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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

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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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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.

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