that included multiple knowledge bases, akin to interdisciplinarity, accounted for only around 20% of the activities offered in the vocational Baccalauréat (high school diploma or A level) and the Brevet de Technicien Supérieur (BTS, a vocational training certificate) (DGER, 2018). Nevertheless, progress in this area has been made since the launch of the "Teaching to produce differently" plan in 2013. Some training courses, in engineering schools in particular, are entirely devoted to agroecology, even if they are often under the dominant prism of one discipline in particular, such as ecology for example. The issue of pesticide-free production is not yet addressed as such, due to the lack of knowledge on the subject, except in training courses on organic farming. It therefore seems important to question the current organisation of agricultural education and, in particular, the need to develop interdisciplinary teaching activities to support future farmers and their advisers in the move towards pesticide-free production. For example, assessing the triple performance (economic, environmental and social) of innovative practices that make it possible to avoid pesticides would be useful not only to introduce students to them, but also to gain perspective on their application in different contexts. Furthermore, current teaching is based on perfectly established scientific facts or proven methods. However, practices leading to a significant reduction in pesticide use are emerging, often stemming from the practices of pioneering farmers and often varying from one geographical area to another. It might therefore be desirable to devise new ways of teaching these elements that are still under construction, adapting them in particular to the diversity of locations and relying more on innovative farmers (Gardiès and Hervé, 2015). Finally, learning to manage uncertainty, assess risk and undertake transitions are essential skills for today's farmers. Agricultural training courses should enable students to acquire these skills (DGER, 2018). For this, the use of serious games, in particular those coupled with a modelling tool, are an interesting avenue because these games enable a multitude of factors to be considered (weather, choice of crop management etc.) and their consequences to be visualised simply (Jouan *et al.*, 2020). At the same time, project-based training encourages autonomy and decision-making by allowing students to work on concrete problems.

In addition, in order to support skills development among farmers, a policy of promoting work-study higher education (sandwich courses) at all levels could be envisaged. This would enable young people with little schooling to pursue longer studies, such as engineering school, and thereby acquire additional skills, particularly on subjects such as transition management and implementing overall strategies, taking into account all the technical, environmental and economic constraints facing farmers. Finally, facilitating access to high-level continuous training for farmers by simplifying their financing and even promoting access to temporary labour during training courses would represent an interesting policy.

Peer support to facilitate learning in real-life situations

Situated learning, based on the analysis of problems and innovations encountered on the farm, is often seen as an important aspect of training. This form of group learning is likely to develop mutual support between peers, encouraging the adoption of new practices and fostering exchanges on possible solutions and the potential difficulties of implementing them (Garforth *et al.*, 2003). Various initiatives to encourage this learning process are already being developed in the field, based on existing structures such as agricultural development groups (known as GDA in France) and agricultural technical study centres (known as CETA in France). Other initiatives exist within DEPHY-Écophyto groups (Box 7.2), in the economic and environmental interest groups (known as GIEE in France) set up in 2014, or internationally in farmer field schools. Within these groups, the role of the adviser is to facilitate dialogue between farmers, to contribute specific knowledge and to encourage the emergence of appropriate solutions. This is known as joint experiential learning, i.e. a method in which an adviser and farmer jointly contribute to learning (Eshuis and Stuiver, 2005).

Such bottom-up, participatory learning is far from the norm today (Klerkx and Jansen, 2010). Its development could, for example, be supported by a policy of subsidising farmer membership and the tools available to advisers. This is all the more important as it can be difficult for an adviser to get the group to break out of conventional patterns and address farmers' day-to-day problems. The risk is to remain in a kind of "field trip" mode, tackling tactical rather than strategic problems and, in particular, not integrating the environment outside the plot or long-term steps (Cerf *et al.*, 2019).

Box 7.2. The Écophyto plan: highly ambitious objectives with disappointing results

The Écophyto plan was launched in 2008 by the French government and has since been revised several times. The Écophyto I plan (initially known as the Écophyto 2018 plan) was launched in 2008, with the aim of reducing pesticide use by 50% "if possible" within 10 years. The first plan therefore set a target that required us to go beyond optimising practices and implement a genuine redesign of cropping systems (Jacquet *et al.*, 2011). To achieve this objective, it included a number of different actions. First, the establishment of the DEPHY-Ferme network, which still brings together demonstration farms today. In 2014, there were around 190 groups of around 10 farms covering France's major crops. In addition to these working farms, experimental pesticide-saving systems have been set up (DEPHY-Expé systems). The second pillar of the Écophyto plan is the biological monitoring network, which aims to observe pest presence.

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It is published weekly, in the form of BSV bulletins ("Bulletins de Santé des Végétaux", or plant health updates), which are adapted to each region and aim to enable farmers and their advisers to better target the real need for intervention. Other actions concern the training of (future) farmers *via* the "Teaching how to produce differently" scheme, the introduction of a certificate of aptitude, called Certiphyto, which is required to have the right to use pesticides, and the production and dissemination of tools and knowledge on pesticide-saving systems. The plan also includes a research component on Integrated Pest Management (IPM) (see Chapter 2), as well as on the environmental and health impacts of pesticides. Over the 2009-2014 period, Écophyto I was funded to the tune of €361 million, half of which came from the RPD (pollution tax) levied on pesticide vendors. Five years after its implementation, the first plan was overhauled, as it had failed to set the right trajectory for achieving its objective (50% less pesticide use), with pesticide use increasing by 8% over this period.

In 2015, Écophyto II was launched, reaffirming the goal of halving pesticide use in 10 years. To achieve this, new actions were introduced, such as plant protection product saving certificates CEPP (Box 1.11): this scheme requires pesticide vendors to carry out actions validated by an independent commission and contributing *a priori* to a reduction in pesticide use. The Écophyto II plan also sought to transition 30,000 farms to low levels of pesticide use. In view of the persistently inadequate results in terms of pesticide reduction, the second plan has also been reworked. In 2018, Écophyto II+ plan was announced, benefiting from €71 million per year. It aims to consolidate the DEPHY network and also incorporates the issue of phasing out glyphosate. Within this framework, new objectives have been identified: redefining the limits of untreated zones (known as ZNT), ending the use of glyphosate before 2021, reducing pesticide use by 25% before 2020 and 50% before 2025 (Ministry for Ecological Transition and Solidarity, 2018). Nevertheless, the expected reductions have not taken place for the time being, with the exception of the elimination of products deemed the most harmful such as carcinogenic, mutagenic or reprotoxic (CMR), proven or presumed (CMR 1) and suspected (CMR2), where a significant drop has been recorded mainly due to the mass withdrawal of marketing authorisations (see Chapter 1). Nevertheless, the dynamism of many DEPHY groups and the changes in practices they have been able to initiate represent a definite step forward that should be extended to all farmers.

The evolution of farm advisory services

Drastically reducing pesticide use implies an in-depth redefinition of the cropping system (Chapter 3). This rethinking must cover all practices and not just those directly related to pests by integrating, for example, nitrogen fertilisation, while ensuring that changes in practices do not jeopardise a farm's economic equilibrium. Here, strategic advice is likely to play a key role (Box 7.3). This type of advice is necessarily personalised and long-term. In this respect, it differs from the low-cost, standardised consulting offer that has been common until now (Labarthe and Laurent, 2013).

Some studies suggest that the development of strategic advice involves an overhaul of the agricultural advisory profession (Cerf *et al.*, 2010; Guillot *et al.*, 2010). The back office, which develops the content to be offered to farmers (by setting up experiments, for example), would need to be strengthened, in order to provide front office advisers with the numerous local references needed to disseminate new practices. It would also be useful to identify and analyse the practices of farmers who have successfully reduced pesticide use in order to produce knowledge that can be disseminated. As this back office work is costly, one solution would be to create "competence clusters" in certain areas: bringing together different agricultural development organisations, or even technical institutes, they would provide solid proof of the effectiveness of new practices, while pooling the costs of advice and maintaining local roots (Labarthe *et al.*, 2013; Reymond *et al.*, 2012). This would be particularly relevant in the case of biocontrol, which suffers from a lack of adoption by farmers, due in particular to the lack of supply by distributors, the complexity of its implementation, its heavy dependence on local conditions, but also the lack of proof of the efficacy of some biocontrol solutions (Villemaine *et al.*, 2021). Here, too, we could consider setting up an innovation tracker, focusing on situations where biocontrol practices have been implemented in order to help demonstrate their efficacy. Complementing this, the development of farmer-researcher experiments, where experimental plots are made available by farmers and studied by researchers, is an interesting approach. They help to perfect innovative systems and produce references to demonstrate to as many people as possible the benefits of pesticide-free systems (Thomas, 2018). Finally, the development of strategic advice raises the question of the privatisation of advice: a Europe-wide study has shown that it is easier for private agricultural development organisations to offer personalised advice, as the advisers working for them generally have a smaller number of farms to monitor. However, the privatisation of advice must not be at the expense of accessibility, particularly for smaller farms (Knierim *et al.*, 2017).

Box 7.3. What is strategic consulting?

As of January 1, 2021, France's law on agriculture and food (EGALIM) (no. 2019-361) required the separation of pesticide sales and advisory activities with the aim of reducing pesticide use. As part of this, farmers are obliged to receive strategic advice on pesticide use in order to renew their Certiphyto, the certificate that is required in order to have the right to use pesticides. This institutionalised strategic advice consists of two stages. First, a diagnosis is made of the overall context of the farm, its pest and disease management and its current plant protection strategy. Next, an action plan is defined to reduce the use and/or impact of pesticides, in line with the farmer's technical and economic objectives and short- and medium-term plans. In addition to this mandatory strategic advice, the farmer can benefit from specific advice throughout the season (for the use of a product in particular), but this advice, like strategic advice, can only be offered by structures independent of pesticide sales (Ministry of Agriculture and Food, 2021). Companies involved in sales may, however, advise on biocontrol solutions and all solutions covered by plant protection product saving certificates CEPP action sheets (Box 1.11). They are also required to provide safety advice on the use of the pesticides they sell.

The strategic council institutionalised by the French law on agriculture and food (EGALIM) represents an interesting basis for the strategic advice as defined in this chapter. With the aim of drastically reducing pesticide use, it might also be advisable to include a diagnosis and potential overhaul of the entire cropping system, proposing the introduction of diversification crops and landscape infrastructure chosen for its ecosystem services, for example. Taking this a step further,

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strategic advice can also be aimed at enabling farmers to receive subsidies or have their farm certified for their alternative practices. Finally, strategic advice will be fully effective if it is implemented on a sufficiently large scale so that a collective of farmers can benefit from it, enabling certain actions to be implemented, such as landscape infrastructure, to produce their full environmental potential.

Key messages

Current agricultural training policies are mainly based on the creation of farmer groups to facilitate peer-to-peer learning and the implementation of more personalised farm advisory services. Recent studies suggest that it would be worthwhile supporting an evolution of this model towards more strategic farm advice and support for farmers, i.e. enabling them to see beyond the field scale by integrating the whole of the farm's socio-economic and natural environment. Such developments may require a transformation of the business models of many of the organisations that have traditionally provided these advisory services, such as cooperatives and Chambers of Agriculture. State support will undoubtedly be needed to sustain this type of development. Similarly, in view of the environmental objectives set, it seems desirable that agricultural training, both initial and continuing, should also benefit from a thorough overhaul. In particular, it now seems essential to be able to pass on existing knowledge and know-how about agroecological practices to farmers.

⏩ Regulatory instruments: what role do they play in the regulation of pesticides?

For several years now, pesticides have been subject to an unprecedented intensification of regulatory pressure (Thibierge and Chevallier, 2013). Already complex and numerous, the rules governing the marketing and use of pesticides are increasing significantly[21], with a direct impact on the strategies of agricultural stakeholders. Two key facts characterise the new rules. On the one hand, they reduce the range of substances available for crop protection. On the other, they reduce the utilisable agricultural areas where they can be applied. However, these regulatory constraints do not have an unequivocal effect on the transition to pesticide-free farming systems.

Fewer chemical molecules available?

While some new active substances are still registered, others commonly used by farmers for plant protection are regularly withdrawn from the market or their use is restricted (Box 7.4). This phenomenon stems from several concomitant legal logics.

First and foremost, is the European Union (EU)'s refusal to reauthorise the marketing of some pesticides of proven toxicity. The list is now long: atrazine, chlordecone, paraquat, dichloropropene, cyanamide, propisochlor, permethrin,

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[21] The https://www.pestidroit.fr website lists all the sources and legal literature on pesticides.

dimethoate and others. In 2013, three substances (clothianidin, thiamethoxam and imidacloprid) belonging to the neonicotinoid class were banned because of the dangers they pose to pollinator health[22]. This decision was followed in France by a near-total ban on pesticides from this family (law no. 2016-1087, August 8, 2016). Although derogations were allowed in 2020 in certain sectors particularly exposed to epidemiological risk, such as sugar beet, they were only allowed for a limited period, expiring on January 1 2023 (Grimonprez, 2021).

Box 7.4. Pesticide authorisation case law

French courts are increasingly scrutinising the legality of pesticide marketing authorisations and do not hesitate to invalidate them in the name of the precautionary principle. For example, the Nice Administrative Court annulled the authorisations for several pesticides containing sulfoxaflor, on the grounds of the significant risk of toxicity to pollinators[23]. Other criticisms (harmfulness to aquatic organisms, reprotoxicity and suspected carcinogenicity in humans) led the Tribunal and then the Lyon Court of Appeal to withdraw the marketing authorisation for Roundup Pro 360[24] on the grounds of a manifest error of assessment. Although these decisions are still isolated, they herald an increase in the number of appeals against pesticides and an increasingly exacting attitude on the part of judges compared to the past. The result should be a tighter filter for accessible molecules.

The comparative assessment procedure between pesticides and their non-chemical alternatives[25] is a second lever enabling an EU country to ban pesticides (even though they are registered) on its territory. Mandated by the French government as part of its glyphosate phase-out plan, Anses submitted this controversial substance for analysis in 2018. The main uses of glyphosate were reviewed (viticulture, arboriculture and arable crops), as well as the practical and economic impacts of using alternatives (Carpentier *et al.*, 2020; Jacquet *et al.*, 2019a, 2019b). At the end of this evaluation, Anses concluded that a certain number of glyphosate uses should be banned, but also that application rates should be reduced where the herbicide is still deemed necessary (Anses, 2020).

In this spirit, the European Court of Justice, while validating the general system for placing pesticides on the market, has called for greater rigour in the evaluation of substances. Not only does it recommend that the most reliable scientific data available and the most recent results of international research be taken into account, and that the studies provided by the applicant not be given predominant weight in all cases, but it adds that the procedure for authorising a substance for plant protection use must include, in addition to an assessment of its own effects, the cumulative

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[22] Implementing Regulation (EU) No. 485/2013, May 24, 2013; General Court of the European Union, 1st Chamber, May 17, 2018, Case Nos. T-429/13 and T-451/13.

[23] TA Nice, Nov. 29, 2019, no. 1704687.

[24] TA Lyon, Jan. 15, 2019, no. 1704067, Comité de recherche et d'information indépendantes sur le génie génétique; CAA de Lyon, 3e chambre - no. 19LY01017-19LY01031 - Société Bayer Seeds SAS - Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail, June 29, 2021.

[25] Regulation (EC) of the European Parliament and of the Council no. 1107/2009, Oct. 21, 2009, art. 50.2.

effects — known as cocktail effects — of the substances with each other and with the other components of the product[26].

In order to improve transparency in the approval of plant protection products and in line with its "farm to fork" strategy, Europe has no choice but to reform its evaluation procedures, with a view to making them more stringent, particularly with regard to public access to the studies used by companies, and the long-term toxicity of products[27]. If this new regulatory framework was to become a reality in the near future, it would probably threaten the continued market presence of certain controversial substances, such as succinate dehydrogenase inhibitor (SDHI) fungicides, about which there is an increasing number of scientific alerts (Libération, 2018).

Less land eligible for treatment?

In addition to measures to reduce the number of substances available, regulations governing rural areas are increasingly restrictive with regard to the use of plant protection products. As a result, pesticides have been banned from an ever-increasing number of areas. First and foremost, there are the protected areas, in view of their environmental interest, whether by regulation (nature reserves, classified sites, remarkable biotopes, green and blue corridors etc.), or at the initiative of land managers (conservation bodies and local and county councils). Although the rules observed vary from one site to another, the tendency is to exclude from these areas practices that are detrimental to respect for the environment, which may be more or less directly related to the use of synthetic pesticides. Such protection schemes, once confined to environments with high biodiversity values, are now being extended to more ordinary areas, particularly with a view to better protect drinking water catchment areas, which are regularly exposed to diffuse pollution.

Spatial discrimination also takes the form, more or less everywhere, of portions of land where chemical treatments are prohibited: safety distances known in France as ZNT. Buffer strips have long been established near water sources (streams, ponds etc.). In France in 2014, they were applied in the vicinity of establishments accommodating vulnerable people (schools, hospitals, hospices etc.) and then to the benefit of all residents living near treated plots in 2019 (Grimonprez and Bouchema, 2020). With regard to residential areas, the distance where no pesticides can be sprayed now depends on the type of crop treated (high or low[28]), the category of product used (more or less dangerous), what is specified in the authorisation for each product and, finally, what may be provided for in neighbourhood charters drawn up at the departmental level[29], providing a real headache for farmers. Consequently, these criteria can result in a significant surface area that a farmer can no longer protect with chemicals. Furthermore, the risk of violating these rules is not negligible; while it is rarely

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[26] CJEU, Oct 1 2019, Case C-616/17.

[27] See the European Commission's proposal of April 11, 2018 to reform the risk assessment procedure concerning food safety; followed, on January 16, 2019, by the Parliament's draft to improve the authorisation procedure for pesticides within the EU.

[28] High crops (orchards) carry a greater risk of aerial drift than low crops (cereals).

[29] Charter system nevertheless invalidated by the Constitutional Council: Decision no. 2021-891 QPC, March 19, 2021, association Générations Futures et autres.

the case, a penal sanction can be given. Winegrowers from Villeneuve-de-Blaye in Gironde recently experienced this, having been convicted by the Bordeaux Court of Appeal for treating their vines in high winds near a primary school[30].

For the past two years, the mayors of some communes have been trying to go further than these general restrictions, either by establishing greater distances (50 metres, for example), or by banning pesticide use in their territory altogether. We should note that since the entry into force of France's "Labbé" law on January 1, 2019, all phytosanitary treatments are banned in public spaces (both local authorities and public establishments) under Code rural, art. L. 253-7, II. However, municipal by-laws that are flourishing in France at present prohibit treatments even on private plots. This local regulation has so far been prohibited by the administrative courts[31]. But until when? Local elected representatives are determined to considerably tighten the conditions governing pesticide use on the grounds of the health of their fellow citizens.

A new approach to pesticide law

With its essentially negative approach (do nothing), regulation shows its intrinsic limitations. It is not enough to simply forbid something and to create, in the collective agricultural imagination, an alternative path that will win support. It is not just "without" pesticides that farmers will have to operate, but "with" alternative positive methods, which they will naturally seek to exploit. This last point invites us to explore two lines of research.

The first is the development, within the regulations themselves, of a genuine status for alternatives to synthetic pesticides. Their definition should be clarified to determine whether it includes certain so-called "alternative" pesticides, even if it means introducing derogation rules for them when they are distributed or used. At present, the system is highly disorganised (between low-risk substances, biocontrol, basic substances, natural preparations of little concern etc.) and difficult for stakeholders to understand. Furthermore, we need to determine how alternatives can replace the products currently in use with similar levels of efficacy. This would involve identifying and even standardising practices that work, but also defining new conditions for evaluating non-chemical solutions and their contribution to crop protection. Last but not least, mass dissemination of alternatives in the field will require the principles of IPM to be officially enshrined in the rules governing the farming business (rural leases, land regulation, environmental zoning, production specifications etc.).

The second area for investment is the necessary interconnection of regulatory standards and economic instruments (subsidies, taxation, insurance etc.). In the short term, the costs incurred by changes in practices will only be bearable if they add value for farmers, in particular through differentiation at the marketing stage. The prerequisite is to be able to identify and recognise the superior quality

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[30] CA Bordeaux, 6th ch. corr., Nov. 18, 2020, no. 19-00849. Grimonprez (B.) and Terryn (F.), Pesticides: les enfants empoisonnés, les viticulteurs condamnés, *Droit de l'environnement*, February 2021, p. 70.

[31] CE, Dec. 31, 2020, no. 440923.

of products produced using less or no synthetic pesticides. Identifying alternative practices, labelling them and remunerating them at the chain and end-consumer level will certainly act as a lever for some agricultural segments (animal products, wine, fruit and vegetables).

Box 7.5. Law and the systems approach to transition

The question arises as to whether public policies should favour an analytical approach, considering crop protection method by crop protection method, in the logic of substituting one polluting practice for another which is more virtuous, such as biocontrol, or whether they wish to favour a systemic approach taking the farm — and therefore crop health and pest control — as an inseparable whole. This is made possible by voluntary commitments (e.g. "system" agri-environmental and climate measures) or certification, such as organic agriculture or France's high environmental value scheme (known as HVE) which allow farmers to use a logo on their products. While HVE certification is relevant from an agronomic and even economic point of view, it is also less precise and less strict than organic agriculture and has several levels of commitment. The risk, which has yet to be fully assessed, is that, dependent on the content of the specifications for the different levels of commitment, it may very well require a high commitment, leading the way to transition, or a lower commitment which, under the cover of a more flattering label, authorises the perpetuation of past phytosanitary traditions (Aubert and Poux, 2021).

But the actors implementing agroecological practices that reduce pesticide use have other values too: social, environmental, landscapes, which the market, in particular internationally, is unable to perceive, and therefore to integrate and reward. These collective, non-market values will essentially be financed by public funds: what is generically referred to as "payments for environmental services" would appear to be essential support for low value-added mass production, some of which is destined for export (cereals and oilseeds). In this context, it would be interesting if such values were recognised in international trade agreements.

Key messages

The law has become an essential determinant in farmers' decisions to use pesticides to protect their crops. Substances admitted to the market are increasingly strictly screened, with more in-depth assessments of their long-term toxicity for humans and the environment. The courts no longer hesitate to review and overturn decisions taken by health authorities on the grounds of the precautionary principle. Taking the immediate environment of farms into account also complicates application practices. More areas are facing limits or bans on the use of synthetic pesticides in order to protect biodiversity, water quality and, more recently, the health of local populations. This regulatory arsenal, however well-founded it may be, can bring some stakeholders to a standstill or penalise their economic competitiveness. Hence the importance of combining real alternative solutions with the essential restrictions on use, and of encouraging the implementation of new crop protection levers. These alternatives must be given a much better-defined status in law, which should provide for simpler access (sometimes without marketing authorisation) and prioritisation on the basis of equal efficacy. More broadly, this means modifying the general regulatory framework for pesticides, currently based on Regulation (EC) n°1107/2009, to take better account of new crop protection practices.

⏩ Subsidising alternatives to pesticides: how can we improve the effectiveness of agri-environmental measures?

For many years now, the CAP has included economic instruments designed initially to reduce the harmful effects of agriculture on the environment, and then gradually to recognise that agriculture provides services other than the production of food and non-food biomass, providing financial support for farmers' pro-environmental practices. To this end, second-pillar agri-environmental measures (AEM, known as MAE in French) have been in place since 1992, cross-compliance since 2003, and greening in the 2014-2020 programming period.

AEM, which are of particular interest to us here, are subsidies paid to farmers in exchange for the adoption of more environmentally friendly practices (Box 7.6). These are voluntary instruments with farmers remunerated by the community for the environmental services they provide (e.g. reducing pesticide use), but they are most often paid on the basis of the additional costs farmers have to bear and not on the value society places on the environmental improvement generated (e.g. water quality)[32].

The AEM principle differs from that of pollution taxation, which aims to make polluting emissions more costly, or from the polluter-pays principle, which consists of having the polluter bear the costs of measures to prevent, reduce and remedy pollution. While these different tools all aim to achieve the same objective, AEM have been by far the most widely used in agricultural activities over the past few decades. They have proved their effectiveness in bringing about specific improvements in the practices of farmers who have chosen to sign up to a contract, particularly in the early years of implementation (European Court of Auditors, 2020; Primdahl *et al.*, 2003). However, they have also been heavily criticised for their cost, in view of the low environmental impacts achieved (Pe'er *et al.*, 2019). Currently, new avenues need to be explored to improve the environmental efficiency of CAP payments.

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[32] AEM follow the same logic as payments for environmental services (known in France as PSE), with the difference that the level of compensation they offer is calculated on the additional costs generated by the change in practices provided for in the specifications. However, assessing the value of this service is particularly complex. In this respect, the question of AEM versus PSE is partly akin to the equally debatable question of measures with "obligations of means" versus measures with "obligations of results".

Box 7.6. AEM: voluntary instruments

AEM are multi-year contractual schemes, generally lasting from five to seven years. They are aimed at farmers who voluntarily commit, in return for remuneration, to implementing practices considered to be favourable for the environment, over and above regulatory obligations. Since their introduction in 1992, numerous operational variations have been introduced in line with successive CAP reforms. Initially focused on biodiversity and water quality, their scope was broadened during the 2014 CAP reform by integrating climate issues, giving rise to "agri-environmental-climate measures" (known as AECM). Two types of AECM were then proposed: on the one hand, "system" measures aimed at an overall change on the farm or the maintenance of virtuous systems, and on the other, "plot" measures targeting a specific practice.

AECM have also been territorialised, i.e. integrated into agri-environmental and climate projects (known in France as PAEC) led by local stakeholders and selected by regional councils (CEP, 2021). In practice, each region identifies areas with high environmental challenges, within which calls for projects are issued to local operators (e.g. a Chamber of Agriculture or a water syndicate). The proposed PAEC include the AECM offered to farmers and the facilitation planned to help them subscribe to the measures and meet their commitments.

Despite efforts to improve the definition and relevance of AEM, contract agreement rates still remain extremely low. For example, according to data from the Observatoire du Développement Rural for the period 2015-2020, the number of AECM beneficiaries containing a PHYTO unit commitment (i.e., aimed at reducing the use of plant protection products) generally does not exceed 300 in total per region, an exception being the Languedoc region with more than 1,000 subscribers (ODR, 2021).

Agri-environmental and climate measures: mixed results

AECM, five-year contracts between farmers and the State, are emblematic of the public authorities' willingness to support agroecological transition efforts with subsidies. Over the 2014-2020 period, the budget allocated to these measures across the EU reached more than €16 billion out of the €100 billion European Agricultural Fund for Rural Development (EAFRD) budget. This is equivalent to just 2.4% of the total CAP budget, including the first and second pillars (European Commission, 2020). Several studies suggest that AECM have mixed effects. Indeed, measures dedicated to reducing pesticide use in viticulture may have had a positive effect, but hardly a lasting one. For example, a study carried out in southern France showed that the least demanding AEM (eliminating the use of herbicides only between vine rows) actually led to an average 40% reduction in herbicides in years when weed pressure was high. In contrast, in "easy" years when weed pressure was rather low, beneficiaries actually made less use of herbicides, which were unnecessary that year, and ultimately behaved exactly as they would have done in the absence of AEM (Kuhfuss and Subervie, 2018).

However, the results of the most demanding AEM in terms of specifications (conversion to organic agriculture or its maintenance, for example) are more encouraging, as they suggest that this type of AEM would have a significant impact on farmers' practices, whatever year is considered (Jaime *et al.*, 2016; Kuhfuss and Subervie, 2018). More generally, some studies suggest that the impact of AEM would be all the greater when the subsidy represents a non-negligible part of a farmer's income. In any case, this is what emerged for France, as well as for the UK, Italy and Germany over the 2000-2006 programming period (Arata and Sckokai, 2016). In addition to criticisms of AEM's unrestrictive nature, the low level of farmer participation is also seen as a failure of the scheme. With only a third of farms involved in the 2007-2013 programme (Zimmermann and Britz, 2016), farmer participation is much lower in France than in other European countries, such as Austria, Finland and Sweden (Pufahl and Weiss, 2009).

Causes of AEM shortcomings

In recent years, a number of studies have highlighted the consequences of low farmer participation in AEM, emphasising the fact that that below a certain number of hectares committed to a transition scheme, or in the absence of good spatial organisation of everyone's efforts, no significant environmental gain could be recorded (Dupraz *et al.*, 2009). In addition to the fact that most AECM schemes are limited to specific territories with high environmental challenges, such as water quality, many farmers in these territories choose not to participate.

In addition to the low level of participation, the implementation of AEM is beset by two serious problems (Lichtenberg, 2004). First, they are costly to administer on a large scale, because they require a monitoring system (and, where applicable, sanctions) to be established for each farm involved. Reducing the associated costs means defining contract specifications and eco-conditionality criteria based on elements that are simple to verify, which is a challenge in the case of pesticides because these products, like the crops for which they are used, are numerous and heterogeneous.

Second, the incentive power of AEM contracts is limited. Once farmers have complied with the conditions of the contract they have signed or which entitles them to the subsidy to which they aspire, they currently have no economic interest in continuing to further reduce their pesticide use (Carpentier *et al.*, 2005). Furthermore, by offering a single payment to a wide range of eligible farmers, the AEM scheme in fact selects mainly those individuals whose cost of changing practices is lower than the subsidy offered by AEM. In extreme cases, where the effort required of the beneficiary represents no additional cost, the AEM has the effect of subsidising farmers for doing nothing more than they would have done in the absence of the subsidy. This is known as the windfall effect. This is the case, for example, of farmers who receive a subsidy for planting nitrate-fixing intermediate crops, much of which would have been planted in the absence of any subsidy (Chabé-Ferret and Subervie, 2013).

Experimenting with new levers

The recent increased interest in experimental and behavioural economics has made it possible to develop and test policy and/or organisational innovations *in situ*, by mobilising the main stakeholders in the scheme in question, i.e. farmers themselves, and taking their preferences into account (Mamine *et al.*, 2020; Thoyer and Préget, 2019).

The innovations proposed aim to increase the impact of the scheme by raising farmers' participation rates and/or to improve its effectiveness in terms of changing agricultural practices, in particular reducing the windfall effects (Behaghel *et al.*, 2019).

Offering more flexible contracts

AEM have sometimes been criticised for their rigidity in the face of uncertainties linked to variations in market prices or meteorological instability. For example, work on the creation of pesticide-free buffer zones in Denmark showed that farmers demanded on average €128 more per hectare per year to accept five-year AEM rather than one-year ones (Christensen *et al.*, 2011). The same study also showed that they were willing to forego €137 per hectare per year for the possibility of breaking the contract at any time. In the same vein, a recent study showed that French winegrowers were willing to forego €114 per hectare per year for the possibility, one year out of five, of not respecting commitments to reduce herbicides and ensure grass cover in vineyard plots (Lapierre *et al.*, 2023). These results suggest that increasing flexibility in AEM contracts would improve their adoption (or reduce their cost), with the risk, however, of losing environmental effectiveness.

Encouraging coordination between farmers

In order to increase farmer participation in AEM while promoting a certain spatial coherence in the areas committed to them, proposals have been made to include specific premiums in AEM. These premiums would make it possible to take into account threshold effects or spatial requirements by integrating, for example, an "agglomeration bonus", i.e. additional remuneration for each plot that borders another plot already committed to an AEM (Vaissière *et al.*, 2018). Using premiums like this could encourage the creation of a biodiversity corridor or the protection of the entire banks of a watercourse (Banerjee *et al.*, 2014).

Another solution would be to offer AEM incorporating a "collective bonus", whereby farmers would be rewarded for their individual participation, but would also receive a bonus when a predefined target in terms of the total area committed was reached at the intervention's territorial scale, for example a watershed (Kuhfuss *et al.*, 2016). This proposal was tested with a sample of 300 French winegrowers, who took part in a hypothetical choice experiment designed to reveal their preference for this type of bonus, as part of an AEM subsidising the reduction of herbicide use. The results of this study showed that the introduction of the bonus had the effect of significantly increasing the probability of farmer participation in the scheme (Kuhfuss *et al.,* 2016).

Agri-environmental auctions

One way of improving the efficacy of AEM contracts would be to abandon the fixed payment system (where a single amount per hectare is offered to all farmers) in favour of an agri-environmental auction system (Ferraro, 2008; Thoyer and Saïd, 2007). In this type of system, farmers are invited to offer an environmental service contributing to the predefined objective (a reduction in pesticides, for example), and the amount they wish to receive for the service in question. The farmers' offers are then ranked on the basis of an environmental score and the amount requested. Finally, only the best bids are selected and paid the amount requested (Kuhfuss *et al.*, 2012). Here we are moving from a uniform payment system open to all willing farmers, to a system of so-called "discriminating" payments based on farmers competing for access to contracts. In this type of scheme, a farmer who is already performing well will have an interest in going even further in mastering the alternative practice.

This system offers several advantages over the current system of fixed payments. First, it makes it possible to change the practices of the most polluting farmers, who may ask for a high amount but whose change in practices is likely to generate a significant environmental gain. Second, it avoids paying farmers to adopt practices they would have adopted in the absence of an AEM (the windfall effect), since here the farmer is encouraged to reveal their true opportunity cost, i.e. a price close to the cost of the effort made (if farmers ask for more, they run the risk of not being selected). In the United States, 80% of agri-environmental payments are allocated in this way (Kuhfuss *et al.*, 2012). The first French experiment in agri-environmental auctions was conducted in 2010 by the Artois-Picardie water agency, in collaboration with the Chambers of Agriculture and the State services for the watershed (Kuhfuss *et al.*, 2012). The aim was to plant grass cover to improve water quality in areas with high environmental challenges (catchment areas). The AEM contracts were found to be more flexible and better adapted to each farm than traditional measures. However, the competition between farmers to win these contracts was sometimes poorly perceived, as farmers are used to the "box office" logic of AEM, where a correctly completed application is an accepted one (Kuhfuss *et al.*, 2012). This agri-environmental auction system is also likely to be mobilised for pesticide reduction (Behaghel *et al.*, 2019).

Exploiting peer effects

In the same vein as the collective bonus, other innovations have emerged aimed at exploiting the potential for coordination within a group of farmers, in order to increase participation rates in AEM. However, unlike the bonus, these innovations rely on non-monetary levers known as "social norms". So, when a farmer chooses to voluntarily contribute to an environmental public good, they may be driven by descriptive norms (which urge them to do the same thing as individuals in the group with which they identify) or by injunctive norms (which urge them to do what society expects them to do) (Le Coent *et al.*, 2021). Based on this observation, instruments known as nudges have been developed.

From an economic point of view, nudges are behavioural incentives that have an effect on human beings *via* the activation of cognitive biases or emotion-related behaviours, and not on the purely rational individual modelled by economic theory (Raineau, 2018). Applied to agriculture, nudges consist, for example, of communicating the number of farmers who have already implemented virtuous practices, such as better irrigation water management, in order to encourage other farmers to do the same (Chabé-Ferret *et al.*, 2019). Simple and inexpensive, these instruments can thereby modify individual behaviour without creating bans or subsidies. Nudges are also a way of encouraging farmers to renew their commitment to an AEM (Wallander *et al.*, 2017), or to maintain an environmentally friendly practice after an AEM has ended (Kuhfuss *et al.*, 2016). However, although these tools achieve good results in certain situations, their impacts on farmers' actual behaviour in a plan seeking to drastically reduce pesticide use have yet to be confirmed.

Key messages

Although AEM were conceived at a time when pesticide-free farming was not the objective, they are nonetheless a key public policy tool for supporting agroecological transition. However, it has to be said that this instrument, as currently defined, has a number of limitations that generally prevent it from achieving its environmental objectives. Several avenues of research have been opened up in recent years, aimed not only at increasing the rate of farmer participation in this type of scheme, but also at increasing their impact on farmers' practices. Four types of innovation are now considered as promising for building AEM to encourage the adoption of alternative practices to pesticides: those that make AEM more flexible, those that encourage coordination between farmers in their efforts to preserve the environment, those that exploit peer effects (i.e. social interactions between farmers in the same group with similar preferences), and those that strive to integrate the full diversity of farmer profiles into the definition of the proposed payment.

⏩ Taxation systems: how can we make them acceptable?

Given current production practices and market conditions, pesticide use is often the most profitable way for farmers to protect their crops, even if low-input management approaches can also be profitable. To reduce the profitability of pesticides, taxation is the preferred instrument. But to be effective, it must be implemented at a sufficiently high level and take into account the effects on farmers' incomes.

Taxation: strong incentives, but penalising for farm incomes

Taxation is an incentive instrument whose main interest is to reduce the profitability of using the taxed input, thereby encouraging the adoption of any available means (whether agronomic or technological) of reducing its use. This property is particularly interesting in the case of pesticides: as there are potentially numerous alternatives to pesticides, this instrument leaves farmers free to choose the solutions best suited to them. In theory, a tax on pesticides would encourage farmers to optimise their pesticide use, and should mechanically generate demand for alternatives to pesticides or for pesticide-saving production practices (Carpentier *et al.*, 2005). Taxes also have the advantage of being relatively inexpensive to implement on a large scale (Finger *et al.*, 2017), as they can be levied directly on domestic manufacturers, importers or distributors of pesticides. Unlike other instruments such as AEM, they do not require monitoring at the farm level and therefore generate few administrative costs. Given that French and European pesticide targets are now (almost) aligned[33], taxing pesticides on an EU-wide basis could be considered. This would have the advantage of not distorting competition between Member States. However, it could have an impact on the competitiveness of European agricultural products on world markets.

The main drawback of taxes is that they have a negative (and significant) impact on the income of the taxed sectors and the competitiveness of the goods they produce (Carpentier *et al.*, 1999). This is probably what makes pesticide taxation “unacceptable” today, both from the point of view of farmers and public decision-makers and explains why it is one of the least used economic incentive instruments for reducing pollution in practice (Finger *et al.*, 2017; Lefebvre *et al.*, 2015). Here, we find the limits of the polluter-pays principle as enshrined in European legislation. Finally, an argument often put forward against the introduction of a tax on pesticides is that an increase in pesticide prices would have little influence on pesticide demand, as their price elasticity is low (Pedersen *et al.*, 2020; Skevas *et al.*, 2013). Moreover, France’s general tax on polluting activities has not led to a reduction in pesticide use (Box 1.10). It should be stressed, however, that estimates on the elasticity of pesticide demand are most often short-term elasticities, assuming constant production practices and targets. However, current conventional production practices are technically dependent on pesticides and profound changes are essential if we are to do without them. Recent work tends to show that the demand for pesticides is more elastic once we consider that farmers have the opportunity to adopt practices that reduce their use (Femenia and Letort, 2016). Nevertheless, other explanations can be put forward, including farmers’ attitudes to risk (Box 7.7).

Box 7.7. Insurance: a substitute for pesticides?

One of the factors that could explain the massive use of pesticides is the desire of farmers, and the sectors in which they operate, to limit the risk of production losses as much as possible, as well as the desire to have clean fields and harvests. Pesticides help limit the damage caused by pests and therefore the economic risk linked with a smaller harvest. Depending on how risk-averse the stakeholders concerned are, they may decide to implement measures to limit these risks, such as increasing the dose or frequency of pesticide treatments and intervening in a preventive and systematic way (Carpentier, 1995). In this context, insurance is often seen as a potential substitute for pesticide use. By insuring their harvests, farmers would have an incentive to reduce the amount of pesticides applied, as losses due to pests would be compensated by insurance companies (Aubert and Enjolras, 2014). In addition, this could also facilitate the introduction of diversification crops, which are essential for reducing pesticide use, but which to date often suffer from more variable yields than major crops (Cernay *et al.*, 2015).

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[33] The farm to fork strategy of the European Green Deal, published by the European Commission in 2020 targets reductions in agricultural pesticide use similar to those set out in France’s Écophyto plans.

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Various types of insurance can be offered, such as yield insurance (known as crop insurance), or income insurance (less developed in the EU). In Italy, maize growers have successfully tested an insurance policy designed to compensate for production losses in the absence of insecticide (neonicotinoid) use (Furlan *et al.*, 2021). However, empirical evidence of the impact of insurance on pesticide use remains ambiguous and several studies have found that insurance does not lead to a decrease in pesticide use, but to an increase (Möhring *et al.*, 2020). This counter-intuitive phenomenon can be explained by the fact that insurance also influences land-use decisions: insured farmers are more inclined to opt for intensive production, which generally involves high pesticide use. So, the development of insurance as a tool for reducing pesticide use must be approached with caution (Möhring *et al.*, 2020).

Combining incentive taxation and redistributive compensation payments?

Is it possible to neutralise the negative effects of taxes on farmers' incomes (at least to a large extent), while retaining their incentive power to reduce pesticide use? Setting a low tax rate preserves farmers' incomes but has little effect on their pesticide use. Taxes can only be a real incentive if their rate is sufficient, which is not the case at present (Box 1.10). One solution would be to combine taxation with a system of redistribution of the proceeds to farmers themselves, making it fiscally neutral and having no impact on the income of the agricultural sector as a whole[34]. To be effective, this compensation system must have several features. Income support paid to farmers must not depend, or at least as little as possible, on the pesticides used by each farmer, so as not to counteract the incentive properties of the taxes. To this end, compensation amounts could, for example, be established on the basis of data on average pesticide expenditure per crop (to limit reductions in the acreage of the most pesticide-intensive crops), and taking into account the region (taking into account the influence of soil and climate conditions). The amount of the tax could also be increased progressively according to an announced timetable, so as to give farmers time to adapt their practices. This type of system would "reward" pesticide users below the regional average and "penalise" those above it. It would therefore benefit those at the forefront of pesticide reduction, by supporting their incomes, and actively constrain the heaviest pesticide users by having a negative effect on their incomes. It would make it possible to impose high levels of tax while preserving farmers' overall incomes and thereby encourage the most technically and economically efficient pesticide-saving practices.

Key messages

The aim of taxation is to encourage farmers to change their practices by reducing the profitability of pesticide use. Although inexpensive and relatively easy to implement, taxation must be set at a high level to be effective. As a result, it has the disadvantage

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[34] Bontems (2019) discusses the theoretical properties of a compensatory taxation scheme for polluting emissions and summarises recent literature on the subject. Bureau *et al.* (2019) analyse the interest of such a scheme for greenhouse gas emissions, highlighting the incentive role of taxes and the role of neutralising taxation-related income effects assigned to the tax revenue redistribution system.

of reducing farmers' incomes and limiting competitiveness on world markets. To neutralise these negative effects, one solution would be to combine taxation with distributive payments or income support. So as not to cancel out the incentive properties of taxes, these income subsidies could be calculated on the basis of data on average pesticide expenditure, taking into account crop type, and soil and climate conditions. Such a system would theoretically make it possible to impose high tax levels while largely preserving farmers' incomes. Other complementary levers, such as the plant protection product saving certificates CEPP scheme (Box 1.11), which promotes and encourages virtuous practices and mobilises economic stakeholders surrounding the farm, could be advantageously combined with taxation and redistributive direct payments (Huyghe and Blanck, 2017).

⏩ Food product differentiation: how can we increase the interest in pesticide-free products?

Although consumers have been showing a growing interest in labelled products for several years and declare that they are prepared to pay more for environmentally friendly products, currently only 6% of French household food purchases involve organically certified products (Agence Bio, 2020). A detailed understanding of how consumers value the "environmental attribute" is therefore necessary in order to identify the demand levers likely to be activated in the consumption of pesticide-free or zero-pesticide products.

Differentiation strategies and quality labels

Producers' adherence to an environmental certification programme can represent a value-generating differentiation strategy, and this can be an integral part of the diagnosis of the strategic advice provided to farmers. In fact, when there is a premium granted by consumers for an "environmental attribute" (e.g pesticide-free) and the premium offsets the extra cost linked to the production method induced, then it may be appropriate to differentiate products according to this attribute (Ambec, 2017; Bonroy and Constantatos, 2015). However, it is not always easy for consumers to monitor the actual implementation of sustainable practices by producers and the environmental attribute then remains a "belief attribute" that can generate a problem of trust on the part of consumers. To limit this asymmetry of information between producers and consumers, a number of eco-friendly labels have been developed. The development of digital tools is also helping to increase transparency by facilitating traceability from one end of a supply chain to the other: consumers can access product information by flashing a QR (quick response) code. Tools, digital or otherwise, are also used to score food products according to their nutritional qualities, or even their environmental impact (Soutjis, 2020). Although these ratings may be open to criticism, the inclusion of pesticide use in the final score could certainly encourage the consumption of pesticide-free products.

Consumers are not always willing to pay a premium for eco-certified products (Delmas and Grant, 2014) and the proliferation of environmental certifications is confusing for consumers (Brécard, 2014). It is important for environmental certification to be identifiable, understandable and trustworthy. This credibility differs from one certification body to another. More often than not, the downstream sector (i.e., processors and distributors) is not in the best position to certify the environmental characteristics of products and consumer confidence appears to be higher when certification is provided by a government body or a third-party certifier (Innes and Hobbs, 2011; Yokessa and Marette, 2019). The choice of certification type is therefore important. Furthermore, information campaigns on eco-certification or on the impact of pesticide use sometimes appear as a means of promoting sustainable practices; they require consideration of the attributes that consumers value through certification.

Pesticide-free products: what is in it for consumers?

Determining the value that consumers attribute to the environmental characteristics of food products can prove complex, as sustainable products are "impure public goods", i.e. they simultaneously generate public and private benefits (Kotchen, 2005). Consumer evaluations of environmental attributes can therefore stem from either selfish or altruistic motivations. First, the consumption of pesticide-free products may be linked to the private benefits generated by potential health advantages. Research has shown that the value attributed by consumers to organic products is partly linked to the recognised impact of consuming these products on their health (Loureiro, 2003). So, there is probably a positive correlation between consumer interest in the impact of pesticides on health and the price they are willing to pay for pesticide-free produce, at least for fresh produce (Florax *et al.*, 2005).

Second, the consumption of pesticide-free products can be linked to the public benefits generated by reduced environmental contamination. The consumption of pesticide-free products is beneficial for the population as a whole (e.g. by preserving resources for future generations by maintaining biodiversity etc.), but it relies on an individual effort (paying a higher price for pesticide-free products). This individual contribution, which does not lead to an immediate private gain, is therefore linked to pure altruism, defined as taking into account the expectations of others in a disinterested way (Fehr and Schmidt, 1999). This individual effort is also linked to the warm glow effect, whereby a donor increases his or her individual utility through the act of giving (Andreoni, 1990). In the case of pesticide-free products, the aim is to derive satisfaction from the fact of helping to preserve the environment. These two dimensions of environmental enhancement need to be considered when promoting certification, as the tools used will differ according to the type of consumer motivation. For example, while "no pesticide residue" certification guarantees consumers the absence of active substance residues and thereby responds to the search for increased health quality (private benefit), "pesticide-free" certification provides the additional assurance of the absence of environmental pollution linked to the use of pesticides (public benefit).

Taking into account consumer heterogeneity when adding value to products

Taking into account individual heterogeneity — preferences and motivations vary from one individual to another — is crucial to understanding how consumers value products. Certain characteristics, such as gender, age and education level, can be important determinants of an individual's sensitivity to an environmental attribute. Other elements also explain preferences, such as consumers' knowledge of sustainable development issues, their values (individualism/collectivism, surpassing oneself/self-improvement, altruism/selfishness etc.), or their personality traits (Peschel *et al.*, 2019). This fine characterisation of consumers would therefore make it possible to more specifically target information campaigns aimed at promoting sustainable agricultural practices (or environmental certifications).

Key messages

To promote pesticide-free practices among consumers, we need to establish certification based on precise specifications that reduce the asymmetry of information between consumers and producers. Advances in sensor technology (Chapter 6) could soon facilitate the monitoring and control of such specifications. The proliferation of environmental certifications can lead to confusion that diminishes the efficacy of these schemes. A rationalisation (by limiting or grouping together) of the number of certifications for pesticide-free production therefore seems necessary to make it easier for consumers to identify the specific features of each certification. Furthermore, the multi-dimensional aspects of food products (nutritional, environmental, sensorial etc.) can generate multiple and particularly complex decisions for consumers. While a pesticide-free product can be expected to generate greater value, the environmental dimension alone will not ensure this if it is at the expense of sensorial qualities such as taste or appearance.

⏩ Territorial collective dynamics: how can we encourage coordination among stakeholders?

In addition to standard environmental policy instruments such as subsidies, taxes, regulations and certification, other levers such as the self-organisation of stakeholders on a territorial scale are likely to be activated to encourage the transition to reduced pesticide use.

Unlike public action, which is based on coordination induced and administered by the State, collective action originates in the chain or territory and is generally not driven by the State. More often than not, the actors who initiate collective dynamics aim to develop alternative or agroecological cropping systems (Ploeg *et al.*, 2012). Even if these solutions have yet to be developed (Petit *et al.*, 2019), bottom-up collective action and territorial coordination represent an interesting way out of pesticide use.

The value of bottom-up collective action to get rid of pesticides: the example of resistant varieties

The recent development of disease-resistant varieties in France is an emblematic example (Hannachi *et al.*, 2021). While the use of pest-resistant varieties is an effective way of reducing pesticide use without reducing crop profitability (Loyce *et al.*, 2012), the mass use of the same resistant variety in a given area can lead to resistance failures (Rouxel *et al.*, 2003), sometimes resulting in increased pesticide use. To avoid this, it can be effective to coordinate the spatial diversification of cultivated varieties on a territorial scale (Fitt *et al.*, 2006).

Although never before envisaged to manage the problem of pesticides, such coordination has already been implemented in France to limit cross-pollination between non-erucic oilseed rape, producing oils for food use, and erucic oilseed rape, reserved for industrial uses and toxic if ingested (used in lubricants, detergents, plasticising agents etc.). Since the two types of oilseed rape are inter-fertile, to avoid harvesting erucic crops in fields sown with non-erucic crops and vice versa, an economic interest group (GIE Pollen), made up of seed companies, industrialists and inter-professional organisations, was created to manage the allocation of oilseed rape varieties on a territorial scale. In 2015, the scheme managed 20,000 hectares and 300 farmers through contracts and premiums that influence the choice of the varieties sown and introduce isolation distances between crops and rotations of varieties over time. In the specifications, quality thresholds and premiums refer to the idea of farmers' "collective responsibility", suggesting that the system in place is more than the sum of individual actions, but involves collective interdependencies and resources (Hannachi *et al.*, 2021).

If these stakeholders already have such collective arrangements in place, why do they not consider them for the territorial management of resistant varieties and the phasing out of pesticides? The first reason is the absence of sufficiently strong incentives and advantages to preserve the sustainability of resistant varieties and establish territorial coordination. In the case of oilseed rape, by coordinating their efforts, actors manage to collectively create added value, which is shared between stakeholders through premiums linked to results or the pooling of the means of production. These bonuses also help to offset the additional costs generated by coordination efforts. The second reason is linked to the low visibility of collective interests: in the case of resistant varieties, stakeholders are unlikely to be able to identify strong enough collective advantages to motivate them to build a collective strategy. Finally, unlike the situation of the coexistence of oilseed rape varieties, the management of varieties to avoid losing resistance is based on a tension between an organisational cost today and a benefit for tomorrow.

Promoting coordination and creating collective territorial dynamics

The emergence of bottom-up collective action necessarily involves interactions between stakeholders, enabling individual interests to be transformed into collective ones. Such interactions can be facilitated by the use of mediation tools, such as action research workshops. In 2016, an action research workshop was organised to work on the issue of oilseed rape varieties resistant to phoma, one of the crop's main diseases (Hannachi et al., 2021). The various actors in the sector explored the benefits and ways to set up their own organisation for the collective management of resistant varieties. They then realised that this organisation could be less difficult than expected. The workshop facilitated collective action by calling for the social construction of common interests. For the first time, all the breeders marketing oilseed rape seeds in France decided, despite the competitive nature of the business, to create a group to discuss monitoring and coordinating the deployment of resistant varieties in French territories. A transdisciplinary research programme bringing together breeders, Terre-Inovia and INRAE was signed in 2020. This programme, known as Club Colza, is due to last 10 years and will explore the development of monitoring tools and coordination methods.

However, the emergence of self-organisation depends on certain conditions. The first is the need for new interactions to be established in "organisational ecosystems", such as Club Colza, which bring together a diversity of actors who are already organised to some degree. When it comes to these common-good issues, the State can play a facilitating role, supporting self-organisation. State involvement is sometimes necessary to bring together, mediate and build trust between economic stakeholders who are often competing for market share. Such developments are already underway and have proved effective, including in the case of sustainable disease management in agriculture (Charrier *et al.*, 2020). The second condition is the importance of considering actors' rationales as human and evolving. It can be difficult for some actors to consider the environmental impacts of their decisions when these impacts are not included in their individual cost-benefit calculations. To remedy this, it is important to develop tools that make visible problems that can be resolved through collective commitment, enabling stakeholders to evolve their rationales and better take into account their interdependencies. In the case of varietal resistance, there are currently resistance monitoring tools developed by agricultural technical institutes and private companies, but these tools only help individual decision-making (at the level of the variety, not the territory). To encourage transition, it might be worthwhile developing collective tools that go beyond the individual scale of the farm and explore collective strategies in territories. In this respect, action research through companion modelling, which involves the use of multi-agent models and multi-actor role-playing games as tools for representing and simulating the functioning of socio-ecological systems on a territorial scale, is a promising prospect (Poggi *et al.*, 2021). Finally, it is important that the new organisational ecosystems be multi-actor, linking the upstream and downstream sections of the value chain (Thomas *et al.*, 2020).

Key messages

The coordination of farmers and collective dynamics within territories represent interesting, and sometimes indispensable, levers for moving away from pesticide use. By coordinating on a territorial scale, farmers and other stakeholders are likely to develop innovative and effective solutions to problems that require management on a scale beyond the individual. A new role is therefore possible for collective economic structures such as cooperatives (Hannachi *et al.*, 2020). To achieve this, tools are needed to help the various stakeholders understand their respective constraints and find common solutions, moving beyond the individual scale and promoting collective strategies. However, such initiatives need organisational ecosystems to emerge and develop. In this respect, the State is likely to play a role, moving from prescribing standards to inducing collective dynamics (Box 7.8).

Box 7.8. FAST research project: facilitating public action to move away from pesticides (2020-2026, financed in the frame of the Priority Research Programme "Cultivating and Growing Crops Differently")

The transition to pesticide-free agriculture can be fostered by various public and private initiatives, the details of which have yet to be determined. The FAST research project aims to provide a theoretical framework and solid empirical evidence for the effectiveness of various public actions aimed at triggering a large-scale transition to pesticide-free agriculture. To this end, research is being carried out into the potential barriers and facilitators to this transition. In particular, work is being carried out on the spatial and collective mechanisms likely to encourage a sharp reduction in pesticide use. New economic instruments are also being developed and tested, through both modelling and field experiments. This approach will allow FAST to propose concrete solutions (political and organisational), directly usable by public decision-makers and stakeholders, whose effectiveness is assessed using different approaches, such as experimental economics or action research, as well as large-scale simulation models (INRAE, 2024b).

⏩ Conclusion

A transition to pesticide-free agriculture does not rely solely on the development of technical solutions. It also requires the implementation of policy and organisational innovations to enable and foster the adoption, adaptation and large-scale deployment of alternatives to pesticides. Various types of policy instruments have been designed and used to date to reduce pesticide use — mainly bans of molecules, agri-environmental contracts, taxation and technical support — with a limited ambition in terms of reduction, as the fruit of negotiations between stakeholders, and have had mixed success. However, there are many ways of improving the effectiveness of these measures and, theoretically, there are many other instruments available.

Training and support systems for farmers wishing to adopt alternative practices already exist, but could be considerably improved by funding farm advisory services geared towards more strategic advice for system redesign, more ambitious training in agroecology and the involvement of various stakeholders in the value chain and territory. The regulatory framework is also likely to be improved, in the sense of greater transparency in the approval of plant protection products, to support the stated European strategy "From Farm To Fork" and also by defining a genuine status for alternatives to synthetic pesticides or, more precisely, for crop protection alternatives. The effectiveness of voluntary schemes such as AEM are historically weak and likely to be improved through a variety of innovations, currently considered to be best practice: more flexible contracts, payments that encourage coordination between farmers, payments that exploit peer effects, or payments that allow farmers to be remunerated according to their actual efforts. A pesticide taxation system, combined with a system to compensate for the effects of the tax on incomes, would be able to act as the driving force behind an effective policy to reduce pesticide use and, ultimately, to phase out pesticides by affecting all farmers. The creation of new standards in the food sector, too, would be a powerful lever for transition, giving real visibility to pesticide-free products. Finally, the collective dynamics that already exist in certain chains, and which aim to go beyond the individual scale of the farm to build solutions on the scale of an entire territory, also constitute a promising means of action. This may involve, for example, redesigning the supply of food to mass caterers, or setting up territorial food projects (known as Projets Alimentaires Territoriaux in France) aimed at establishing sustainable agriculture in local areas. While none of the current PAT have a pesticide-free objective, many of the 197 schemes awarded the label to date are based on organic farming and, furthermore, are concerned with reducing the impact of local food production on the environment. Further research is now needed to analyse the feasibility and assess the potential economic and environmental impacts of these new political and organisational levers.

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General conclusion

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This book sets out the current knowledge on the factors that explain the massive use of pesticides and develops priority areas of research to achieve pesticide-free agriculture while ensuring crop protection for a safe and affordable food to all. A series of chapters, each focusing on a different area of action, helps us to grasp the complexity of such a change and the need to give priority to global and systemic approaches. Avoiding synthetic pesticides, or those that have a significant impact on the environment, is an ambitious but necessary step if agriculture is to meet the challenges of preserving the environment and public health, producing goods in sufficient quantity and quality, and ensuring the economic viability of farmers and their businesses. Agriculture has to meet these objectives in a context of global change and food transition. This shift will require scientists from different disciplines to work together, as well as a profound change in research paradigms. New and extremely fertile research fronts have been described in this book. But beyond research, it is society as a whole and actors in the agricultural world who are concerned by the necessary change in strategies and behaviours. The summary presented in this book focuses on French agriculture, and is based on research results and projects run all over the world with some focus on projects of the French Priority Research Program “Growing and Protecting Crops Differently”. The goal of pesticide-free agriculture requires the necessary collaboration on a European and international scale. It must also be considered in conjunction with other major issues affecting the redesign of farming and food systems: climate change, biodiversity restoration, preservation of water resources and soil fertility, and food security.

⏩ Pesticide-free as a new paradigm for research

Various strategies for drastically reducing pesticide use are outlined in the chapters of this book. They are based on agronomy, biocontrol, plant breeding, agricultural equipment, as well as policy and market levers. Although we have chosen to present the challenges successively by theme, it is important to again emphasise that it is through combined actions from these different fields that effective solutions are most often found. For example, advances in biocontrol must be considered in conjunction with the redesign of cropping systems and the breeding of new varieties. At the same time, innovations in processing and marketing channels need to make these solutions more attractive to farmers and consumers alike. Each chapter thus represents a component of an overall strategy for phasing out pesticides, generating research priorities and needs in distinct but complementary scientific fields and disciplines.

To drastically reduce pesticide use in agriculture, we argue that research must be conducted within a framework that excludes the use of pesticides. This means exploring all research fronts, starting from the target point through a back-casting approach, rather than seeking to modify what already exists through an incremental approach. This marks a paradigm shift from a gradual reduction in pesticide use to a breakthrough or rupture, and a rethinking of crop protection, in which prophylaxis, and hence the reduction of pest pressure, plays a central role. This change of direction allows us to explore unprecedented research fronts, with the potential for transformative innovation. But it also forces us to rethink the ways in which research collaborates with the actors involved in this change, from farmers to upstream and downstream companies. The search for solutions adapted to local contexts and territories is also a necessary condition for this change and requires new participatory research practices.

In this book we have not dealt with the consequences of this new strategy for the organisation and operation of the research and innovation system itself. Without going into the subject in depth, we believe that researchers will only be able to pursue these new avenues of research if the organisation, incentives and funding of research are rethought with this objective in mind. For example, long-term project funding must be encouraged to enable interdisciplinarity, risk-taking and sufficient investment in both basic and participatory research topics. Researchers themselves must also be encouraged to become involved in the process of designing solutions, helping them to prioritise the knowledge they need to produce in order to contribute to the innovation process (Toffolini *et al.*, 2020). The Priority Research Programme "Growing and Protecting Crops Differently" was designed with this long-term philosophy in mind[35].

⏩ Pesticide-free: an international issue that affects all stakeholders in agricultural and agrifood chains

This book is deliberately focused on French agriculture and therefore addresses the issue of becoming pesticide-free on a French scale. This choice was made to better illustrate the challenges of this change for French agriculture. However, it is important to emphasise that maintaining the competitiveness of French agriculture on a European scale requires that the whole European agricultural sector simultaneously commits to the objective of drastically reducing pesticide use. It was with this in mind

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[35] The projects selected are funded for an unprecedented six-year period, compared with the usual three years in other calls.

that the European Green Deal was launched in 2020, providing a particularly conducive framework for a far-reaching transition in crop protection in all European countries. Research to develop pesticide-free agriculture will require the collaboration of researchers from many countries, particularly in Europe, as it will require the mobilisation of all the skills scattered across the EU and beyond and the pooling of resources. A transition to pesticide-free limited to France makes no sense from the point of view of the expected environmental impacts because the restoration of biodiversity cannot be considered on the scale of a single country. Against this backdrop, a European research alliance was created in 2020 to promote the emergence of European projects based on what has been undertaken as part of the French Priority Research Programme “Growing and Protecting Crops Differently”. This European Alliance, entitled “Towards a Chemical Pesticide-Free Agriculture”, has brought together 37 research organisations in 21 European countries. It aims to contribute to a sustainable European agricultural and agri-food system, free from synthetic pesticides or from those that have a significant impact on the environment, through the development of interdisciplinary research and innovation programmes (INRAE, 2024).

Developing pesticide-free agriculture will have an impact on all actors in the agricultural and agri-food sectors. As explained in the first chapters of this book, the use of pesticides does not depend solely on technical and economic factors that are intrinsic to farming operations, but is also linked to the organisation and operation of the supply chain. Over the past few decades, the various players upstream and downstream of agricultural production have effectively adapted their activities and strategies to the low-cost availability of pesticides. A drastic change of objective therefore requires a commitment from all actors in the agricultural sector, who will have to innovate to change their strategy and adapt their activities to the new requirements inherent in new production methods. This change goes beyond the practices of farmers, who are only one link in this long and complex value chain. Consumers will also have to change their practices and consumption habits. Targeted and appropriate public policies will be essential to support and encourage these actors to change, and a number of possible measures have been presented in this book. In addition to support for farmers, upstream and downstream companies will certainly need support during the transition phase, to enable the innovation needed to create new value chains. As far as consumers are concerned, it would be illusory to offer the same products at the same low prices as today. The development of new food habits will be paramount, combined with a real consideration of the economic constraints of some people, in a spirit of fairness for access to quality food. Nevertheless, these radical changes also bring opportunities: offering consumers new products thanks to the new varieties and crops being developed, to have a healthier and more diverse diet, or to be more autonomous in running a farm without certain inputs and ensuring the supply of new ecosystem services. In the end, pesticide-free agriculture is as much a social choice as a technological challenge, and can prove profitable for the greatest number of people. Designed to ensure the supply of common goods in the same way as the production of private goods, pesticide-free agriculture provides an indispensable service to future generations.

Finally, the question arises as to the risks incurred by farmers during such a major transition. In systems designed to dispense with chemical protection, based on natural regulations and effective prophylactic measures, the risks of crop loss are controlled much more effectively than in conventional systems in which pesticides are eliminated. However, in a pesticide-free approach, the risk of insufficient pest control remains, particularly during the implementation phase of new practices and the recovery of high levels of biological regulations. If farmers are to make a lasting commitment to this approach, they need to be able to cover this risk financially. To achieve this, it is possible to develop insurance or actuarial systems, provided that the risk is not systemic and that each farmer has used all the practices suited to his/her situation.

The necessary transition in crop protection relies heavily on the restoration of biological regulation at the scale of agricultural plots, farms and landscapes, once again mobilising all the innovations that research will make possible. What is uncertain, however, is the speed with which agricultural environments will regain these regulations. After decades of pesticide use, residues of these products persist in soils, even when grown using organic methods, this is what Riedo *et al.* (2021) call "the ghost of the conventional agricultural past".

⏩ Thinking pesticide-free alongside other challenges in sustainable agriculture

The ambition to be pesticide-free is part of a broader vision of a more sustainable agriculture, from an environmental, economic and social points of view, meeting both present challenges and needs of future generations. From this point of view, plant health, like biodiversity, can be thought of in terms of a common good, for which our responsibility towards future generations requires us to take ambitious actions now in order to preserve it. However, the use, or lack of use, of pesticides has an impact on other major issues. At first glance, the fight against climate change may appear to contradict certain pesticide-free practices. For example, mechanical weeding as currently practiced generates potentially more greenhouse gas emissions than pesticide use. However, this is only a partial view, since to effectively grow crops without pesticides, an in-depth rethinking of the cropping system is most often necessary, involving, for example, the increasing plant cover and modified landscape structure which stores carbon. The increased frequency of extreme weather events due to climate change could also complicate the implementation of pesticide-free strategies. For example, particularly mild and humid conditions lead to heavy attacks of mildew in viticulture, which currently can be very difficult to manage without the use of synthetic fungicides or copper sulfate. The development of effective prophylaxis combined with advanced epidemiological surveillance can limit this phenomenon in well-designed pesticide-free systems. In all cases, strategies for restoring biodiversity will need to take climate change into account.

Climate transition means a change in temperature patterns, with a tendency towards a global average increase and greater inter-annual variability. But it also has a major impact on rainfall patterns and water availability. France, and more broadly Western Europe, is currently characterised by a temperate climate with significant rainfall distributed throughout the year. As a result, with the exception of a few spring-seeded crops and specialised crops, most crops are rainfed and irrigation is limited, essentially being used for adjustment purposes. However, climate scenarios point to a change in rainfall patterns, with a reduction in water availability in summer and an increase in rainfall in autumn and winter, accompanied by an increase in evapotranspiration due to higher average temperatures and an increase in extreme storms. This uncertainty about rainfall patterns adds complexity to the changes of cropping systems. Indeed, water availability is essential for the introduction of new species into production systems for diversification purposes, as well as for the establishment of relay cropping systems, and the installation of service plants and intermediate crops likely to improve pest management. Reflections on a move towards pesticide-free production systems therefore need to consider the issue of water availability to ensure that pesticide-free systems can be implemented, while taking into account the diversity of local conditions across France.

In addition to water, the use of mineral fertilisers must also be questioned. The strategy we have developed in this book, which focuses on pesticides, has consequences for the use of synthetic fertilisers, particularly nitrogen and phosphate. We know that synthetic fertilisers, which are massively used in conventional agriculture, enable us to achieve the yields and yield regularity that we currently have. But synthetic fertilisers are derived from non-renewable resources: nitrogen fertilisers are obtained from natural gas, while potassium and phosphate fertilisers come from rock deposits whose availability is dwindling and which, being found in a very small number of countries worldwide, gives rise to strategic insecurity. Failure to take these factors into account would call into question the sustainability of an approach in which the removal of pesticide use is targeted in a way totally independent of fertilisation management. So, unlike organic agriculture, the pesticide-free agriculture we propose will continue to use synthetic fertilisers, but this use is set to decrease. As highlighted in Chapters 3, 4 and 5, the design of pesticide-free agriculture must be accompanied by changes in practices and systems with regard to fertiliser requirements. On the one hand, cropping systems need to incorporate more legumes, which fix nitrogen from the air symbiotically, thereby limiting the need for nitrogen fertilisers, and species such as lupin, chickpea and buckwheat, which have particular ways of mobilising the insoluble phosphorus that is present in our soils. On the other, plant breeding must identify varieties capable of better exploiting nutrients within organic complexes (present in soil, manure or slurry) and of interacting with their biotic environment for defence purposes, instead of selecting varieties solely on their ability to exploit nutrients from fertilisers and water per unit of biomass. Finally, by giving a major role to soil quality for better protection against telluric parasites, pesticide-free agriculture also helps to increase soil fertility, which also has the added benefit of increasing carbon storage. Therefore, even if the aim of pesticide-free farming is not to stop using synthetic fertilisers, it is part of an overall strategy to reduce their use and make farms more autonomous with regard to these inputs.

Finally, the perspective of pesticide-free production raises the question of global food security. One of the potential weaknesses of developing pesticide-free systems is the reduction in yields, which could undermine agriculture's ability to feed the world. Although the use of synthetic fertilisers limits this phenomenon compared to organic agriculture, it is unlikely that the current yields of certain crops, such as wheat, which are currently grown very intensively, will be maintained without pesticides. But to simply stop at this observation means that we are thinking in terms of a constant system, with the ambition of producing the same agricultural products at the same places. In a logic of redesign, however, this hypothesis is discarded and there is the possibility of producing other crops and other species. Contrary to the assumption of lower production, the combination of crops, the introduction of service plants and relay cropping with several crops produced in the same plot in the same year, make it possible to envisage increasing biomass, energy and protein production. Pesticide-free farming will also have an impact on the types of crops produced. This will undoubtedly lead to a reorientation of trade flows for certain crops with, for example, a reduction in the dependence on imports for grain legumes due to their increased inclusion in crop rotations. In fact, the move towards pesticide-free farming raises the question not only of how we want our agricultural model to evolve in the 21st century, but also of how we want our food systems to evolve. Changing consumption habits and relocating processing chains are therefore key levers for pesticide-free agriculture. Hence, while research into pesticide-free farming represents a paradigm shift in crop protection, it is also part of a wider process of profound change in agricultural and food systems, essential for truly sustainable development, capable of meeting the food, climate and biodiversity challenges facing both present and future generations.

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Acknowledgements

The editors and authors are grateful to Myriam Tisserand, manager of the Priority Research Programme "Growing and Protecting Crops Differently", for her help in finalising this book.

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Publication: Aude Boufflet
Layout: EliLoCom
Print: XXX
Legal deposit on publication : XXX

The use of chemical pesticides is a major societal concern due to their negative impact on the environment and health. The French Priority Research Programme "Growing and Protecting Crops Differently", led by INRAE, has a structuring role in the evolution of scientific communities and in the emergence of scientific fronts enabling pesticide-free crop protection. The aim of this book is to explain the foundations of this strategy and the principles for action. On a course to pesticide-free agriculture, research is attempting to overcome current obstacles and produce breakthrough innovations in the biotechnical and socio-economic fields.

In addition to research, teaching and the agricultural sector, this book also targets actors in innovation, development and advisory services.

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39 €
ISBN : 978-2-7592-3994-8

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Éditions Cirad, Ifremer, INRAE
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ISSN : 1777-4624
Réf. : 02972