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REVIEW ARTICLE

Pesticide-free agriculture as a new paradigm for research

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Abstract

Reducing pesticide use has become a goal shared by several European countries and a major issue in public policies due to the negative impacts of pesticides on the environment and on human health. However, since most of the agri-food sector relies on pesticides in these countries, substantially reducing pesticide use is a complex issue. To overcome this situation, we argue that agricultural research has a major role to play and must adopt a pesticide-free paradigm to expect a deep impact on pesticide use. In this article, we explain why this new paradigm is needed and outline research fronts that it will help address. These research fronts are related to five strategies: (1) redesigning cropping systems to enhance prophylaxis, (2) diversifying biocontrol strategies and associated business models, (3) broadening the scope of plant breeding to include functional biodiversity and evolutionary ecology concepts, (4) setting new goals for agricultural machinery and digital technologies, and (5) supporting development of public policies and private initiatives for the transition toward pesticide-free agri-food systems. The corresponding research activities must be managed conjointly to develop systemic and coupled innovations, which are essential for reducing pesticide use significantly. We therefore provide examples of cross-cutting objectives that combine these fronts while also highlighting the need for interdisciplinary research projects. By doing so, we provide an overall orientation for research to achieve sustainable agriculture.

Keywords Cropping systems · Biological control · Microbiome · Breeding · Epidemiological surveillance · Digital agriculture · Collective action · Pest regulation · Mission-oriented research

Contents

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1 Introduction

Today, pesticides have become the cornerstone of the predominant agricultural systems (Popp et al. 2013). In the European Union (EU), pesticide sales reached 370 million kilograms in 2018 (Eurostat 2020a). The pesticides sold the most (by mass) are fungicides (46%), followed by herbicides (35%) and insecticides (11%) (Eurostat 2020a). Pesticides and other technological advances of the Green Revolution enabled farmers to drastically increase crop yields and countries to improve food security (Cooper and Dobson 2007; Hedlund et al. 2019). However, reducing pesticide use has become a goal shared by several countries and a major issue in public policies (Barzman and Dachbrodt-Saaydeh 2011; Lee et al. 2019) since negative impacts of pesticides on the environment and on human health have been demonstrated unambiguously. First, pesticides are considered to be one of the major drivers of the decline in biodiversity due to the exposure of non-target organisms in cultivated areas (Geiger et al. 2010; IPBES 2016; Sánchez-Bayo and Wyckhuys 2019). Second, soil and water have been contaminated in the long term due to off-target movement of pesticides (Pietrzak et al. 2019; Pelosi et al. 2021). Third, pesticide residues, detected in many food products and present in the air, represent a critical issue for human health, especially since the "cocktail effect" (i.e., chronic exposure to several substances, including endocrine disruptors) is not yet well understood (Fantke et al. 2012; Panseri et al. 2019).

The first policies to reduce pesticide use appeared in the 1980s in Denmark; they were then developed more extensively in the EU from the 2000s (Pedersen and Nielsen 2017). In 2009, EU Directive 2009/128/EC encouraged implementation of integrated pest management (IPM) strategies, but did not set quantitative reduction targets: each member state had to set objectives and the means to achieve them through National Action Plans (European Parliament & Council 2009). Although member states set a wide variety of actions, their objectives converged toward reducing environmental risk rather than decreasing pesticide sales, since risks vary according to a pesticide's active substance(s) and how it is applied (Barzman and Dachbrodt-Saaydeh 2011).

Despite these initiatives, however, progress in reducing the risks of pesticide use has been limited (European Court of Auditors 2019). Pesticide use in the EU even increased by 11% from 2010 to 2018 (FAOSTAT 2020). To explain this failure of pesticide policies, several reports mention a lack of proper indicators to monitor pesticide use and little implementation of agronomic principles to reduce pesticide use, such as IPM (European Court of Auditors 2019; RISE Foundation 2020). A lock-in of the entire agri-food chain around pesticide-based systems was also identified, which explains the great difficulty that many stakeholders, including farmers, have in changing their activities due to interconnected obstacles (Guichard et al. 2017; Lechenet et al. 2017; Möhring et al. 2020a). Meanwhile, scientific evidence has accumulated and fueled public awareness of pesticide risks (Schaub et al. 2020). Today, the EU has strengthened its ambition and placed pesticide reduction at the center of its objectives. The Green Deal goal of the EU includes agriculture-related objectives, particularly concerning pesticide use and nitrate losses (European Commission 2020a). Regarding pesticides, it has set an objective of reducing current pesticide use by 50% by 2030. A recent report highlights that this target is unlikely to be reached in light of current trends (Guyomard et al. 2020). Indeed, profound and disruptive changes in the entire agri-food sector are necessary to achieve this goal, from cropping systems to value chains. Agronomic, technological and organizational innovations must be developed along with appropriate economic incentives (Guyomard et al. 2020).

Therefore, the social, economic, and technological conditions that favor strong reduction in pesticide use are questioned: do we have the knowledge and means to reach zero-pesticide? What knowledge is lacking to be able to avoid using pesticides? How should farmers and the entire agri-food chain adapt their activities? What is the role of research in making this radical change possible?

To achieve the zero-pesticide ambition, and unlock the entire agri-food chain, we argue that agricultural research has a major role to play by developing original research fronts. This assumption falls within the approach of several research initiatives, in particular the French Priority Research Program "Growing and protecting crops differently" and the European Research Alliance "Towards a Chemical Pesticide-Free Agriculture" (https://www.era-pesticidefree.eu). These initiatives propose a new goal for agricultural research to produce the knowledge (including the methods and tools) needed to target pesticide-free agriculture by 2040. Indeed, many research programs in the EU aim to reduce pesticide use to differing degrees. However, by remaining in a framework in which pesticides are still a solution, it is difficult to initiate a paradigm shift for research, which is essential for radical innovations to emerge. In contrast, our goal for research, and the agricultural sector in the longer term, is to stop using pesticides (Fig. 1). Moving from curative crop protection to prophylaxis and pest regulation based on agroecological principles and targeting the entire upstream and downstream value chains are the basic principles of this new goal. Here, the term "prophylaxis" covers all the means other than chemical pesticides implemented to prevent the appearance or development of pests within the crops. It is the main possible strategy for growing without pesticides, since it precisely aims to reduce the pressure that pests exert on crops. In this article, we (1) argue for the need for research oriented toward zero-pesticide use, (2) identify key research fronts required to manage crop health

Fig. 1 Introducing flowerbeds at the edge of the field makes it possible to reproduce semi-natural habitats that are rich in plant biodiversity and offer habitat and trophic resources to the auxiliaries; this during a large part of the year, especially during periods when there is no more culture in place. By keeping the auxiliaries in these strips, farmers enable them to more easily play their role of natural pest control in neighboring plots, provided that the practices on these plots be well thought out. Photograph by Stéphane Cordeau (INRAE, plateforme CA-SYS).

without pesticides, and (3) propose scientific challenges that enhance synergies between these fronts. Throughout this article, we use "pesticide" to refer to "chemical pesticides," defined as synthetic or natural pesticides that have a negative impact on the environment and human health (including some products used in organic production or for biocontrol).

Section 2 describes the current obstacles to reducing pesticide use, the strategies already implemented to reduce it and why it is necessary to set a pesticide-free objective to advance research. Section 3 presents research fronts related to this transition, while Section 4 identifies cross-cutting challenges. The conclusion summarizes our points.

2 Why does agricultural research need to set a pesticide-free target?

2.1 The current agri-food chain greatly depends on pesticides

In Western countries, each part of the agricultural sector, from farms to marketing channels, relies on the use of pesticides (Cowan and Gunby 1996; Wilson and Tisdell 2001). After 1945, the objective of increasing agricultural production led to intensification of agriculture based on a strong increase in the use of mechanization, fertilizers, and pesticides. High-yielding varieties, pesticides, and fertilizers allowed the development of farming systems based on sowing a less diversified range of crops at higher densities, which often led to an increase in pests (used hereafter to refer to all undesirable insects, fungi, weeds, and pathogens). In this context, pesticides provided effective crop protection against pests and thus contributed to the success of this transformation of agricultural systems (Meynard and Girardin 1991; Delecourt et al. 2019). The intensification of agriculture, enabled by pesticides, fertilizers, and mechanization, has increased productivity per hectare and per worker, and has been associated with an increase in farm size, to the detriment of biodiversity (Ricciardi et al. 2021). Farming systems have become more specialized and simplified, which led to a decrease in natural regulations and an increase in pesticide use to control pests. The dependence of these systems on chemical inputs has thus progressively increased.

The widespread use of persistent and systemic pesticides has become one of the main drivers of the decrease in ecosystem services and natural pest control, which fosters the use of even more pesticides (Meehan et al. 2011; van der Sluijs 2020). In parallel, the development of pesticide resistance, related to their high use, has also led to an increase in their use. These two trends have resulted in the emergence of a "pesticide treadmill" (Bosch 1989; Bakker et al. 2020). Related to the simplification of cropping systems, pesticides are currently the main tool used to decrease the risk of production losses (Chèze et al. 2020). In addition, the increase in farm size and the decrease in the relative share of family labor in relation to land and capital has continued throughout the last decades and resulted in an increasing recourse to external workforce. The low share of family labor in total labor force and the use of contract work are often accompanied by a greater use of pesticides (Nave et al. 2013). The objective of maximizing yield, which is not always led by economic rationality, can also contribute to high levels of pesticide use (Pedersen et al. 2012). In addition, peer judgment, seen as norms, has an influence since farmers' reduction of pesticide use appears to be influenced strongly by whether other farmers also reduce (Stallman and James 2015; Bakker et al. 2021).

Upstream and downstream sectors have been organized to facilitate and benefit from the intensification of agriculture, leading to a technological lock-in around pesticide use (Wilson and Tisdell 2001). Agricultural machinery companies and plant-breeding firms have focused their efforts on technologies and species that are suitable for intensive production systems (Beus and Dunlap 1990; Fitzgerald 2008). The varieties selected and sold are those whose characteristics allow processing technologies to be optimized, without necessarily considering their sensitivity to diseases (Nuijten et al. 2018). Since companies that sell pesticides are farmers' main advisors for using pesticides, they tend to encourage pesticide use in their marketing and distribution strategies (Wilson and Tisdell 2001). Furthermore, extension services remain dominated by approaches oriented to finding one solution to each problem, with little emphasis on systemic approaches that address a set of problems or propose changes in several aspects simultaneously. In addition, the lack of value chains for new crops that would help diversify crops is often identified as a main obstacle to agroecological transition and pesticide reduction (Meynard et al. 2018). Beyond this issue, the lack of creating added value across all sectors is the factor that limits implementation of pesticide-free practices the most. Since the products from these practices are not sold at higher prices that conventional ones, farmers have no incentive to implement them. In specific sectors (e.g., fruits and vegetables), implementing pesticide-free practices can also be compromised by market demands for undamaged products (Skevas and Lansink 2014). Undoubtedly, the market does seldom consider the impact of pesticides on human health or the environment (Becker 2017).

2.2 Limits of current strategies to reduce pesticide use

Two main consistent strategies for reducing pesticide use currently exist: IPM and organic agriculture. IPM is the cornerstone of EU policy to reduce pesticides (European Parliament & Council 2009). In the EU definition, IPM aims to combine "all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms" and "encourage natural pest control mechanisms" (European Commission 2017a). The EU has supported the research and implementation of IPM through National Action Plans (European Commission 2020b), based on the idea that pesticide use can be substantially reduced by developing IPM at a large scale (Lamichhane et al. 2015). In this context, research efforts have focused on developing alternative pest control methods and optimizing pesticide use through smaller doses (Barzman and Dachbrodt-Saaydeh 2011). However, this strategy has not been effective since pesticide use has not decreased in the EU (FAOSTAT 2020). Several factors can explain this strategy's low impact (Deguine et al. 2021). First, there is a lack of added value for the sectors that implement IPM, which does not increase the value of products for farmers. Second, there is a wide range of IPM-based practices, from "light IPM" to "strong IPM," and farmers often adopt only parts of the spectrum of IPM principles (Lefebvre et al. 2015). However, since IPM practices have only partial effects, it is necessary to combine several of them and seek to optimize their synergies to achieve substantial effects on pests. Until now, the dominant food system has implemented a "weak" ecological modernization process within agriculture. However, to both feed the world and strongly decrease the environmental impacts of agriculture, agro-ecological approaches should require a "strong" move toward a new type of regionally embedded agri-food eco-economy, thus requiring disruptive technical changes in agriculture (Horlings and Marsden 2011).

In comparison, organic agriculture clearly reduces pesticide use since it prohibits the use of synthetic fertilizers or pesticides, while maintaining soil fertility and closing nutrient cycles (Reganold and Wachter 2016). Organic agriculture represents a growing sector in the EU: the area of organic farmland increased by 74% from 2008 to 2018, but it still covers a small percentage of all farmland (8% in 2018) (Eurostat 2020b). Organic systems still tend to have lower yields than conventional systems (Seufert et al. 2012), even though they are offset at the farm scale by the higher prices of certified organic products, lower input use, and agro-environmental premiums in some countries. In addition, some technical issues, especially those related to weed management, are not yet fully solved. Depending on the type of crop production, organic systems can also have more variable yields, which increases risks (Lesur-Dumoulin et al. 2017; Knapp and van der Heijden 2018; Smith et al. 2019). Finally, certain products authorized for organic production can be harmful to the environment, such as copper, which is widely used in arboriculture and vineyards. Therefore, organic production practices must also be improved to increase yield and reduce risks.

Consequently, we consider that it is relevant to define a third strategy: the pesticide-free agriculture, which bans the use of all chemical pesticides (including synthetic and natural pesticides that have negative impacts on the environment and human health). Like IPM, pesticide-free agriculture should be based on a combination of methods that limits the impact of pests and enhances their natural regulation. However, avoiding pesticides completely requires going further than IPM by deeply redesigning systems and breakthrough innovations at multiple levels of value chains. Compared to organic agriculture, allowing synthetic fertilizers to be used in pesticide-free agriculture could limit the loss of productivity. Yet, due to the environmental impacts of nitrogen fertilization, fertilization practices should necessarily be rethought and potentially reduced compared to what it is in current cropping systems. More generally, fertilization should have to be scrutinized in pesticide-free systems since nitrogen availability affects the plant's primary and secondary metabolism, which in turn can affect plant defense and nutritional quality of crop for pests.

However, redesigning cropping systems and adopting technological innovations, which we expect will make it possible to phase out pesticides in the future, may lead to a decrease in yields (Colnenne-David et al. 2017). Indeed, the redesign of cropping systems should no longer have as a primary objective the maximization of yields. Although it can be hoped that once natural regulations are established, the loss of productivity will be reduced, the yields will remain lower and more variable. The objectives of profitability, resilience, and environmental services must be given priority over productivity objectives: this requires a paradigm shift from IPM. Recognition and support by markets, through certification and/or public policies, may however be necessary, especially during the period of transition.

2.3 Research toward pesticide-free agriculture: a disruptive paradigm today to build solutions for tomorrow

Until recently, research on pesticide-free systems in France involved only a few projects. Few experiments have been performed, which limits assessment of their economic performance under a variety of agricultural conditions and their ability to be scaled up (Colnenne-David et al. 2014, 2017; Cellier et al. 2018; Grandgirard et al. 2019). Experiments with promising results have been performed in other countries (e.g., on field crops in Canada) (Nazarko et al. 2003; Schoofs et al. 2005). However, research on pesticide-free agriculture remains rare. Indeed, agricultural research concerns itself with pesticide dependence: most research programs are looking for progressive reduction of pesticides and focus mainly on substitution solutions (Vanloqueren and Baret 2009). This trend gives little priority to research that could lead to disruptive agroecological innovations, not only for pesticide-free agriculture but also for reducing pesticide use greatly. It can be likened to a “fixation” effect, which is characterized by the development of common and conservative solutions to address a complex problem that should require breakthrough innovations (Jansson and Smith 1991; Vourc’h et al. 2018).

One solution for overcoming this fixation effect is to clearly state that pesticide-free systems are the goal for future agricultural systems, and that to achieve this goal, research needs to work within a pesticide-free paradigm right now. This redirection of research would justify investing in fundamental research, whose impacts are not visible in the short term. In parallel, to orient research better, knowledge production needs to be brought closer to innovation production, and in return, innovation communities need to be fostered to combine actions to reach zero pesticide use (Toffolini et al. 2020). Connecting research and innovation would help overcome the fixation effect and thus enable thinking outside the usual research frameworks (European Commission 2018; Klerkx and Begemann 2020). Indeed, a pesticide-free research would require enhancing systemic research and designing and scaling up combinations of techniques. This paradigm should be considered as “mission-oriented” and innovation-related research (Pigford et al. 2018; Klerkx and Rose 2020; Mazzucato et al. 2020), in which current obstacles are identified, research designs breakthrough innovations to orient fundamental approaches, and new drivers of change emerge to reach the ambitious changes targeted (Destatte 2010).

To achieve this goal, connections between public and private research and development must be strengthened (Fuglie et al. 2017). Previous technical innovations emerged and spread mainly through top-down dynamics: researchers produced knowledge that was transferred, sometimes with difficulty, to research and development organizations, which adapted it into applicable techniques and then disseminated it to farms. In contrast, it has been clearly shown that the pesticide-free objective cannot be limited to top-down approaches, but should also value the expert knowledge and know-how of stakeholders, including farmers. This bottom-up approach therefore aligns with the conceptual framework of AKIS (i.e., Agricultural Knowledge and Innovation Systems), which calls for stakeholders along the entire agricultural value chain to interact in order to manage knowledge and develop innovations among them (Knierim et al. 2015). Doing so would foster open innovation and blur the boundaries between scientists and practitioners (Chesbrough 2003; Berthet et al. 2018). In particular, these knowledge flows and innovation-design processes can be managed and supported through participatory research and cooperation organizations, such as living labs, which represent promising tools to enhance open innovations (Kok et al. 2019). This approach is particularly important because many of the solutions that will be developed will not be generalizable everywhere and will require situation-specific innovation. Thus, they must be designed as closely as possible to target situations by considering the resources available and the objectives of the stakeholders concerned, and by closely relating agricultural production and consumption, to engage entire value chains in the design of these radical transformations (Meynard et al. 2017).

Research toward zero-pesticide use will not be achieved without close collaboration among disciplines. Disruptive and innovative research axes are more likely to emerge within interdisciplinary work because different knowledge bases should be combined, shared, and renewed (Le Masson et al. 2016; Vourc’h et al. 2018; Brun et al. 2021). In particular, it is essential to involve social sciences to study socio-economic obstacles that could hinder implementation of innovations, as well as social organizations that could enhance development of disruptive innovations (Villemaine et al. 2021). Overall, complex issues, such as the elimination of pesticides, require deep innovations based on new knowledge but also on dedicated policies and an overhaul of value chains. In this context, the shift from pesticide-dependent to pesticide-free agriculture will require a profound and coordinated change in research paradigms.

This change also requires a transformation of the research and innovation system itself. Researchers will be able to pursue these new strategies of research only if the organization, incentives, and funding of research are rethought with this objective in mind. Interdisciplinarity and risk-taking must be encouraged, both in the way research is funded and in the recognition of this investment in the careers of researchers. Project funding must encourage this interdisciplinarity and be sufficiently lasting to allow work to be carried out over the long term, both on fundamental research topics and on participatory research involving farmers and the entire agri-food sector.

3 Research fronts related to five strategies to achieve the pesticide-free goal

To achieve the pesticide-free goal, several strategies have to be implemented simultaneously. These strategies were developed by considering the fields of knowledge and the scientific disciplines that call for new research fronts. We have thus distinguished what came under (1) agronomy, (2) genetics, (3) biological control, (4) machinery and digital, and (5) economic and social sciences. First, regarding agricultural sciences, cropping systems should be redesigned based on agroecological principles to implement radical change from a curative approach to a prophylactic approach. Second, regarding biological control, biocontrol solutions should be diversified and enhanced to be tailored to a variety of environments and practices. Third, regarding genetics, breeding programs should involve concepts of functional biodiversity and evolutionary ecology. Fourth, regarding machinery and digital, agricultural equipment should be modified to facilitate the transition to pesticide-free agricultural practices, while digital technologies should help optimize pest control and improve epidemiological surveillance. Fifth, regarding economic and social sciences, public policies and private initiatives for the transition toward pesticide-free systems should be implemented.

3.1 Redesigning cropping systems to enhance prophylaxis

Studying and designing practices in a variety of situations: from generic to tailored solutions To date, in developed countries, except for organic agriculture, the technical innovations designed and the way they spread were consistent with dominant high-input systems. For pest control, these solutions were almost only chemical products (except for a few biocontrol solutions) applied either before the occurrence of pests to prevent their emergence (e.g., weeds, fungi) or when they are observed (e.g., mainly insects, but also diseases and weeds to a lesser extent). Pesticide use in agricultural systems cannot be reduced greatly with curative techniques alone; doing so will depend greatly on non-chemical preventive practices that enable prophylaxis (i.e., all technical actions implemented to prevent the occurrence, spread or damage of pests beforehand). In conventional systems, prophylaxis relies on nature-based mechanisms, which can be enhanced by implementing combinations of practices that influence the multiple components of agroecosystems. Prophylaxis not only involves technical actions directly enhancing pest regulations (e.g., flowering strips favoring the development of auxiliaries), but also techniques that slow down the development of pests within the crop (e.g., lower plant densities enhancing a more airy microclimate), or that decrease the pest development/spreading (e.g., a lower and different fertilization management decreasing spore production for aerial fungi-based diseases, or lowering weed growth), or that disrupt the pest cycle (e.g., diversifying the crop sequence). While pest-control solutions consistent with high-pesticide systems are generic and applicable to every situation, nature-based solutions should be adapted to the specific characteristics of the agricultural situation (e.g., soil and climate conditions, value chain, workload) (Meynard et al. 2003; Rusch et al. 2010; Médiène et al. 2011; Duru et al. 2015).

To date, however, the effects of alternative practices have rarely been studied in a wide range of environments or cropping systems since research was used to produce generic rules and recommendations from a few experiments. The kind of tailoring needed would benefit from the initiative and experience of pioneer farmers and experimenters, and from expert knowledge, derived from action in real environments, within an open-innovation process (Chesbrough et al. 2014). Approaches developed recently, such as on-farm innovation tracking (Verret et al. 2020; Salembier et al. 2021), system experiments (Debaeke et al. 2009), hybridization of farmers' experience and scientific knowledge (Girard and Magda 2020), co-design of farming systems (Le Gal et al. 2011), and support of farmers' engagement in agroecological practices (Catalogna et al. 2018; Leclère et al. 2018), are emerging methodological bases. They help to identify, analyze, pinpoint, and assess a large set of combinations of practices oriented toward pest regulation. They should be developed specifically to help farmers develop, implement, and improve their practices, thus supporting farmers as designers (Salembier et al. 2018).

Experiments to address multiple stresses in real and situation-specific conditions Another method is experimentation, specifically comprehensive experiments, which have long been the methods that agronomists used most to produce technical innovations (Salembier et al. 2018). Experiments are usually performed under controlled or mono-stress conditions (e.g., water, or nitrogen, or one pest that decreases growth and yield) to analyze effects of each factor independently and to produce general response laws. For pesticide-free systems, enhanced research should aim to characterize effects of combinations of practices that can address multiple stresses in real and situation-specific conditions. In such a wide range of situations, production of generic knowledge should benefit from hybridizing local scientific knowledge and know-how to deal with the diversity of environments and support locally adapted action. More recently, system experiments were developed; they aim to assess and sometimes gradually improve consistent combinations of practices that target one or more goals (Debaeke et al. 2009; Lechenet et al. 2017). Few system experiments have targeted high performance in pesticide-free systems (Colnenne-David et al. 2014). By identifying the specific processes behind this performance, these experiments help to design and assess prophylaxis-oriented systems and potentially scale out the robustness of their performance, process-based reasoning, and the practices they implement.

Renewing assessment of practices Since input-intensive agriculture and its related practices were developed mainly to increase yield, innovative agronomic practices are first assessed for their impacts on yield. In contrast, pioneer farmers, who implement innovative low-input practices, often rely on other satisfaction criteria (e.g., maximize the average gross margin calculated over several years, reduce workload). They use such criteria to define the technical changes they progressively implement on their fields, thus building their technical transition toward agroecology (Toffolini et al. 2016; Verret et al. 2020; Salembier et al. 2021). In recent years, numerous multicriteria assessment tools have been developed (Sadok et al. 2009), but they generally assess impacts of entire complex systems, including processes from the "cradle to the grave" (Deytieux et al. 2012; Nemecek et al. 2015). However, these tools do not support farmers in the step-by-step design of their agroecological systems. Indeed, more research should be dedicated to developing indicators aiming to support farmers' actions in the uncertainty (due to the huge knowledge gaps and the high variability of the impacts of practices depending on the context). In parallel, other tools should be created to enhance, capitalize, and share their learning during the change of their cropping systems toward ambitious challenges.

Developing coupled innovation to enhance diversification Diversified cropping systems are one of the most powerful ways to reduce pesticide use (Ratnadass et al. 2012), but they may result in products whose characteristics do not correspond to the demand or available processes of agri-food value chains (Magrini et al. 2016; Meynard et al. 2018). Moreover, development of new crops, which is currently rare in research and in the practices, is hampered by a lock-in situation in the entire agri-food system, including a lack of market for agricultural products from these crops and new practices (Magrini et al. 2016; Meynard et al. 2018). In particular, developing intercropping (i.e., growing at least two species partly simultaneously on the same field) raises two questions: on the one hand, the grain sorting from both species, and on the other hand, the valuation of crops with high agronomic interest but low value in the downstream sector, such as legumes (Magrini et al. 2018).

To unlock dominant systems, innovations in the field should be coordinated with innovations at other steps of the value chain, especially downstream with processing innovations. Stimulating such coupled innovation processes, which aims to connect innovation processes in agriculture and food sectors to support healthy and sustainable agri-food systems, calls for specific research (Meynard et al. 2017; Brun et al. 2021). To date, most innovation and design in these sectors have been separated due to specialization of skills, knowledge, and methods. To make coupled innovation possible, methods should be developed to manage these multi-stakeholder systems to increase sharing of knowledge and targets (which are largely disconnected), coordinate design processes, and assess innovations for a variety of criteria that connect agriculture and food, as successfully demonstrated for coupled innovation in cropping systems and machinery (Salembier et al. 2020).

Including the landscape scale in pest management Pests, such as most insects and many fungi, disperse widely into the environment, sometimes over large distances. Thus, to prevent their spread, practices should be changed not only at the field scale, but also at the landscape scale (i.e., organizing practices at a large scale, which requires the involvement and coordination of many stakeholders). This management complexity is one reason why research on pest management has rarely considered the landscape scale. More generally, there is a lack of information available about the performance of most preventive measures as a function of their degree of adoption at a landscape scale (Benoît et al. 2012). Pesticide-free agriculture thus requires designing pest-suppressing landscapes that combine green infrastructure, landscape mosaics, and related practices (Fig. 2). To develop these landscapes, stakeholders in the territory must be involved in the design process, since they must be coordinated, and assessing consequences of changes in practices at the individual scale is not sufficient (Moreau et al. 2019). Participatory methods with this goal are being developed, and new tools to monitor processes of change at the territory scale should be designed and developed, due to new digital capacities, as developed for water in catchments (Prost et al. 2018). Beyond coordinating stakeholders, strong political will must emerge to reverse the trend of specialization of production, which is largely responsible for the oversimplification of landscapes (Roschewitz et al. 2005).

Fig. 2 Pesticide-free agriculture cannot be conceived without managing the spatial heterogeneity of landscapes: the design of mosaics of cropping systems, in interaction with semi-natural habitats, is essential to promote the ecological processes that lead to natural regulation of pests. Here, the continuity of the hedges enhances the flow of organisms. Photograph by INRAE.

3.2 Diversifying biocontrol strategies and associated business models

For simplicity, we use "biocontrol" to refer to a broad range of pest-control methods. It refers to the four strategies of biocontrol that use living organisms, as defined by Eilenberg et al. (2001): (1) "classical biological control," which corresponds to introducing an exotic, usually co-evolved, biocontrol agent for permanent establishment and long-term pest control; (2) "inoculation biological control," which corresponds to releasing a living organism so that its populations become established and control a pest for an extended period, but not permanently; (3) "inundation biological control," which corresponds to the use of living organisms to control pests when control is achieved exclusively by the released organisms themselves; (4) "conservation biological control," which corresponds to modifying the environment or existing practices to protect and enhance specific natural enemies to reduce effects of pests. In addition, we also use "biocontrol" to refer to a variety of substances produced by living organisms (but without using these organisms directly): semiochemicals (e.g., pheromones, kairomones), metabolites, plant extracts, and plant-defense stimulators. These substances may be natural extracts or chemically synthesized molecules provided that the latter are identical to natural molecules.

Changing and diversifying business models of the biocontrol sector Business models currently used by the private biocontrol sector are similar to those of the chemical pesticide sector. These business models are based on selling large quantities of products that are promoted for their short-term measurable efficacy, short-term economic competitiveness, and simplicity of use. By applying this rationale to biocontrol methods, practitioners actually implicitly depreciate these methods because they compare them directly to chemical pesticides based on characteristics that do not correspond to those of most biocontrol modes of action (e.g., mid- or long-term regulation, prophylaxis) and do not promote the overall sustainability of these methods. Practitioners also overlook business models based on services rather than products. The associated value chains and supply chains are also organized to produce, distribute, and use chemical pesticides, not biocontrol products and services (Glare et al. 2012). Analyzing and developing a variety of business models adapted to each type of biocontrol and food chain appears as an interdisciplinary axis of research (e.g., management, sociology, economy, agronomy, biology), which is particularly important for the growth of biocontrol in sustainable pesticide-free agrosystems and food chains (Fig. 3). Such research is extremely rare, although some researchers have occasionally investigated commercialization models (e.g., Harman et al. 2010). This would enable organizational innovations, such as novel or adapted value chains and business models, modifying and diversifying the current industrial sector of biocontrol.

Defining biocontrol strategies and priorities by anticipating the needs of the most sustainable cropping systems and food chains Expectations regarding biocontrol are highly unfocused since practitioners want biocontrol solutions to be developed for all target pests that are formerly or currently controlled by broad-spectrum chemical systems. Private and public investment and market analyses are driven without scientifically based criteria and often rely on criteria traditionally used for developing chemical pesticides (e.g., targeting large markets in terms of hectares affected by a pest or

Fig. 3 The use of *Trichogramma* micro-wasps against lepidopteran pests has been an undeniable biocontrol success story for several decades. Despite this success, this example also illustrates the kind of biocontrol challenges that can be facilitated in a pesticide-free system perspective. The use of biocontrol strategies could be drastically increased (it is currently limited to 10–20% of potential target areas), diversified in terms of target crops, and based not only on massive inondative releases but also on inoculations followed by long-term management of populations. These evolutions can be fostered by the development of new business models, which deviate from the current strategies conceived for massively used pesticides. Photograph by Jean-Claude Malausa.

niche markets with no current control solution). Analyzing the issues that pests cause in pesticide-free cropping systems while identifying biocontrol solutions adapted to each issue should become a research and innovation activity in itself. It should be based on analyzing (1) pest control issues in a variety of cropping systems and associated agri-food chains with high environmental, economic, and social sustainability (and representative of systems that will become widely used in the future); (2) factors that influence the severity of these pest issues in these systems; and (3) the fit of potential types of biocontrol strategies (e.g., classical, conservation) with the target pest issue, cropping system, and agri-food chain. Doing so would comprehensively identify needs of each type of agri-food chain and geographic area, and would provide insights into the expected role and technical and economic characteristics of potentially relevant biocontrol strategies. This will enable research and innovation investment strategies and market analysis methods to be adjusted for both public and private stakeholders.

Redirecting efforts to focus on interactions of biocontrol with other agroecological practices rather than with pesticides Research and innovation resources are allocated to studies of the compatibility and interactions of biocontrol with chemical pesticides, while interactions among agroecological practices are currently overlooked. However, farmers' crop management choices (e.g., plant species, crop treatment, rotation) shape plant health. For example, crop management practices can modify the soil microbiome, which might impact plant health since it is the initial reservoir from which beneficial plant microbes are recruited (Hunter et al. 2014), as shown for fertilization (Zhu et al. 2016). Redirecting efforts to focus on the compatibility and interaction between biocontrol and other agroecological approaches (e.g., agronomic practices, resistant cultivars, digital tools, machinery) is essential to clarify strategies for developing biocontrol for pesticide-free systems. Future research should focus on impacts of (a)biotic factors and agronomic practices applied to biological mechanisms involved in biocontrol. Doing so would enable specific recommendations for using biocontrol methods depending on the characteristics (e.g., environmental factors, practices) of each target cropping system. Likewise, factors that support the success of agronomic practices based on managing biological pest-regulation processes (i.e., conservation biocontrol mediated by agronomic practices) could be identified. The knowledge produced about interactions between biocontrol and other mechanisms will be critical to enable the design of cropping systems that implement genuine IPM. This need, which has been raised for decades, has been inhibited by the dominance of systems based on chemical pesticides (Thomas 1999).

Designing implementation of biocontrol at the landscape scale Following the pesticide model, biocontrol is used and planned mostly at the field/farm scale, although it often requires thinking at the landscape scale. Despite success stories that combined biocontrol methods at the landscape scale (e.g., mating disruption using pheromones and sterile insects to control Lepidoptera (Thistlewood and Judd 2019)), landscape-scale strategies of pest management are still rarely implemented in practice, perhaps because they appear more complex and less economically favorable in the short term than field applications of chemical pesticide. Research on biocontrol solutions to be implemented at the landscape scale should be highly prioritized. These challenging research activities may require a combination of modeling and experimental work at larger or smaller geographical scales (from a few fields, e.g., for sexual disruption, to large geographical areas, e.g., for landscape management-based conservation biocontrol). In parallel, social and technological sciences must be combined to consider all factors that influence successful implementation of these strategies. In particular, frameworks in social sciences and innovation management should be developed to characterize value chains and territories in which biocontrol is to be used, as should digital tools to ease monitoring and action planning at the landscape scale. These kinds of research activities should lead to the production of knowledge, tools, and policy recommendations that will facilitate implementation of landscape-scale and collective strategies that use biocontrol along with other agroecological practices.

Prioritizing modes of action other than short-term biocides Methods that do not rely on biocides or organisms are currently overlooked and/or underexploited (e.g., mating disruption, pull–push strategies, plant-defense elicitors, microbiome management). While many research and innovation projects focus on identifying direct antagonists of pests (e.g., predators, parasites, parasitoids), more attention could be paid to other modes of action, particularly if they allow for sustainable approaches based on regulation rather than short-term and localized eradication (Aubertot et al. 2005). A promising area of applied research deals about the management of pest populations by manipulating semiochemicals and odorscapes, which enable a variety of pest control methods with little or no negative impact on local biodiversity, such as trapping, push–pull strategies, and mating disruption (Conchou et al. 2019). Understanding complex interactions between plants and microorganisms is another main research front. Indeed, the microbiome, which is associated with plant leaves, roots, and seeds, has a tremendous and yet untapped potential to improve plant resilience (Trivedi et al. 2017; Hartman et al. 2018). Manipulating plant immune systems is another promising perspective (Pieterse et al. 2014; Romera et al. 2019; Nishad et al. 2020), especially if its timing during plant development can be controlled. Such research would pave the way for developing control methods based on bio-inputs oriented toward greater sustainability. Indeed, these methods impact biodiversity less than biocide (bio-)inputs, and their application is based more on qualitative than quantitative strategies.

Developing biocontrol based on mid-/long-term management of pest populations Given the dominant use of curative chemical pesticides and associated value chains, biocontrol activities that rely on long-term services tend to be marginalized. In particular, conservation biocontrol and classical biocontrol have been particularly neglected despite their history of success and their often outstanding cost–benefit ratios (e.g., from 1:50 to > 1:3000 for classical biocontrol programs performed in New Zealand and Australia in the past few decades) (Page et al. 2006; Hardwick et al. 2016). In addition, the diversity and density of resident natural enemies, as well as the pest-control services they provide, are rarely the target of routine detection and surveillance by or for practitioners. This strongly limits the potential for sound implementation of conservation biocontrol or inoculation biocontrol adjusted to the needs of cropping systems. Research needs to be reoriented to develop biocontrol strategies based on long-term regulation of pest densities. It could consist in studying factors that influence regulation of pests by resident organisms (i.e., conservation biocontrol) and their large-scale implementation by practitioners, as well as the use of dedicated sensors and tools to perform this monitoring. It would also be relevant to analyze factors that drive the success of strategies that rely on inoculation and temporary or permanent establishment of beneficial organisms (i.e., inoculation and classical biocontrol). Greater investment in these research axes should provide practitioners with a range of methods and strategies for conservation, inoculation, and classical biocontrol that enable mid-/long-term pest regulation, accompanied by business models and tools that facilitate their establishment and adoption.

3.3 Broadening the scope of breeding programs to include functional biodiversity and evolutionary ecology concepts

Enhancing functional biodiversity at multiple scales Plant breeding is a vibrant science with cutting-edge technologies that provide new solutions to increase food security, but breeding programs still require several years to decades to obtain new crop varieties (Tester and Langridge 2010). To decrease the cost associated with releasing new varieties, breeding programs have progressively focused on a few crops, such as those in the Poaceae family (e.g., maize, rice, wheat). By doing so, they restrict the options for benefitting from genetic diversity in fields or the landscape, even though this diversity is an important way to regulate crop pests. Indeed, genetic uniformity promotes strong and directional selection pressure on pathogens. To limit this pressure, breeders can develop deployment strategies that include new varieties to foster diversification and new cultivars with different resistance genes as well as the ability to coexist (intercropping) without negative interactions such as competition for resources (Fig. 4). However, doing so has a cost that should be balanced by its side benefits on the environment and health. These strategies based on managing host (i.e., crop) genetic diversity can be introduced in time (i.e., rotations) or space (e.g., plant mixtures, landscape mosaics) (Veres et al. 2013; Snyder et al. 2021). Beyond the benefits of implementing more complex rotations with new species, intra-field genetic heterogeneity can generate countless ecological interactions. Indeed, coexisting species or genotypes can achieve synergies when they consume different resources or have different natural enemies, or when their resources or enemies vary in time and/or space. Some of these combinations protect plants effectively (Johnson et al. 2015), while enhancing soil quality and its connections to ecosystem services (Cong et al. 2015; Zhou et al. 2019). However, progress remains to be made to identify new complementary combinations of species and to select mixtures of varieties and populations that show increased resistance; they should include new cultivars but not ignore underused or forgotten species and cultivars (Chable et al. 2020). In parallel, targeting pesticide-free agriculture argues for including classic and emerging ecological theories about functional biodiversity and evolutionary ecology in plant

Fig. 4 Intercropping enhances plant diversity in order to limit yield losses due to pests. This diversification scheme requires species and varieties adapted to coexist and to interact with the environment. The various stages of plant breeding and selection must therefore account for new criteria to optimize the adaptation and interaction capacities of plants with their biotic environment. The expected benefits are a better resistance and a great associated diversity to regulate the feedback loops between the soil and the plant diversity (REMIX project, INRAE (2021)). Photograph by Edith Le Cadre.

breeding programs to capture benefits of genetic diversity (Gaudio et al. 2019). Some European programs as DIVERSIFY or REMIX on cropped species (refer also to the European initiative "Crop Diversification Cluster") pointed out some results that support this assertion (Annicchiarico et al. 2019; Jäck et al. 2021). Genetic diversity could indeed promote species diversity in plant communities (Prieto et al. 2015; Meilhac et al. 2019), through genetic and ecological mechanisms (Meilhac et al. 2020). Thus, increasing diversity requires considering jointly multiple levels of biodiversity (i.e., genes, population, or community). To date, breeding programs have had difficulty deriving value from the benefits of inter- or intra-crop mixtures due to the few traits that they consider (Litrico and Violle 2015). In contrast, breeding programs have aimed for the standardization required by the food supply chain.

The genetic basis of "ability to co-exist" traits for all major crops requires renewing methods and criteria in selection programs (Sampoux et al. 2020). Co-existence traits are crucial to breeding programs that aim to foster diversification since they enable plants to share and adapt to the environment (Hill 1990; Hinsinger et al. 2011). However, cultivar performances in pure stands are rarely identical to their performances in plant mixtures because demand for a particular resource can outstrip the supply, thus leading to a shortage of resources. This difference is sometimes observed under agroecological practices such as direct drilling or conservation agriculture (Peltonen-Sainio et al. 2009; Sampoux et al. 2020). Thus, combinations of specific ecological activities, as close as possible to agroecological systems, should be considered as breeding criteria, even though they complicate the design of experiments and related statistical methods (Hill 1990). Emerging translational biology, comparative biology, and plant community ecology can provide new insights into target plant traits that must be implemented to cultivate species in diversified and pesticide-free agroecosystems.

Integrating the variety of pesticide-free practices and the environment in breeding Current breeding programs create productive cultivars, but their productivity remains conditioned by agricultural practices. Indeed, the expression of genetic potential, which defines the genetic yield potential, depends on pesticide, water, and nutrient inputs, especially since breeding is performed for standardized cropping systems. Therefore, when the availability of water or nutrient is not synchronized with the plant needs, the genetic yield potential can be reduced, making observed yield lower than potential yield. This yield gap can sometimes be observed when certain agroecological practices, such as direct drilling or conservation agriculture, are implemented (Peltonen-Sainio et al. 2009; Voss-Fels et al. 2019). Developing new practices to eliminate pesticides can also lead to this situation; thus, more research is needed to include these new practices in breeding. However, beyond the practices, a crop's direct environment should be considered when breeding new varieties. Indeed, the genotype × environment × management ($G \times E \times M$) equation of the breeder's objective is to derive value from genetic resources in the face of environmental heterogeneity (Prieto et al. 2015; Litrico and Violle 2015; Meilhac et al. 2019). Following this perspective, participative breeding should be developed. Indeed, farmers could be part of the breeding innovation (Berthet et al. 2020). First, participative breeding help preserve in situ genetic resources under climate change and innovative practices and then address evolving genetic capacities in addition to ex situ approaches (Hawtin et al. 1996). The reproduction and selection on farm allow for a continuous evolution and adaptation of crop populations in response to natural selection and selection performed based on desired characteristics defined by site-specific conditions or practices. Second, through seed exchanges, crosses, or mixtures, participatory breeding could foster genetic diversity. Accordingly, innovative programs combining breeder's and farmer's selection approach can contribute to the release of new varieties to solve the ($G \times E \times M$) equation (Dawson and Goldberger 2008). While promising, such new approach of breeding raises new issues dealing with evolutionary processes and organization leading to a certain unpredictability that can be overcome with an efficient dialogue with all tenants (stakeholders, farmers, researchers). In particular, developing predictive models based on data-driven approaches, assisted by new mathematical and statistical learning methods, and on crop models may provide credible genotype responses to the environment and management practices (Messina et al. 2020; Cooper et al. 2021). This modeling approach, or in silico trials, can also benefit from innovations in agricultural machinery by including data captured by sensors and digital agriculture mapping to broaden analysis to a wider range of soil and climate conditions.

Broadening the scope of breeding by integrating interactions with soil and microorganisms In addition, little research on lasting effects of plant legacies through complex plant–soil feedback has been performed, even though plant ecology has demonstrated the latter's benefits for crop protection (Putten 2003; Wang et al. 2017). Plants influence soil biota, including pathogens, directly through root exudation or by modifying nutrient and water availability, and indirectly through litter fall. These organisms in turn can influence plant performance either positively or negatively. Domestication and breeding select the most productive species with resource-acquisition traits, thus neglecting other plant functional traits. Extending plant-trait approaches to soil biota and including them in breeding programs is a promising research front, especially since agricultural systems make it possible to choose crop species and varieties (Mariotte et al. 2018). Accordingly, unexpected benefits could be included in farmers' assessments of new diversification crops, especially when improvements in soil quality (e.g., soil structure) are observed with fewer external resources or a smaller workforce. Dedicated research should address such complex plant–soil feedback. In particular, it would be interesting to distinguish individual drivers induced by plants and their interaction with nutrients, exogenous inputs, and pests. To do so, experiments under both controlled and field conditions are needed. Finally, interfaces between plants and their environment must be monitored to take advantage of this progress. Accordingly, sensors or new indicators that complement soil quality and fertility indicators (e.g., plant rhizosphere indicators) must be developed.

Future plant-breeding programs should focus on plants' ability to steer their microbial communities as a heritable trait to deliver the next generation of microbe-improved plants (Gopal and Gupta 2016). Indeed, promising research consists of considering a plant as a super organism, a holobiont, composed of the plant itself and its microbiome (Vandenkoornhuyse et al. 2015; Agnolucci et al. 2019; Bailly et al. 2019). Doing so would enable simultaneously breeding crops and their associated microorganisms and/or plant traits that promote beneficial microorganism interactions. Considering microbe genes in addition to a host plant's genome would thus increase the plant's ability to cope with abiotic and biotic stress (Berendsen et al. 2012; Liu et al. 2020) and changing environments (Classen et al. 2015). To address these objectives, the discrete interplay between plants and microbes must be understood better. In particular, research should focus on distinguishing function versus microbial diversity relationships, as well as the influence of rare taxa or strains that define the satellite microbiome in addition to the core microbiome (Jousset et al. 2017).

Beyond the technical aspects of multi-trait phenotyping, registering microbe-improved plants is a burden for breeders according to current mandatory criteria, such as distinctness, uniformity, and stability, that define the concept of a variety (Louwaars 2018; Jamali et al. 2020). International and national policies for registering new varieties based on performance in high-input systems should be renewed by initiating research on new criteria. Beyond microbe-improved plants, this change could also enable value to be derived from participatory breeding and consideration of a crop's direct environment in breeding. However, this would not be possible without the engagement of policy makers and relevant stakeholders (e.g., research centers, breeding companies, farmers' unions).

In addition, breeding programs have inadvertently selected plant traits that impair the ability of plant communication to recruit and select beneficial microbes compared to that of wild types or wild relatives (Berendsen et al. 2012; Pérez-Jaramillo et al. 2016, 2018). One known example is the inability of elite wheat varieties to develop interactions with several mycorrhizal fungi of great importance in capturing potassium or phosphorus and fostering healthy plant growth. Because these genetic abilities were present in ancient cultivars, they could be reintroduced into modern varieties (Jacott et al. 2017; Sawers et al. 2018). Finally, facilitating effective interdisciplinary research among plant geneticists, ecologists, and agronomists in charge of cropping system design is crucial to reveal de novo solutions for agriculture. This kind of holistic approach is essential due to the complex multi-trophic and aboveground–belowground relationships in agroecosystems (Kostenko et al. 2012; Dias et al. 2015; Wurst and Ohgushi 2015; Mariotte et al. 2018; Li et al. 2019). Altogether, managing the plant microbiota through appropriate management practices and crop management design can be considered to influence agroecosystem health (i.e., "One Health") and, by extension, socio-ecological systems (i.e., "EcoHealth", as defined by Mi et al. 2016).

3.4 Setting new goals for agricultural machinery and digital technologies

Developing equipment adapted to agroecological practices Currently, most agricultural machines are adapted to cropping systems that rely on pesticide use. This choice has influenced field size and has ultimately shaped landscapes (Jepsen et al. 2015). Current machines are thus adapted to large fields and were designed to optimize pesticide use (e.g., precision of application, high speed to benefit from periods when pesticides can be applied) (Smith 2018; Berenstein and Edan 2018). Most machines are designed to have curative action against pests, in particular as a substitute for herbicides, but they do not use much data, which allows for targeted and automated action. The development of precision agriculture opens up the possibility of managing pests and diseases by mechanical actions. However, the vast majority of precision farming applications consists of optimizing the use of pesticides, and this is therefore part of the current paradigm relying on pesticides (Gossen and McDonald 2020). Overall, development of mechanized prophylaxis remains limited. More research on big data and machine learning would improve pest detection, monitoring practices, and crop health (Ip et al. 2018; Korres et al. 2019). It would advance the design of equipment and thus enable non-chemical agricultural management decisions to be tailored in time and space (Bongiovanni and Lowenberg-Deboer 2004; Finger et al. 2020). In particular, new technologies enable knowing exactly where crops are located within a field in order to spare them, while controlling the rest of the cultivated space (Liu et al. 2019). For example, at the field scale, controlling the location of seeds precisely using GPS makes it possible to hoe between rows and within each row, thus eliminating the need for herbicides (Griepentrog et al. 2005). Intercropping is a highly effective technical lever for managing pests without pesticides (Stomph et al. 2020), with several biological and ecological processes involved in this control (Ratnadass et al. 2012). Yet they often require specific machinery to sow (as diverse as alternating rows of each species, sometimes at different depths, mixed rows or relay-cropping) or to sort the harvested products, thus limiting their extension. In addition, robotics is a tool to replace human labor for the most tedious tasks, such as weeding, or to perform actions to combat pests (Fig. 5). For example, aphids can be vacuumed up not only to monitor their populations but to help maintain them at low densities (Belding et al. 1991; Schmidt et al. 2012). Indeed, development of preventive robotics may solve several limits of the present situation, in particular the slowness of robots: if the robot's objective is to decrease pest pressure by removing contaminated plant parts, high speed is not essential. At another stage of the value chain, innovations should improve sorting abilities in order to facilitate processing of grain harvested from intercrops (Meynard et al. 2018). This is also relevant when crops are interlocked on the same field (e.g., living mulch) without being intended for harvest (Wortman et al. 2012). Overall, the equipment of these innovations must cover the needs of main crops and diversified crops at low cost.

Fig. 5 The ability to control weed management in the row is a key lever for implementing herbicide-free practices. Machines providing physical weeding in the rows are starting to be offered by various manufacturers. Here, the task is carried out by the BIP BIP robot that combines three fundamental functionalities: observation of the row with a camera, analysis of the situation with on-board algorithms, and carrying out an appropriate action (i.e., mechanical weeding with great efficiency and without harming the crop). Photograph of prototype 5 of the BIPBIP system designed for intra-row mechanical weeding of vegetable crops, taken by Louis Lac for the BIPBIP-project, funded by the French National Research Agency).

Promoting the adaptability of the equipment to a variety of environments Current equipment is highly standardized and lacks adaptability: it is designed to cover the needs of farmers with large farms, which tends to increase machine size and power (Kutzbach 2000). This trend has contributed to the intensification and standardization of agroecosystems, characterized by the same dominant crops around the world. To benefit from natural regulation, however, pesticide-free agriculture will require developing smaller machines, adapted to smaller fields and local conditions. Research on the adaptability of equipment must thus be developed. This can be done in two ways, which can coexist. Smart machines should be developed that self-adapt to local conditions using embedded sensors (Berducat et al. 2009). This self-adaptation could relate to navigation, speed, or the precision of action (Tisseyre 2013). In comparison, self-built machines should be designed from open-access knowledge to provide new opportunities for farmers (Joly 2017). Indeed, in addition to limiting individual purchases of high-tech but expensive equipment, some machinery cooperatives have developed their own equipment or provided "fablabs" in which farmers can make their own modifications. By doing so, they can simultaneously redesign their cropping system and equipment, which therefore become adapted to the local context and the farmers' specific needs (Salembier et al. 2020). In parallel, research should focus on economic models that would support production of small series of equipment by small and medium enterprises.

Improving in-field epidemiological surveillance through innovative monitoring tools Current decision-making tools are dedicated mainly to supporting curative rather than preventive agronomic practices. In particular, information about the risk of crop loss delivered to farmers is based mostly on the weather forecast only and is not influenced by preventive actions that farmers could have taken. More research should be developed on combining monitoring and prediction tools that consider and support preventive agronomic practices (Rossi et al. 2019). Indeed, efforts are currently underway to adapt decision-making support to the specific characteristics of biocontrol (Giles et al. 2017), but other innovative tools should also be developed. Technological advances in sensors, the "Internet of Things" and big data processing could together provide the ability to quantify and consider subjective or measured probabilities of pest occurrence or crop loss. Doing so could reduce farmer uncertainty, particularly by developing systemic decision-support and design-support tools that ease strategic decisions built on preventive practices. Decision-making tools could also be improved by combining farmer perceptions of risk and economic utility (Gent et al. 2010).

In addition, epidemiological surveillance must be expanded by generalizing monitoring methods (Sankaran et al. 2010). Indeed, epidemiological surveillance seldom provides information about the potential of natural regulations to control outbreaks of a given pest, which would thus allow farmers to avoid a pesticide treatment. In pesticide-free agriculture, epidemiological surveillance should include a wide variety of organisms, from pests to auxiliary organisms, to provide valuable information about potential natural regulation at a large scale. Research should thus focus on monitoring methods to improve and extend in-field epidemiological surveillance. In particular, the next generation of networked sensors should be designed using molecular assessment to model epidemiological risk and share metadata with stakeholders (Mahlein 2015). For example, sensors based on insect pheromone receptors are promising tools that could provide early warning of invasive insect pests (Tewari et al. 2014). Other types of sensors include molecular assessment that uses nanotechnology systems such as lab-on-a-chip devices: they could provide a promising option for effective detection and analysis of diseases caused by microorganisms (Martinelli et al. 2015; Kashyap et al. 2017). To do so, breakthrough innovations in biocontrol are expected to provide detection and recognition of insect pheromones, as mentioned (Sect. 3.2) (Conchou et al. 2019). Beyond sensors, development of big data will increase transparency of production processes by enabling traceability, in particular of input use (Finger et al. 2020; Fielke et al. 2020). By doing so, policies may become more effective due to lower transaction costs between farmers and authorities (OECD 2019). It can also lead to the development of dedicated agri-food chains that derive value from low-input farming through price bonuses and thus pay farmers for using more sustainable practices (Choe et al. 2009).

Expanding monitoring areas by including non-agricultural reservoirs Finally, epidemiological surveillance is still limited in space (i.e., cultivated fields), time (i.e., short term), and purpose (i.e., pests). Indeed, current epidemiological surveillance relies on direct observation of pests and specific data from relatively short-term events within or next to cropped fields. It therefore does not consider inoculum reservoirs or the presence of auxiliary organisms in non-agricultural areas. However, the recent concept of One Health asserts that most new animal and human diseases come from disturbed natural environments that are reservoirs of disease vectors (Cunningham et al. 2017). Research on expanding the One Health paradigm to crop production is thus an interesting option. Expanding this concept of plant disease epidemics would involve monitoring risk factors for the proliferation of pests by including non-agricultural reservoirs within epidemiological surveillance (Morris et al. 2009) to detect pests as early as possible and thus optimize the preventive approach necessary for prophylaxis. In addition, it would be interesting for epidemiological surveillance of plants, animals, and humans to share at least some of the technology to compare their results and improve prevention and forecasting abilities (Zinsstag 2012; Davis et al. 2017). Effectively integrating the plethora of potential indicators from smart sensors, social networks, digital maps, and remotely sensed imagery would enable the next generation of epidemiological models to be developed and innovative tools that support decision-making by farmers and other stakeholders to be created (Rapport et al. 1998). Overall, the next generation of agricultural equipment should facilitate implementation of preventive actions: in an integrative way, sensors and the sensor-machine interface must work on connecting epidemiological risk and the actions of machines designed to decrease risks due to pests.

3.5 Implementing public policies and private initiatives for the transition toward pesticide-free systems

Improving the effectiveness and acceptance of public policies To date, pesticide-reduction policies have fallen short of expectations, and reasons why more effective ones have not been developed must be determined. One explanation is that most policies are designed independently of each other, especially environmental and agri-food policies. Some policies target pesticide reduction while others still support current production systems. Furthermore, agricultural policies do not address food issues, even though the agroecological transition should involve the entire food chain. This is clearly the case of the EU's Common Agricultural Policy, which has failed to include pesticide issues in its instruments and to connect food issues to agri-environmental issues (Guyomard et al. 2020). Several studies confirm that policies must be combined to achieve convincing results (Lee et al. 2019; Guyomard et al. 2020; Möhring et al. 2020b). Thus, research should focus on cross-effects to combine policies, including food policies, more effectively and to identify potential synergies (Pedersen et al. 2020). Progress should also be made to combine more effectively the types of public policy instruments that can be implemented to reduce pesticide use: regulatory, economic, and informational (Vedung 1998).

To encourage implementation of these policies, one fundamental rationale is the hidden costs of pesticides. Indeed, impacts of pesticide use on the environment and health lie at the source of costs (e.g., health costs, pollution-control costs) borne by private and public stakeholders. These costs can be associated with "negative externalities." They are difficult to assess, and only a few studies on this issue are available (Bourguet and Guillemaud 2016). New methods should be developed to ease and standardize this assessment. Specific research projects should focus on this issue by developing a multi-disciplinary framework that integrates epidemiology, ecology, and toxicology, in particular. These research projects should be closely related to the practices currently used in the field, in particular how farmers apply pesticides (e.g., climate conditions, equipment) and protect themselves (e.g., protective equipment) (Garrigou et al. 2020). Such research would ease the social acceptance of policies while potentially accelerating changes.

Fostering collective actions at the landscape scale The limited impact of agri-environmental policies can be explained by their focus on individual farmers. Recent studies showed that changes in practices depend not only on individual actions but on the wider context (Schoonhoven and Runhaar 2018). In particular, adoption of innovative practices to reduce pesticide use can be encouraged by collective approaches in which the sharing of experience with peers (i.e., other farmers perceived to be like-minded) is essential (Chantre et al. 2015; Bakker et al. 2021). Thus, research on spatial and collective mechanisms is needed to drive transition to pesticide-free agriculture. Innovative instruments should be designed to target not only individual farmers but also groups (e.g., farmers, other stakeholders involved in territorial initiatives), while addressing the issue of "free riders" who may defect from the common strategy. Among these instruments, "nudging" is a promising tool that uses various types of psychological bias to favor targeted decisions. For example, nudging implemented through a conditional collective bonus can create a pro-environmental social norm that encourages farmers to reduce pesticide use (Kuhfuss et al. 2016). Nonetheless, further research should better define the characteristics of such policies to ensure their effectiveness and foster their implementation.

Supporting farmers' innovation networks In the EU, farms' economic structures are increasingly capital-intensive. This issue is closely related to demographic changes in the agricultural sector: the number of farmers is decreasing, which tends to increase the size of farms and encourages simplification of crop management and the search for increasing productivity per worker (European Commission 2017b). At the same time, the outsourcing of agricultural activities to dedicated companies is increasing, and these companies are more inclined to use conventional practices that do not lead to a reduction in pesticide use (Nguyen et al. 2020). More research on economic models of farms and their pesticide use is needed, in particular regarding workload and their compatibility with transition to pesticide-free agriculture. Indeed, practices that tend to reduce pesticide use are generally considered to be more labor intensive and to require more complex work organization and more skilled labor (Bowman and Zilberman 2013). Since some authors disagree with this assertion (Lechenet et al. 2014), it is necessary to investigate this problem and better understand the constraint of work organization in pesticide-free cropping systems.

In contrast, some farms have already started transitioning toward a strong reduction in pesticides. These farms represent examples to follow, and dissemination of their innovative practices, or of the knowledge derived from these innovations, must be facilitated. To do so, it would be appropriate to support innovation networks and web platforms that foster information exchange and innovative tools between farmers (Sacchettini and Calliera 2017). These innovation networks can focus on specific local conditions, for example through living labs, or be designed to reach a wider audience by relying on digital tools such as dedicated forums (Maria et al. 2021). Indeed, innovation to achieve pesticide-free agriculture cannot be restricted to top-down processes, from research to farmers, but should also enhance the knowledge and discoveries of those working in the field (Fig. 6).

Renewing extension services and training Extension services to farmers have been largely privatized and fragmented in the past decade (Wuepper et al. 2020), and this tends to encourage pesticide use instead of developing preventive measures (Pedersen et al. 2019). Furthermore, extension services, both public and private, provide generic tactical advice at the field scale rather than strategic advice that is co-produced with farmers for specific needs and conditions (Labarthe and Laurent 2013). Thus, research should provide knowledge and innovative organizations to support extension services so they can provide strategic advice at the scale of the entire cropping system, or even at the territory scale, while facilitating exchanges between farmers to promote participatory innovation (MacMillan and Benton 2014). Beyond training farmers, the education of young people who wish to pursue a career in agriculture must be revised. Whether in high schools or universities, training is often disconnected from the latest systemic innovations. A stronger connection between research and teaching is therefore necessary, as is a more interdisciplinary curriculum, mixing for example crop sciences, animal sciences, ecology, and economics (Hilimire et al. 2014).

Paying farmers for pesticide-free practices Beyond the effectiveness of current policies, more ambitious policies to eliminate pesticides must be developed, in particular by paying farmers who use pesticide-free practices. Indeed, the expected redesign and innovations described previously may not be effective immediately after they are implemented: crop yields may decrease due to the removal of pesticides and costs may increase, in particular labor costs. This phenomenon could be temporary, lasting only during a transition period during which natural regulations are not yet established, or more permanent. Payment should thus be offered to farmers who lose income. If the decrease in productivity is permanent, farmers should receive compensation that corresponds to the public goods produced by pesticide-free agriculture (e.g., increased biodiversity), through subsidies or a better added value of products thanks to a specific label implemented by downstream stakeholders. In addition, other types of subsidies could help farmers invest in new equipment for their fields or in landscape infrastructure.

Fig. 6 The in-depth transformation of agricultural practices, necessary for the success of zero-pesticide systems, is enriched by (1) collective design processes that rely on exchanges between practitioners and researchers and promote the exploration of innovative solutions, and by (2) the confrontation of the solutions imagined to real situations of implementation (agricultural plots). Here, a group of farmers, advisers, and researchers observe the results of new practices implemented in the fields (the management of cover crops). Photograph by Laurette Paravano.

Large-scale transition to pesticide-free systems will, however, require significant public spending to fund these subsidies. Financial resources could come from taxing pesticides, which economists often mention as the most effective tool to decrease pesticide use (Finger et al. 2017). However, several studies have shown that the tax rate must be high for taxation to have a substantial influence (Skevas et al. 2012; Femenia and Letort 2016). These taxes would burden farmers economically, but redistributing tax revenues could increase the acceptability of taxes and effectively support the transition toward pesticide-free practices (Finger et al. 2017). Taxation would be a valuable tool to decrease the loss of profitability for farmers, foster political acceptability, and thus guarantee a smoother transition to pesticide-free agriculture.

Promoting the coordination of stakeholders to foster pesticide-free food chains The market can contribute to offset the lower profitability of pesticide-free practices by increasing the added value of agricultural products and considering consumers' willingness to pay. Indeed, shifting toward pesticide-free food chains requires implementing new strategies and reorganizing agri-food chains, from raw production to consumption, including downstream sector (e.g., marketing and processing) (Meynard et al. 2017). Beyond the well-known issue of diversifying crops in agri-food chains (Magrini et al. 2016; Meynard et al. 2018), research on relevant differentiation strategies for food products is needed to foster transition. Several studies show coordinating private stakeholders by fostering contracts between farmers and retailers can help these chains and products to develop. To ensure that they are effective, however, it is necessary to (1) provide long-term commitment (Möhring et al. 2020b), (2) provide technical advice to support the transition (Cholez et al. 2020), and (3) develop a marketing approach that informs consumers (Bazoche et al. 2014). In parallel, developing traceability and tracking tools for consumers will enable labeled products to be developed. By doing so, private stakeholders could become drivers of change: such tools take advantage of consumers' greater willingness to pay for pesticide-free products and provide a price bonus to farmers who meet these specifications (Florax et al. 2005).

Public and private initiatives to support farmers' income are particularly important since farmers do not consider positive externalities of pesticide-free practices, whether internal (e.g., that influence management of beneficial organisms on their farm) or external (e.g., on bees or aquatic organisms), in their decision-making. To consider these elements better, research should also help develop indicators and methods that can help farmers and their advisors consider ecosystem services. In particular, developing new economic accounting tools that include innovative indicators that highlight ecosystem services and consider multi-year practices is a promising research area.

4 Four cross-cutting objectives and their related multi-disciplinary research topics

In the previous section, we identified major research fronts in multiple domains that must be addressed to achieve pesticide-free agriculture. These research fronts should be coordinated to develop coherent systemic innovations that foster the transition. It is particularly important to design innovations that can benefit from each other. For example, agronomic practices and biocontrol solutions should be designed in a coordinated way that enhances natural regulation and allows new relationships between plants and their environment to be established. The associated equipment and choice of crop varieties should also be part of this rationale. Similarly, crop diversification, which is necessary to reduce pesticide use, should be addressed simultaneously at multiple scales and in multiple disciplines, from breeding to social sciences, to remove the many obstacles from upstream to downstream of the agri-food chain. Beyond these examples, we reviewed the five strategies to achieve the pesticide-free goal and identified complementary research topics because of their target, their scales, or the stakeholders involved. This identification then led to a collective design work on cross-cutting objectives and their relative research topics, as detailed in Fig. 7: (1) pesticide-free cropping systems should be based on enhanced natural regulations, (2) pesticide-free cropping systems should rely on tailored practices, (3) pesticide-free landscapes should be designed and enabled by coordinating stakeholders, and (4) pesticide-free cropping systems should be included in value chains. Priority research topics emerge from these cross-cutting objectives that highlight synergies that are needed among the research fronts identified. All of these topics are essential steps to achieve pesticide-free agriculture.

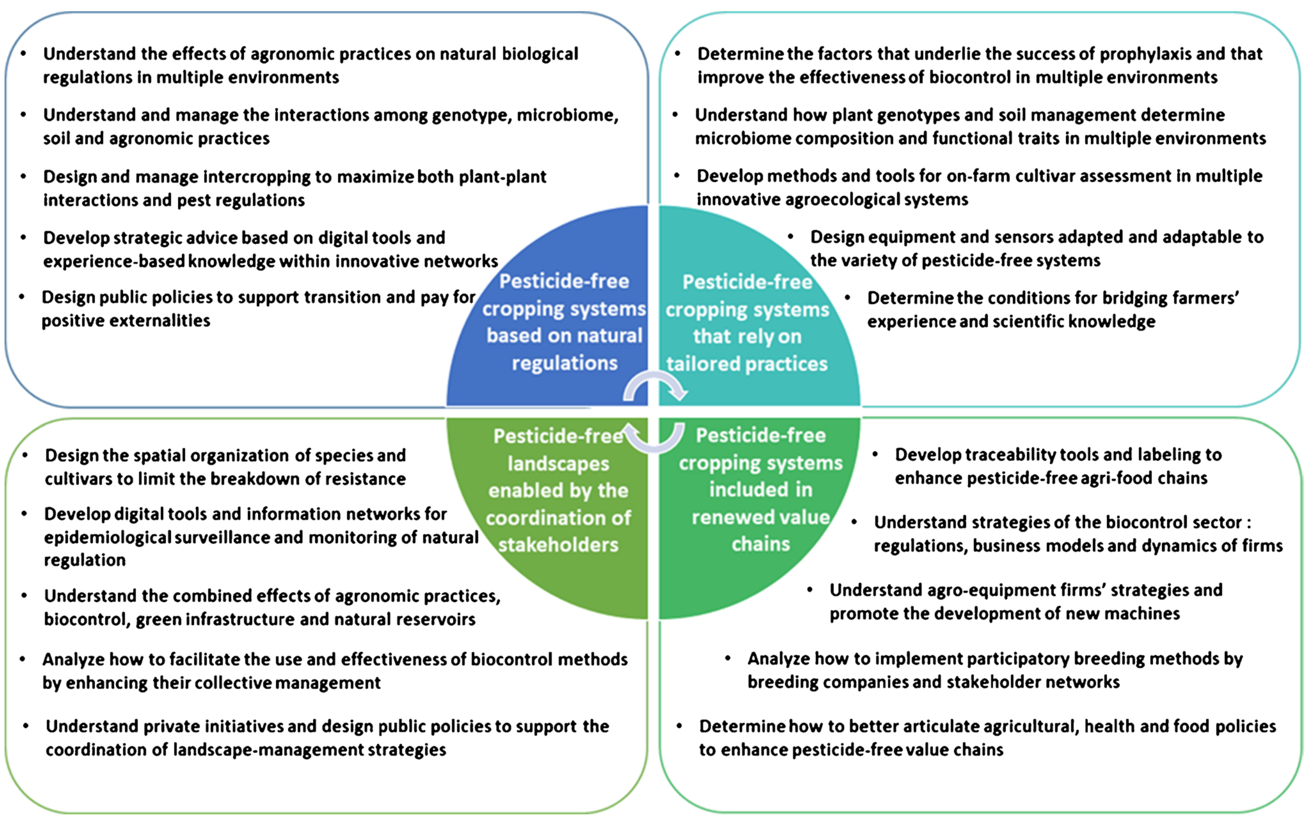

Fig. 7 Cross-cutting objectives and their related research topics. These objectives were designed collectively by the authors from the identification of complementary research topics that (1) belong to the five strategies to achieve the pesticide-free goal and that (2) are characterized by similar targets, scales, or the stakeholders involved.

5 Conclusion

The ambitious objective of pesticide-free agriculture forms part of large societal and planetary challenges, such as preserving ecosystem integrity and protecting biodiversity, defined in the United Nations' Sustainable Development Goals. However, reducing pesticide use substantially is a complex issue since the entire agri-food sector has been organized for decades around pesticides as a cornerstone. Agricultural research concerns itself with pesticide dependence: most current research programs produce knowledge and lead to innovations that can fit directly into current pesticide-dependent agricultural systems. In this context, we argue that a change of course is needed today to find solutions for tomorrow. Agricultural research has a major role to play by developing innovative, cutting-edge research within a pesticide-free paradigm. We identified the research fronts that should be explored to create strategies that will enable pesticide-free agriculture. These research fronts should be strongly coordinated to develop pesticide-free cropping systems based on enhanced natural regulations, built upon tailored rather than generic solutions, designed at the landscape scale and enabled by transforming value chains. However, researchers can pursue these new research avenues only if the organization, incentives, and funding of research are deeply redesigned, with clearly established mission-oriented goals. In addition, funding for long-term projects should be encouraged to allow for enhanced interdisciplinarity, risk-taking, and investment in both basic research topics and participative research that involves farmers and the entire agri-food chain. The entire research and innovation system should also be transformed, including extension services and training.

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Declarations

Conflict of interests The authors declare no competing interests.

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