Pesticide-free agriculture: is a third way possible besides organic and conventional agriculture?

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Abstract

Pesticides are widely used in agriculture to protect crops from animal pests, diseases, and weeds, helping to maintain yields under diverse production conditions. However, their widespread and repeated use has led to environmental contamination, biodiversity loss, and growing concerns about human health. While Integrated Pest Management (IPM) and organic farming have sought to reduce pesticide dependency, both approaches still permit pesticide use, and their adoption remains limited due to technical and economic constraints. In this context, we explore the feasibility of a third way: pesticide-free agriculture based on agroecological crop protection (ACP) principles. Drawing from the *Rés0Pest* experimental network launched in France in 2012, we present ten years of results from nine sites covering a range of pedo-climatic conditions and socio-economic contexts. *Rés0Pest* implemented cropping systems that excluded all pesticide use, including seed treatments, while maintaining synthetic fertilizer inputs. The systems were co-designed through participatory methods, following a system experiment approach that evaluates the effects of a combination of cropping practices and their interactions on cropping system performance over the long term. Results showed that in pesticide-free systems, it is possible to achieve yields comparable to conventional and higher than organic systems and, in some cases, generate higher net farm income. Pest and pathogen crop damage did not significantly increase over time, although weed management remained a key challenge. These findings suggest that technically and economically viable pesticide-free arable systems are possible under certain conditions, and that new solutions are needed to support their adoption across a wider range of contexts. We discuss implications for research, farming, and policy, and emphasize the need for adaptive experimentation and systemic performance assessment to support agroecological transitions.

Keywords: arable crops, livestock systems, pesticide-free agriculture, agroecology, crop protection, sustainable farming

Introduction

Pesticides: an Achilles heel of crop protection

A key feature of industrial agriculture is the need to use pesticides to protect crops from potential pest damage caused by animal pests, weeds, or pathogens to achieve expected yields (Lamine et al. 2010). The high dependency of industrial agriculture on pesticide use is, to some extent, due to the low diversity, agroecosystem simplification, and lack of preventive measures that is commonly found on industrial farms. In simplified agroecosystems several interdependent interactions and ecosystem services are lost, resulting in a disequilibrium (Meehan et al. 2011). In that context, biological regulations that occur naturally to prevent pest development cannot take place and frequent external interventions and inputs are therefore required for crop survival. Nevertheless, after recurrent exposure, pest populations often develop resistance to herbicides, fungicides, and insecticides (Hawkins et al. 2019). When this occurs, new pesticides are sought to replace the previous ones. In doing so, a cycle of dependence is created and with it the emergence of pest populations that are resistant to multiple pesticide chemistries and more difficult to control.

The pesticide-dependent agricultural model can lead to environmental pollution that causes significant damage to biodiversity and human health (Rani et al. 2021). Substantial amounts of pesticides have been detected recently in biota, soil, water and air as well as in very remote areas such as deep waters or sub-polar regions (Leenhardt et al. 2022). Furthermore, highly toxic pesticide molecules can persist in the environment for many years. Accurately measuring the impact of pesticides on biodiversity loss is particularly challenging due to its complex and multifactorial nature (Andrade et al. 2021). However, an increasing number of studies indicate that pesticide use is one of the major drivers of biodiversity decline, and its impact on the drastic reduction in populations of ground beetles, pollinators, and birds is now incontestable (Boatman et al. 2004; IPBES 2019; Sánchez-Bayo 2021) Unsurprisingly, agriculture-intensive areas are the most contaminated by pesticides (Leenhardt et al. 2022).

Since prolonged exposure to these substances undermines the proper functioning of life processes and the sustainability of agroecosystems, there is an urgent need for a profound and radical change in the way crops are protected from damage caused by pests. To date, several strategies have been explored to reduce pesticide use. Among the most popular and encouraging strategies is Integrated Pest Management (IPM), defined by the United Nations' Food and Agriculture Organization (FAO) as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms" (Vétek et al. 2017).

Another popular strategy is organic agriculture, which prohibits the use of synthetic pesticides and fertilizers and emphasizes the maintenance of soil fertility and nutrient cycles (Reganold and Wachter 2016). However, it allows the use of natural-origin pesticides such as copper, which is generally considered less harmful. Yet, repeated applications of copper lead to its accumulation in soils, causing toxicity to plants, soil microorganisms, and earthworms, and potentially disrupting key ecological functions (Adrees et al. 2015; Andrivon and Savini 2023).

Despite a wide range of efforts, pesticide use has continued to increase worldwide (FAO 2024), due to several factors. IPM practices are often only partially adopted by farmers, limiting their effectiveness. In organic systems, yields tend to be lower than in conventional ones, which reduces economic profitability and hinders wider adoption. Moreover, both IPM and organic agriculture still allow the use of certain harmful pesticides, which remain widely used across various cropping systems.

Identifying, evaluating, and effectively implementing agricultural practices that ensure environmental and human health while preserving optimal crop yields is now a top priority in the agricultural sector worldwide (FAO 2018b, 2018a; Mouhamed et al. 2023). This challenge is further intensified by the steady expansion of cropping areas to meet the food demands of a growing global population (FAO 2023), a trend that can also lead to increased overall pesticide use.

Public policies: a crucial lever to shift the pesticide-based agriculture paradigm

Public policies play a key role in shaping agricultural practices to better address environmental and health concerns. In Europe, the Green Deal sets out an ambitious response to today's environmental challenges (Guyomard et al. 2020). Its two main pillars, the Farm to Fork and Biodiversity strategies, lay out a 10-year roadmap to transform food systems across EU countries by 2030 (European Commission 2020). These strategies include concrete targets, such as increasing organic farming, reducing nutrient pollution, and cutting pesticide use. Specifically, the Green Deal aims for a 50% reduction in the use and risk of chemical pesticides, including the more hazardous molecules, by 2030.

At the global level, major bodies such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have highlighted how pesticide-induced biodiversity loss is linked to food, health, water, and climate security, calling for holistic policies that integrate agriculture, environmental protection, and public well-being (IPBES 2025). While these goals are widely endorsed, a critical question remains: to what extent are they achievable in practice? Policies aimed at reducing pesticide use are not new. For instance, DDT was banned in the USA in 1972 (Keane 1972) and Denmark initiated the development of public policies for pesticide reduction as early as 1980 (Pedersen and Nielsen 2017). Since then, similar policies have been gradually emerged across the European Union (EU). Notably, EU Directive 2009/128/EC, established in 2009, aims to reduce pesticide use through national action plans. Between 2012 and 2022, pesticide use in Europe decreased by 7%, indicating a regional decline in contrast to the global trend, where total pesticide use rose by 13% over the same period (FAO 2024). Nonetheless, concerns remain regarding the feasibility of meeting the ambitious goals set out in the European Green Deal (Guyomard and Bureau 2020).

Although pesticide regulations in EU agriculture have led to the removal of a considerable number of hazardous and widely used substances from the market (Kudsk and Mathiassen 2020), a disruptive shift, such as striving for completely pesticide-free agriculture (Finger and Möhring 2024), is necessary to achieve a profound transformation. This transformation requires significant efforts to redesign agroecosystems (Hatt and Döring 2023; Jacquet et al. 2022a). A fundamental step in this process is transitioning from a 'recipe' and input-based model, where crop protection through pesticides use plays a central role, to a process and knowledge-based model, where prophylaxis, a set of non-chemical measures to prevent crop damage before it occurs, forms the core of pest management strategies (Fig. 1).

Agroecological crop protection (ACP): a way out of pesticide dependency

While IPM and organic agriculture have contributed to reducing pesticide dependency, agroecology promotes a more radical and systemic redesign of cropping systems. It goes beyond input substitution to address the root causes of pressure from animal pests, pathogens, and weeds by transforming the structure and function of agroecosystems (Deguine et al. 2021). Agroecology can be defined as "the application of ecological concepts and principles to the design and management of sustainable agroecosystems" (Gliessman 2018). It encompasses three dimensions: a set of scientific disciplines, a body of agricultural practices, and a framework for social transformation (Wezel et al. 2009). Three core principles guide agroecological crop management: producing in alignment with ecosystem functions, maximizing functional biodiversity, and reinforcing biological regulations within agroecosystems (Malézieux 2017). ACP is therefore the application of the core scientific principles of agroecology to crop protection and is structured around three key management pillars: i) prophylactic techniques; ii) integration of plant diversity both temporally and spatially; and iii) preservation or enhancement of soil health (Deguine and Ratnadass 2017; Lucas et al. 2017).

In the field, the implementation of ACP follows a systemic, sequential, and ecologically grounded strategy (Deguine and Ratnadass 2017). It begins with prophylactic measures such as the use of adapted cultivars, crop rotation, cover crop management, healthy seeds, direct seeding, and sustainable irrigation and fertilization. The reduction of pest populations and the promotion of regulatory populations are then pursued through complementary practices, including the establishment of refuge zones, cultivar mixtures, intercropping, trap or repellent plants, field border management, and the creation of ecological compensation infrastructures such as hedgerows, corridors, and herbaceous or floral strips (Fig. 1). Within the ACP framework, pesticides are considered strictly as a last resort, applied only after a thorough assessment of phytosanitary risks (Deguine et al. 2023). Documented field implementations, especially in the tropics, have demonstrated that ACP is an effective approach for designing multifunctional and productive pesticide-free cropping systems (Deguine et al. 2015, 2018; Ratnadass 2017)

To date, few examples exist of pesticide-free cropping systems for temperate arable crops and they mainly concern organic agriculture (Jacquet et al. 2022b). Hence, it is an open question whether pesticide-free, non-organic cropping systems could: i) be technically feasible (i.e., practically implementable with current agronomic knowledge and tools); ii) reach acceptable levels of production; iii) preserve the environment and resources; and iv) ensure sufficient economic returns to farmers with acceptable workload.

In this article, we present the design and performance of an experimental assessment of pesticide-free cropping systems in France. Cropping systems in nine different agricultural regions were set up in a national network called "*Rés0Pest*" (Fig. 3). We describe the design steps for locally adapted cropping systems, underlying agronomic principles, crop sequences, and associated crop management plans implemented at each site, then present results on yields of each cropping system and the net farm income. Finally, we discuss the relevance of implementing systemic approaches based on ACP principles to generate knowledge that can support the design of cropping systems that are less reliant on pesticides, or even entirely pesticide-free.

Research orientation and experimental approach

Rés0Pest is an experimental French network launched in 2012 as part of the French national action plan aiming the reduction of pesticide use by 50% within 10 years (Anonymous 2015). In this network, we adopted a forward-looking research orientation that focused on high-risk, high-reward experimentation. This approach involves testing innovative and unproven strategies that could lead to significant breakthroughs in the development of pesticide-free cropping systems, but which also carry the possibility of failure due to their novelty and the complexity of interactions between agricultural practices. By taking on these risks, we aim to achieve substantial rewards in terms of both scientific advancements and real-world impact. Furthermore, we implemented a systemic experimental approach, considering the entire cropping system at the plot level as the object of study, rather than focusing on isolated technical components.

Here, a cropping system is defined as a given crop sequence (including intercrops and cover crops if appropriate) and the associated set of decision-making rules that govern the cropping management strategies implemented (Boiffin et al. 2001; Debaeke et al. 2009; Lechenet et al. 2017; Sebillotte 1990). Decision-making rules clarify the logic behind technical decisions made in response to field observations, such as changes in environmental conditions, potential agricultural risks, or practical limitations related to labor, equipment availability, or time constraints. Each rule serves a specific function: it aligns the decision with the overall objectives of the cropping system and limitations of the production situation. For example, if a particular condition is observed ('if'), a corresponding set of actions may be taken ('then'). Finally, evaluating the outcomes assesses whether the decisions made have successfully met the intended objectives (Debaeke et al. 2009). In this network, the decision rules corresponded to a simplified version of the decision rule system described by Debaeke et al. (2009). These decision rules were formalized as a list of technical operations aimed at achieving specific objectives and were evaluated based on the degree to which these objectives were met (Table 1).

A systemic experimental approach was used for designing all cropping systems of the *Rés0Pest* network because this approach focuses on ensuring agronomic consistency in the combination of management strategies to be tested. Each cropping system was therefore tailored to meet a set of predefined objectives, making the evaluation of system performance the primary method for assessing the appropriateness of the management strategies tested. This method allows for evaluating impact of the overall combination of techniques rather than the statistical effect of any specific technical choice (Fig. 2). This approach differs from factorial experimental methods evaluating effects of a limited number of factors that vary independently while keeping other aspects of the cropping system constant (Fig. 2). Although factorial experiments allow the use of classical statistical methods to isolate and quantify the effects of each factor and their interactions, they typically provide only limited consistency across the technical, socio-economic, and environmental components of the cropping system. These limitations can compromise the practical applicability for farmers in real-world settings (Meynard 2017).

In system experiments, the set of decision-making rules can be either fixed or iterative (Debaeke et al. 2009; Lechenet et al. 2017). When they are fixed, they allow for the evaluation of cumulative effects of the cropping system on a range of dependent variables such as soil organic matter content, yield performance, and weed seed banks, and help to determine the time required to reach and stabilize an expected function. However, if fixed decision rules are not successful in accomplishing their assigned functions, they can lead to irreversible deterioration of the environmental and socio-economic components of the cropping system and compromise the feasibility of the whole experiment (Lechenet et al. 2017). Conversely, the iterative approach adopted in the *Rés0Pest* network offers flexibility to modify and implement new decision rules between growing seasons. This strategy is organized around learning loops that include four main steps: diagnosis, exploration, implementation, and assessment (Debaeke et al. 2009; Meynard et al. 2023a). This iterative approach acknowledges that experimenters, akin to farmers, learn continuously from observing and evaluating their cropping systems (Coquil et al. 2014). By integrating the learning process from each growing season, it is possible to gradually enhance the performance of the cropping system through fine-tuning the management practices and associated decision rules.

However, allowing the cropping system to evolve over time presents a challenge at the scientific level: it becomes difficult to identify the primary drivers of performance, posing a significant obstacle to scaling up these practices. Moreover, this approach deviates from the standard experimental model, where the effect being studied must remain constant throughout the experiment (Shadish et al. 2002). This constraint calls for a new way to scale up, where the focus shifts from transferring individual high-impact practices to identifying successful combinations of practices and the learning process that can be adapted to different contexts. By embracing this dynamic process, we can inspire and guide the adaptation of practices to local conditions, moving away from a one-size-fits-all model toward more context-sensitive solutions.

Co-design, guidelines and monitoring of pesticide-free cropping systems

At the start of the *Rés0Pest* experiment, we organized participatory workshops, held in person at each site (except for Lamothe, see below), with a duration ranging from 1 to 4 days depending on the site. These workshops brought together farmers, experimenters, farm advisors, technical engineers, and researchers to mobilize scientific and expert knowledge and collectively explore solutions for designing pesticide-free cropping systems. Each workshop was organized following the KCP (Knowledge, Concepts, Proposals) methodological approach described by (Berthet et al. 2016), (Agogué et al. 2014), and (Jeuffroy et al. 2022). The workshops began with an initial knowledge-sharing phase (K), where participants were encouraged to discuss and exchange ideas about known or desired solutions. This was followed by a concept generation phase (C), during which a variety of solutions were identified and evaluated using tools such as the STEPHY calculator (Attoumani-Ronceux et al. 2011) and expert knowledge. At this step, participants collectively selected the most promising solutions for the target cropping system. Finally, during the proposal phase (P), a prototype of the intended cropping system was developed. In the case of the Lamothe site, a simplified workshop was organized for the design of the cropping system, which included only people working on the network and the supervisor of the experimental station.

During the concept generation phase, participants were encouraged to propose innovative solutions within specified guidelines. Two key constraints were initially established: one, the exclusion of all pesticides, including seed treatments; and two, the requirement to include arable crops that are representative of typical farms in each region, including those integrated with livestock systems. Perennial species, cultivated as sole crops or in intercrops, including the legumes alfalfa (*Medicago sativa*), sainfoin (*Onobrychis viciifolia*), purple clover (*Trifolium pratense*), and white clover (*Trifolium repens*), and the grasses ryegrass (*Lolium perenne*) and sweetgrass (*Hierochloe odorata*), were included in rotations as temporary meadows for up to three years. Additionally, three primary objectives were outlined: i) maximize marketable yield; ii) maximize farmer income; iii) limit environmental risks associated with cropping practices other than pesticide use, such as greenhouse gas emissions.

To ensure consistency in the experimental design across the nine cropping systems, a set of methodological constraints was defined:

- Since the available area at each site in the network did not allow for the sowing of every crop in the sequence, at least 50% of the crops had to be sown annually to ensure minimal temporal repetition and to assess inter-annual variability (see (Longis et al. 2024)
- A minimum plot size of 0.48 hectares (minimum width 48 m, minimum length 100 m) was required to facilitate the use of compatible farm machinery;
- A minimum duration of the experiment equivalent to at least one complete crop sequence (ranging from 4 to 9 years for the shortest and longest rotations, respectively) to study the cumulative effects of the crop sequence;
- Performance objectives for each cropping system were to be clearly defined based on the designers' experience and regional crop production standards to evaluate how often the expected result was obtained. Due to the size of the experimental unit, which restricts the number of possible replications, including control treatments was not recommended;
- The inclusion of at least one agroecological infrastructure element, such as a grass strip, hedgerow, or floral strip, was mandatory.

Standardized data collection protocols were implemented to monitor all cropping systems within the network. Key yield components were tracked, such as plant biomass accumulation, grain weight, and grain count. Crop damage was quantified through systematic observation of visible symptoms of animal pest or pathogen attacks (e.g., lesions, necrosis, or chlorosis). These observations were conducted in dedicated observation and monitoring plots in which data were collected at specific growth stages to assess the crop damage temporal progression. Weeds were assessed by counting individual plants, estimating their density and spatial distribution across the plots. Furthermore, auxiliary populations, such as natural predators and beneficial microorganisms, were evaluated based on their relative abundance and species diversity. Soil properties, including physico-chemical and biological characteristics, were measured alongside meteorological data, which are crucial for understanding the environmental conditions influencing cropping system performance. Technical data, including the date, type, and frequency of interventions (e.g., tillage, sowing, and harvesting), the equipment used (e.g., rotary hoe, spiked harrow, header machine), and input applications (e.g., fertilizer, irrigation, seed treatments) were also documented. All data were recorded on a shared online platform, Agrosyst (Peyrard et al. 2023), and stored in Excel files within a project-dedicated SharePoint site.

An annual report was prepared for each site, summarizing the main technical operations conducted during each campaign, the key challenges encountered in achieving yield and quality targets, and a list of potential solutions for the next campaign to prevent and address these issues. This document also assessed the experimenters' satisfaction with the achievement of objectives using a set of decision rules tailored to each cropping system (Table 1). Overall, the annual report captured significant events from the year, interpreted the results, and compiled key messages to share across the network. This document enabled the consortium to identify necessary adjustments for subsequent years to improve the project’s management. Finally, after ten years of experimentation, two researchers involved in *Rés0Pest* data analyses conducted in-person interviews with eight experimenters, two coordinators, and one researcher to gather feedback on their experiences.

Description of pesticide-free cropping systems

The pesticide-free cropping systems of the network were established at nine sites in France with different pedoclimatic and socio-economic conditions. An overview of the number and distribution of plots is presented in Fig. 4. Crop sequences for each site are briefly described in Table 2, and the set of cropping practices is summarized in Table 3. The crop sequence implemented in Bretenière is illustrated to show the underlying reasoning followed to prevent pest damage while preserving yield and crop quality (Fig. 5). Cultural control played a prominent role in the crop management plans of the *Rés0Pest* cropping systems, accounting for 59% of the total practices tested (Table 3). This emphasis stems from the prioritization of prophylactic measures during the design process. Furthermore, *Rés0Pest* crop sequences were more diversified than typical French crop sequences for arable crops, such as canola (*Brassica napus*) - wheat (*Triticum aestivum* L.) – barley (*Hordeum vulgare* L.). The diversification of crop sequence by including new crops such as soybean (*Glycine max* (L.) *Merr*.) and hemp (*Cannabis sativa* L.), the diversification of sowing dates, the use of resistant or tolerant cultivars, and the use of mechanical weed management collectively constitute the core practices to prevent pest attacks across the network.

A graphical scheme was designed for each site to visualize the list of planned cropping practices for pathogen, animal pest, and weed management plans. Fig. 6 depicts an example of selected cropping practices for weed management at Bretenière. The scheme also specified the required agronomic or environmental conditions in which certain cropping practices should be implemented. For example, in the scheme, we indicated that mechanical weed management should be carried out only in situations presenting a high risk of dense weed growth or the presence of highly competitive weed species. In some cases, two alternative options were assigned to a single cropping practice. In the case of soybean, for example, a decision on row spacing was determined by assessment of the risk of occurrence of high weed density. This graphical tool (Fig. 6) was very useful for experimenters to follow or to modify management plans in order to maximize overall cropping system performance.

Agronomic performance of the *Rés0Pest* network

Yield and harvest quality were two key indicators used to evaluate the agronomic performance of *Rés0Pest* crops each year. Since there were no available reference data for expected yields of crops cultivated using synthetic fertilizers but without pesticides, as in *Rés0Pest*, the yield objectives were estimated based on data from public databases (e.g., FranceAgrimer, Agreste) for crops grown under conventional systems (with both pesticides and synthetic fertilizers) and organic systems (without synthetic pesticides or fertilizers) in the relevant region. Thus, the *Rés0Pest* yields were expected to be in the middle range; higher than those of organic systems but lower than those of conventional systems. For less common crops, such as hemp, where official yield data were scarce or unavailable, yield targets were established before field trials, mainly based on expert opinions from agronomists, researchers, and technicians with experience in managing such crops. In both cases, the yield targets were adjusted by the designers to account for the constraint of producing without pesticides, aiming for achievable yield objectives.

To assess the extent to which yield objectives set by the designers were achieved across the network, we calculated the median of the yield obtained and the median of the percentage of yield targets met for each crop tested across different sites and years (Fig. 7). For crops cultivated using different modalities, such as intercropping (growing two or more crops together), companion plants (plants grown together for mutual benefit), or relay cropping (sequential planting of two or more crops in the same field within a single growing season), these values were calculated separately, as the target yields varied. Overall, yield objectives were fully reached (100% or more), almost reached (75-99%), or not reached (0-74%) in 36%, 38%, and 26% of the crops tested, respectively, across the sites and years (Fig. 7). This result indicates that the results are globally encouraging, as yields in most cases were close to the targets, and only a minority of crops had yields significantly below the initial objectives.

Given that sugar beet (*Beta vulgaris* L.) is highly dependent on insecticides such as neonicotinoids (Epstein et al. 2022; Hauer et al. 2017), the designers of *Rés0Pest* initially estimated a 50% harvest loss for pesticide-free sugar beet compared to the average conventional yield. However, over three growing seasons (2014, 2015, and 2017), the yield of pesticide-free sugar beet was double what was initially expected and equivalent to that of conventionally farmed sugar beet in the region during the same seasons. Interestingly, producing pesticide-free sugar beet did not result in higher production costs and did not negatively impact net farm income. Indeed, in the cropping system including sugar beet in the crop sequence and tested in Estrées-Mons, the net farm income was, on average, higher than three times the national minimum wage per month, which is considered high in the French socio-economic context (Fig. 9). This result is particularly remarkable in France, where the use of neonicotinoids was banned due to health concerns but was re-authorized in 2025 in response to severe damage to sugar beet crops by the beet yellows virus and the absence of viable alternative treatments. To date, almost no alternative has been found to replace their function (Hauer et al. 2017), and recent solutions from the National Research and Innovation Plan (INRAE and ITB 2020) are partially effective and not yet scaled up. Indeed, the agroecological principles used to produce pesticide-free sugar beet in *Rés0Pest* could provide valuable insights for producers in the region.

To gain an overview of the yield performance in *Rés0Pest* compared to conventional and organic production systems, we analysed the results for wheat, as it was the only crop in the network produced in eight different French regions over several years. Figs. 8A and 8B show the yield performance of bread wheat for these three production systems by region. Information about the average yield of bread wheat produced conventionally between 2013 and 2020 by region was obtained from the Agreste (2023a) database. The average yield of organically produced bread wheat by region was not available. However, we used the average national yield gap (2018 to 2022, Agreste, 2023b) between conventional and organic production of bread wheat to estimate the regional yield of organic bread wheat. Overall, the yield of pesticide-free bread wheat was lower than that of conventional wheat but higher than that of organic wheat. Similar region-specific results were also observed for durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) at Auzeville and Mauguio, and triticale at Estrées-Mons, Grignon, and Le Rheu (Fig. 8C). However, at the Lamothe site, bread wheat yields were lower than those for organic bread wheat. Importantly, Lamothe was the only site included five years after the creation of the network without undergoing a formal design process involving multiple and external stakeholders and other external actors to the experimental station. This may partially explain the initial mismatch in the choice of the species and crop sequences, which were not fully aligned with the site's pedoclimatic and socio-economic conditions.

The quality of cereal harvests can be affected by the presence of mycotoxins. Mycotoxins are molecules produced by certain fungi that are considered toxic for animal and human consumption when their detectable amount exceeds the tolerable legislative limits. Several *Fusarium* species can infect small grain cereals such us wheat, barley, and oats (*Avena sativa* L.) or maize (*Zea mays L.*) and can produce a type of mycotoxin called deoxynivalenol (DON). In *Rés0Pest*, the concentration of DON ($ng \cdot g^{-1}$) was monitored for each harvest of cereal crops (bread wheat, durum wheat, maize, sorghum (*Sorghum bicolor (L.) Moench*), spring barley, triticale (*Secale x Triticum*), winter barley). On average, the quantities of DON detected in cereal crops within the Rés0Pest network remained below the European legislative limit of 1250 ng·g^{-1} for human consumption and 8000 ng·g^{-1} for animal feed (e.g., triticale in this study; Fig. 10). Only one harvest of bread wheat at Grignon in 2016 exceeded the permitted level, which experimenters attributed to high humidity during production. Although site-specific DON data for conventional or organic cereals in the same regions were unavailable, prior studies indicated no significant differences between organic and conventional systems, with variations driven more by weather conditions, years, locations, and cropping practices like tillage and crop sequence than by type of farming system (Brodal et al. 2016; Mruczyk et al. 2021). Together, these results suggest that an increase in mycotoxin production in pesticide-free production systems may not represent a significant risk.

Insights from experimenters and multi-performance assessments of *Rés0Pest*

Conducting a pesticide-free cropping system was a new experience for *Rés0Pest* experimenters. Accepting the paradigm shift from a pesticide-based agricultural model to one free of pesticides was one of the major barriers faced during the implementation and management of the cropping systems in the network. Experimenters often had multiple concerns about the feasibility of the management plans. However, with the results of the first harvests (2013-2015), experimenters slowly gained confidence in the feasibility and relevance of the approach. Fig. 11 shows examples of the results from *Rés0Pest* trials. Beyond the performance evaluation of pesticide-free cropping systems, the expertise experimenters gained in conducting and exploring the feasibility and environmental benefits of these systems is one of the most valuable outcomes of the network.

Guillaume Auderbert, an experimenter at Lusignan, considered that the knowledge gained at *Rés0Pest* was valuable for improving the management of other cropping systems:
"The *Rés0Pest* trial is a great playground in terms of reducing the use of pesticides. Indeed, it is a real challenge to grow crops known to be pesticide-intensive (e.g., canola), on which synthetic fertilizers are applied. This pilot trial at Lusignan allows us to acquire new knowledge in the management of pests, knowledge that can be re-mobilized for the crop management of other trials of the experimental unit."

Antoine Savoie, experimenter at Nouzilly, thought that the experience of conducting the *Rés0Pest* cropping system offered him the opportunity to exchange ideas with farmers from both conventional and organic agriculture:
“The interest of the zero pesticides approach in conventional systems is that we can exchange as much with organic farmers as with conventional ones. The former are interested in the consequences of mineral fertilization on yields and weeds, while the latter consider the extreme scenario of a total ban on pesticides.”

Philippe Le Roy and Jean-Marc Valdrini, experimenters at Le Rheu, considered that *Rés0Pest* allowed them to test solutions to reconcile the challenge of producing enough food and preserving human and ecosystem health:
"The *Rés0Pest* system trial provides a link between research and the agricultural world. This experimentation can help to meet the challenge of producing enough food, while sustainably preserving ecosystems and human health. The major difficulty with this cropping system, which was set up in 2012, is the control of certain weeds (*Rumex* in particular) and the development of grasses around the edges of the plots, despite the implementation of various levers."

Alain Berthier, experimenter at Breteniѐre, agreed that one of the major difficulties in conducting the *Rés0Pest* cropping system was dealing with weed management. However, the cropping practices he implemented can now be shared with farmers and advisors who are willing to reduce pesticide use:

"The conversion of the plots dedicated to this project to a zero-pesticide system could have seemed a challenge, especially because of the strong presence of classic weeds. However, the various levers put in place, including controlled management of nitrogenous manure and the establishment of cover crops, have made it possible to keep the plots clean after the fifth harvest. The *Rés0Pest* site is regularly visited by groups of farmers and advisors looking for solutions to reduce phytosanitary products or to consider conversion to organic farming."

Net farm income (€·ha^{-1}·year^{-1}) is a key indicator of economic viability in agriculture, as it measures profitability after accounting for all farm expenses and can reflect the ability of cropping systems to sustain farm operations and support livelihoods. Since not all terms of the crop sequences were represented each year in this study, net farm income for each cropping system was calculated in two steps. First, average yields were computed for each crop within the system over at least one complete crop sequence (4 to 9 crop-years depending on the site). For example, at Breteniѐre, yield averages were derived for canola, bread wheat, soybean, spring barley, industrial hemp and pea cultivated across the four plots until completing one full crop sequence (from 2013 to 2020). Second, these average yields were associated to pricing scenarios using FranceAgriMer indices; IPPAP (Indice des Prix du Produit Agricole à la Production Agricole) for crop output prices and IPAMPA (Indice des Prix d’Achat des Moyens de Production Agricole) for input costs, across crop-years from 2013 to 2022, to evaluate price evolution impacts on system profitability (Cellier et al. 2024). Overall, at the Auzeville, Breteniѐre, Estrées-Mons, and Grignon sites, the net farm income was higher than the equivalent of one minimum wage per month in all pricing scenarios from 2013 to 2022. Notably, the Estrées-Mons site showed very encouraging results, with a net farm income higher than the equivalent of three times the minimum wage in most of the pricing scenarios (Fig. 9). In contrast, at sites like Le Rheu, Lusignan, Nouzilly, and Mauguio, the net farm income fell below the equivalent of one minimum wage per month. Calculations focused solely on vegetal production, excluding livestock revenues and costs. This analytical simplification may explain the lower rankings of multi-crop livestock systems at sites such as Le Rheu, Lusignan, and Nouzilly (Fig. 9).

We conducted a socio-economic and environmental assessment of *Rés0Pest* cropping systems after 10 years of experimentation (Cellier et al. 2024) using Criter 5.4 and MASC® 2.0 as evaluation tools (Sadok et al. 2009). According to the durability scale set by MASC® 2.0, the contribution of *Rés0Pest* cropping systems to sustainable development ranged from medium to very high, with a significant contribution to the environmental dimension across all sites (Cellier et al. 2024). The socio-economic contribution, however, was site-dependent. Mauguio, Lusignan, Nouzilly, and Le Rheu showed a low contribution to the economic performance primarily explained by low net farm incomes, whereas Mauguio, Breténiere, Grignon, and Lusignan exhibited a low contribution to the social component, mainly due to the limited workforce used in these cropping systems.

Key lessons after 10 years of the implementation of a pesticide-free experimental network

Working as a network. Implementing, managing, and monitoring a multi-site and multi-year network of pesticide-free cropping systems is a daunting task. Challenges faced by the network ranged from a lack of knowledge about pesticide-free production practices and fears about feasibility to limited financial resources and technical problems with shared databases. Despite these difficulties, the consortium managed to work together for 10 years and complete one or even two crop sequences across the sites. Overall, network members agreed that communication was crucial to support each other, gain confidence, and share knowledge. Experimenters emphasized that the annual meetings and seminars organized among the different experimental units enabled them to inspire each other, progress together, and put collective learning into practice. Furthermore, experimenters often expressed that *Rés0Pest* provided a unique opportunity for them to conduct an experiment where they were encouraged to exchange information with both organic and conventional farmers, learn from their daily observations, and propose new ways of applying basic knowledge in practice to test alternative solutions and/or develop new solutions tailored to their specific contexts.

Interestingly, the *Rés0Pest* experimenters who were interviewed noted that the project significantly changed the way they manage other experiments at the same experimental station. They explained that the knowledge they gained from working on *Rés0Pest* had influenced their approach to experiments where no pesticide restrictions exist. In fact, they mentioned that they now find it challenging to work on experiments that require them to follow predefined and less flexible crop management plans. This shift is largely due to their experience with alternative pest management practices in *Rés0Pest* and their growing preference for working without the use of pesticides.

The valuable knowledge, expertise, and collective learning built throughout the network will be carried forward. In fact, this experience has laid the foundation for a new project called *0Phyto* (2025–2030, funded by the Ecophyto Strategy 2030; Anonymous, 2024), which will continue and expand the ambitions of *Rés0Pest* by integrating experimental data obtained from organic agriculture experimental networks. In *0Phyto*, the core mission remains the same: to support the transition toward pesticide-free agriculture by fostering co-designed, long-term systemic experiments across a wide range of pedoclimatic contexts.

Experimental design choice. While the *Rés0Pest* network aimed to explore the feasibility of pesticide-free cropping systems under real-world conditions, several limitations of the experimental design must be acknowledged. First, not all terms of the crop sequences were represented each year, which complicates the evaluation of inter-annual variability and limits the ability to isolate year effects (Longis et al, 2024). Second, the flexibility allowed in crop management, though necessary to adjust practices and avoid crop failure, compromises the ability to rigorously assess the causal effects of specific practices. This evolving nature of decision rules challenges core conditions of experimental control, such as treatment consistency and the isolation of variables over time, which are essential for valid causal inference as emphasized by Shadish et al. (2002). As a result, *Rés0Pest* experiments did not fully meet the criteria of standard experimental designs.

Instead, they align more closely with the notion of managed observatories (Geslain-Lanéelle 2018; Vereijken 1986, 1992), in which cropping systems are monitored and can be also iteratively adapted based on field feedback and contextual constraints. The *Rés0Pest* experimental design can thus be best understood as a step-by-step learning process, where the primary objective was not to identify statistically significant levers, but rather to achieve multi-performance goals encompassing agronomic, environmental, and socio-economic dimensions (Vereijken 1992). While this limits the internal validity of the findings, particularly regarding causal attribution, it enhances external validity and practical relevance, as it mirrors the adaptive strategies and constraints faced by farmers under real-world conditions.

Implementing such an iterative and adaptive approach within a research context also presented practical challenges. A notable limitation was the limited experience among researchers and technical staff in managing experiments that evolve over time. This was particularly evident in the case of Mauguio, where *Rés0Pest* plots were hosted within an experimental station primarily dedicated to plant breeding trials conducted under strict factorial designs. This institutional mismatch created significant barriers: experimenters reported a lack of time and resources to properly manage the *Rés0Pest* plots, as other station priorities took precedence. Although this is not the sole explanation for the less favorable results observed at this site, it underscores the influence of contextual and organizational factors. Beyond the technical feasibility of pesticide-free cropping systems, human and institutional constraints, such as insufficient experimental support and misalignment between project objectives and station routines, emerged as critical determinants of outcomes across the network. These findings highlight the need for better integration of adaptive experimentation into research infrastructures, and for tailored support mechanisms when transitioning from conventional to agroecological trial designs.

Performance evaluation. Assessing performance in the *Rés0Pest* trials raised several methodological and practical challenges, particularly regarding yield targets and profitability estimations. Although yield objectives were initially defined by the experiment designers using official databases and expert knowledge, the results revealed that for several crops, such as hemp (grain), winter barley, fodder mixtures, meadows (first and second years), sugar beet, and potato (*Solanum tuberosum* L.), the actual yields frequently exceeded the targets. This discrepancy suggests that the objectives may have been underestimated, possibly due to limited experience in managing pesticide-free systems and existing knowledge gaps at the time of design.

Although yields were generally promising and even exceeded initial targets in some cases, they were indeed affected by site x system interactions and interannual variation, resulting in inconsistent yield performance across years and locations. This variability was attributed mainly to human and technical factors (lack of experience, knowledge gaps, limited support, and equipment constraints) alongside biotic (ineffective weed management) and abiotic (drought) challenges, as noted by experimenters. Future efforts should work closely with farmers to scale these experiences, generate robust references, and adopt even more holistic system designs that integrate nutrient and water cycles to address the biotic and abiotic constraints observed in this study and improve robustness, thereby minimizing risks of significant yield and income shortfalls.

Furthermore, evaluating the economic performance of these systems remains complex. A key limitation is the difficulty in assessing profitability, given that pesticide-free products often do not benefit from differentiated market prices. This absence of price premiums significantly constrains the economic viability of such systems, despite their potential agronomic or environmental benefits.

In addition, the multi-criteria evaluation of performance, central to assessing multi-functionality, poses its own set of constraints. Existing tools and frameworks used for this purpose are often perceived as time-consuming and not well-adapted to routine use by experimenters, particularly in diversified and evolving systems like those of *Rés0Pest*. This highlights the need for more ergonomic, flexible, and user-oriented tools that can support the regular and comprehensive evaluation of agronomic, environmental, and socio-economic dimensions. Developing such tools is essential to improve the monitoring and learning capacity of long-term system experiments and to support decision-making in agroecological transitions.

Pesticide-free pest management plans. One of the major concerns of experimenters was the potential for a significant increase in pest populations over time in their systems. However, the annual reports produced by experimenters indicated that no significant changes in pathogen or animal pest populations were observed after 10 years of pesticide-free pest management across the nine sites. In contrast, weed populations were often reported to be more difficult to manage. Based on experimenter observations, weed management failures were cited as one of the main factors explaining crop yield reductions.

Weed management plans at *Rés0Pest* mainly included the diversification of crop sequences, the use of cover crops, and mechanical weeding. However, the establishment of cover crops often failed, especially in site-years affected by drought. Importantly, drought was the second main factor cited by experimenters affecting crop growth and development and explaining yield losses across different sites and campaigns. Consequently, drought was highlighted as a key limiting factor for both yield and effective weed management. Failures in cover crop establishment often resulted in an increased number of mechanical weeding interventions, leading to greater soil disturbance with potential negative effects on soil health, as well as increased consumption of fuel and energy. This underscores the importance of better accounting for the impact of abiotic factors in the crop management plans of pesticide-free cropping systems in future designs. Weed management practices developed by the conservation agriculture community can serve as a valuable source of information and inspiration in this process.

Nutritional management plans. The dual challenge of the *Rés0Pest* project was to manage pest populations with zero pesticides while maintaining the agronomic, socio-economic, and environmental performance of the cropping systems. For this, the fundamental strategy to achieve higher yields compared to organic crops was a tailored synthetic fertilization plan that met crop nutrient demands to improve yields without increasing crop susceptibility to animal pests, pathogens, and weeds, or inducing collateral environmental damage such as nutrient leaching. Taking wheat as an example, the yield performance of pesticide-free wheat was intermediate compared to French departmental yield statistics for wheat produced in conventional or organic systems (Fig. 8). Neither animal pest nor pathogen damage was exacerbated, however, perhaps in part because other cropping practices like rotation, alternated sowing dates or use of resistant cultivars compensated for potential negative effects from synthetic fertilizer supply. The fact that weed populations were more difficult to manage can be explained in part by potential excesses of synthetic fertilizers in some site-years, which could promote eutrophication and favor fast-growing weed species (i.e., disturbance-adapted, early-successional plants) via the paradox of enrichment (Phelan 2009). Indeed, after 10 years of management, experimenters still struggled to find the right doses of synthetic fertilizers to achieve yield objectives without affecting pest management or inducing environmental problems. For wheat however, our results confirmed that mineral fertilization can compensate for yield losses observed in organic agriculture. Unfortunately, unadapted use of synthetic fertilizers is energetically costly, undermines soil health by bypassing the detrital food web and biological buffering, and can be a major source of water pollution through leaching of highly mobile soluble salts.

A more holistic approach to nutrient supply needs to be developed to address interconnected challenges in soil health, pest management, energy efficiency, and the true costs of cropping practices. Nutritional management plans need to mimic natural ecosystem functions, encompassing closed nutrient cycles through soil food webs that retain minerals via microbial turnover and gradual organic matter decomposition to minimize leaching (Phelan 2009). These approaches should also prioritize maintaining micronutrient balance to support protein synthesis, preventing deficiencies that lead to the accumulation of free amino acids and soluble nitrogen, which can favor pest development, while mitigating excesses from chemical inputs that promote proteolysis over the formation of defensive proteins and phenolics (Chaboussou 2004). Enhanced plant-soil synchrony via diverse rotations should align mineralization with crop demands and stimulate soil life to diversify resource pools, thereby reducing weed-crop competition (Smith et al. 2010). Cropping practices such as reduced tillage, intercropping, relay cropping, and the sowing of cover crops can further enhance soil health by preserving its physical, chemical, and biological properties; promoting nutrient fixation (e.g., through legumes); cycling nutrients via root exudates that feed beneficial microbes; and providing biomass inputs that improve nutrient retention, soil structure, and overall fertility. Complementing these practices with innovative recycling processes to develop more sustainable mineral fertilizers (Krüger 2016; Lemaire et al. 2021; Smol 2019; Utai et al. 2022; Wald 2022) would represent a key advance in balancing performance and sustainability in pesticide-free systems, such as the ones in Rés0Pest (Smol 2019; Utai et al. 2022; Wald 2022).

Data management plans. Collecting, registering, and analyzing data were major challenges for *Rés0Pest*'s functioning as a network. First, introducing complex and time-intensive monitoring practices and new virtual shared platforms led to partial and fragmentary adoption and execution by the experimenters. For example, in some cases, experimenters collected and registered data in different formats and platforms and inconsistently followed protocols from year to year. Second, no experimental controls were included in the design of any pesticide-free cropping system due to the high cost of incorporating suitable control treatments in a multi-year, multi-site experimental network. In the absence of a reference, yields were planned to be compared with those of crops grown under conventional and/or organic farming at the experimental station or in nearby areas. However, yield information for the respective crops harvested during the relevant seasons and locations was often not easily available, leading to delays in data analysis and complicating evaluation of the extent to which the initial objectives were met. This resulted in a recurring loop of frustration and a lack of motivation to collect data in subsequent years.

A valuable *Rés0Pest* data set with measurements concerning soil physico-chemical properties, metagenomic analyses, macrofauna diversity, weed population evolution, harvest quality, and experimenter interviews still remains to be analyzed. To prevent similar situations in the future, experimenters agree that progress in the simplification of protocols, the efficiency of data sharing platforms, and the development of methods to analyze complex data sets from system experiments is necessary. This will facilitate straightforward data analyses year after year, helping experimenters to gain an overview of the performance of their systems and to see the importance of providing high-quality data.

Conclusion

Rés0Pest fostered the design, implementation and monitoring of nine pesticide-free cropping systems for arable and livestock crops compared to what is traditionally found in conventional and organic farming in France. Although ongoing in-depth analyses are needed to obtain a clearer and more accurate picture of the performance of *Rés0Pest* cropping systems, our first results provide valuable insights into the feasibility of pesticide-free agriculture. Importantly, after 10 years of implementation (except for 5 years at Lamothe), no observable increases in crop damage caused by animal pests or pathogens were reported by experimenters in most of the growing seasons.

Yield objectives were achieved in many site-years, even for crops whose yield performance is considered to be highly dependent on pesticides, such as canola, sugar beet, and potato. For wheat, *Rés0Pest* results confirmed the hypothesis that yields of pesticide-free crops using synthetic fertilizers can achieve higher yields than organic crops using organic and mineral-based fertilizers. However, ineffective weed management plans and drought were identified as the main factors threatening consistency of pesticide-free crop yields across sites and seasons, highlighting urgent avenues for improvement in these systems.

Rés0Pest's results align with recent studies showing that the productivity and profitability of crops are attainable with a considerable reduction in pesticide use (Lechenet et al. 2017). The socio-economic and environmental assessment of the *Rés0Pest* cropping systems showed very promising results, as the contribution of the systems to sustainable development was generally high across the sites (Cellier et al. 2024). Furthermore, sites such as Auzeville and Estrées-Mons exhibited very high performance in all three components, indicating that pesticide-free arable cropping systems can be feasible in completely different socio-economic and environmental contexts. The multi-crop livestock systems in the network showed less satisfactory results in the economic dimension, suggesting that additional considerations need to be incorporated into the economic model of these systems. Overall, the results obtained in *Rés0Pest* are promising, especially considering that the network did not benefit from any price premium for producing pesticide-free crops.

Since the *Rés0Pest* cropping systems aimed to test the feasibility of breakthrough cropping systems, the designers opted for a radical ban of pesticides. However, farmers can also consider to gradually moving towards pesticide-free or minimal-pesticide-reduced cropping systems by following a step-by-step designing approach (Meynard et al. 2023b). It is important to highlight that part of the knowledge acquired in *Rés0Pest* can be mobilized and readapted in broader contexts to gradually re-design both conventional and organic production systems. In fact, *Rés0Pest* experimenters often used the knowledge they gained conducting their pesticide-free cropping systems to manage and solve problems in other field trials on their farms in either conventional or organic production. The scaling out of knowledge in conducting pesticide-free cropping systems relies on the successive implementation and assessment of a set of practices, values, and processes in real-world conditions. Hence, there is a pressing need for more system experiments, either on commercial farms or on experimental stations, to evaluate, acquire and improve scientific and empirical knowledge by experimenting in real-life conditions and specific environmental and socio-economic production contexts. Such approaches will provide valuable agronomic and economic insights to inform the design of public policies (e.g., incentives, market differentiation) aimed at supporting the agroecological transition.

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Figures

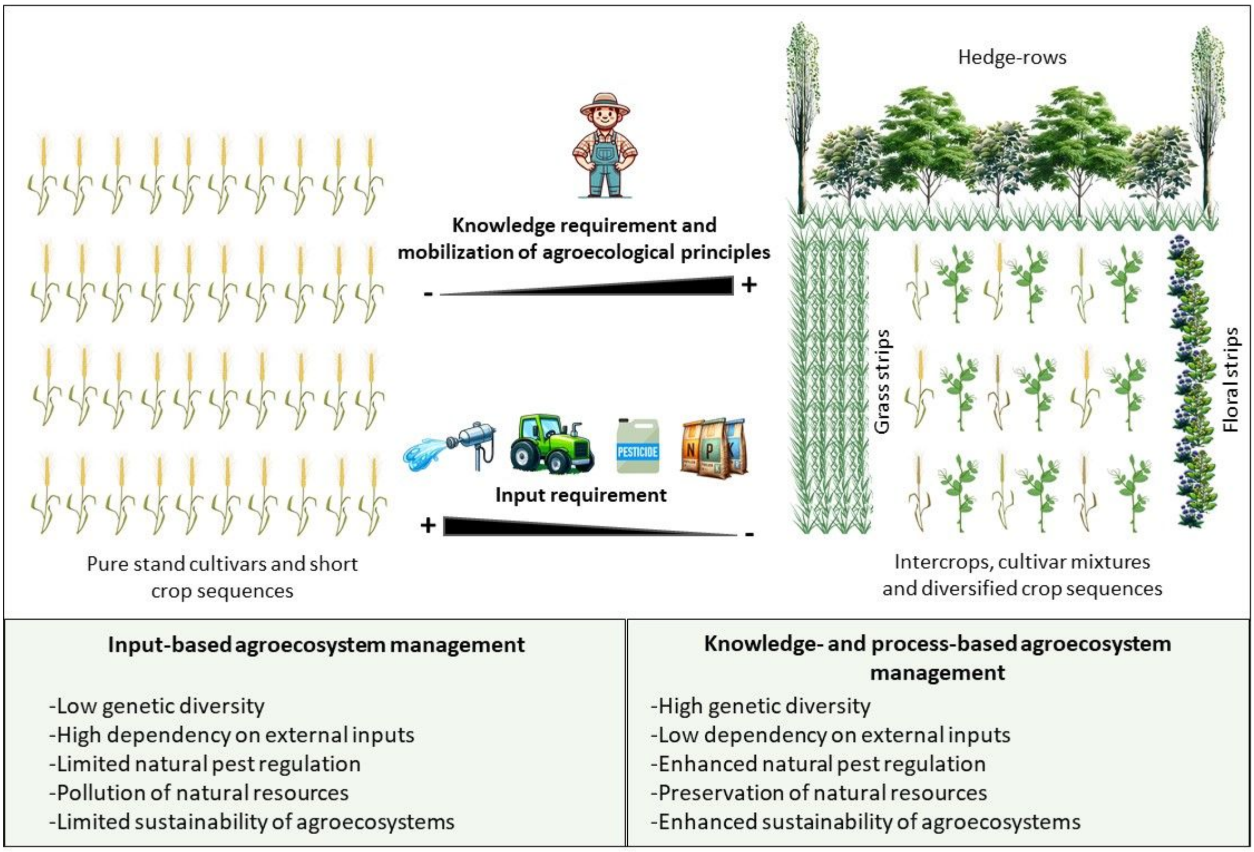
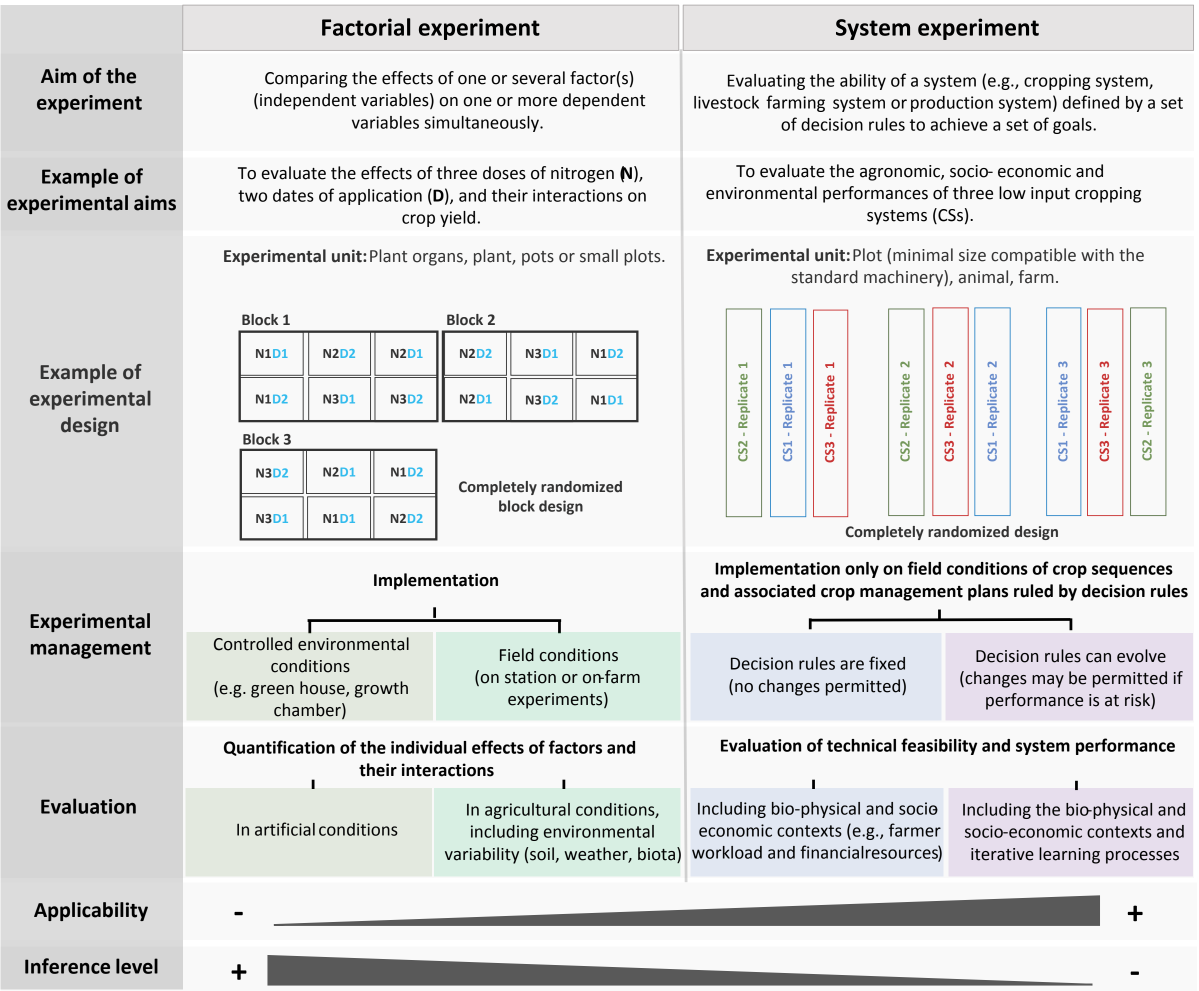


Fig 1. Redesign of crop systems by applying agroecological principles of crop protection. The figure illustrates an example of transitioning from simplified cropping systems, which are characterized by reduced diversity and a strong dependency on external inputs (left), to diversified cropping systems designed by combining complementary cropping practices to reduce dependency on external inputs (right).



	Factorial experiment	System experiment
Aim of the experiment	Comparing the effects of one or several factor(s) (independent variables) on one or more dependent variables simultaneously.	Evaluating the ability of a system (e.g., cropping system, livestock farming system or production system) defined by a set of decision rules to achieve a set of goals.
Example of experimental aims	To evaluate the effects of three doses of nitrogen (**N**), two dates of application (**D**), and their interactions on crop yield.	To evaluate the agronomic, socio- economic and environmental performances of three low input cropping systems (CSs).
Example of experimental design	**Experimental unit:** Plant organs, plant, pots or small plots. **Block 1**: N1D1, N2D2, N2D1 / N1D2, N3D1, N3D2 **Block 2**: N2D2, N3D1, N1D2 / N2D1, N3D2, N1D1 **Block 3**: N3D2, N2D1, N1D2 / N3D1, N1D1, N2D2 **Completely randomized block design**	**Experimental unit:** Plot (minimal size compatible with the standard machinery), animal, farm. CS2 - Replicate 1, CS1 - Replicate 1, CS3 - Replicate 1, CS2 - Replicate 2, CS3 - Replicate 2, CS1 - Replicate 2, CS1 - Replicate 3, CS3 - Replicate 3, CS2 - Replicate 3 **Completely randomized design**
Experimental management	**Implementation** Controlled environmental conditions (e.g. green house, growth chamber) Field conditions (on station or on-farm experiments)	**Implementation only on field conditions of crop sequences and associated crop management plans ruled by decision rules** Decision rules are fixed (no changes permitted) Decision rules can evolve (changes may be permitted if performance is at risk)
Evaluation	**Quantification of the individual effects of factors and their interactions** In artificial conditions In agricultural conditions, including environmental variability (soil, weather, biota)	**Evaluation of technical feasibility and system performance** Including bio-physical and socio economic contexts (e.g., farmer workload and financial resources) Including the bio-physical and socio-economic contexts and iterative learning processes
Applicability	-	+
Inference level	+	-

Fig. 2. Description of factorial and system experiments in agricultural research. The figure highlights the aims, design, evaluation, applicability, and inference level of both factorial and system experiments. "Applicability" refers to how well results and knowledge can be applied to complex, real-world systems, where system experiments have greater relevance despite lower inference. "Inference level" refers to the ability to identify specific causal relationships between variables, with factorial experiments offering higher inference due to their controlled conditions.

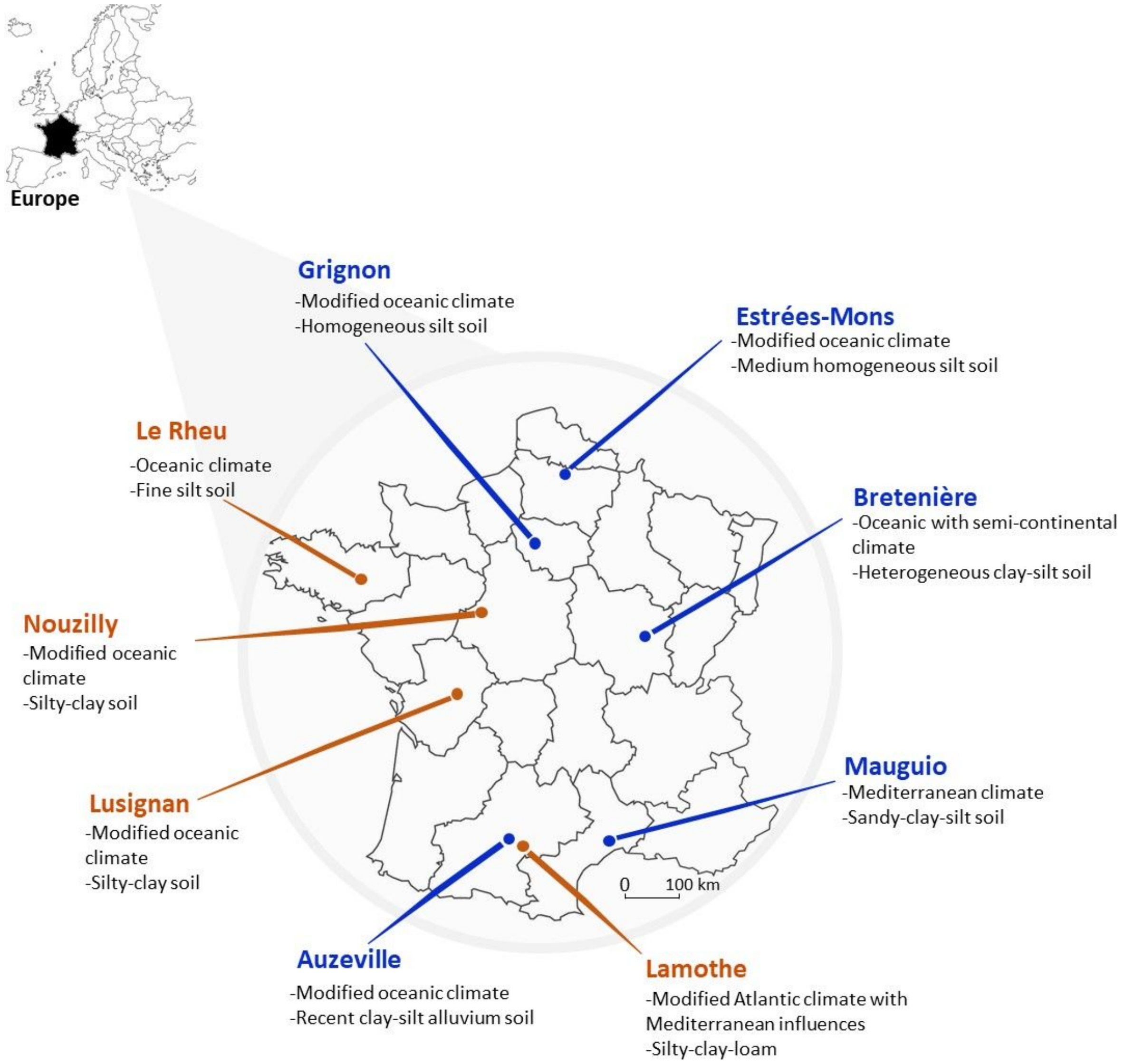


Fig. 3. Location of the nine sites of the *Rés0Pest* network in France. Names of experimental stations and main climate and soil features are indicated for each site. Colors represent cropping systems with arable crops (blue) and with multicrop-livestock (orange).

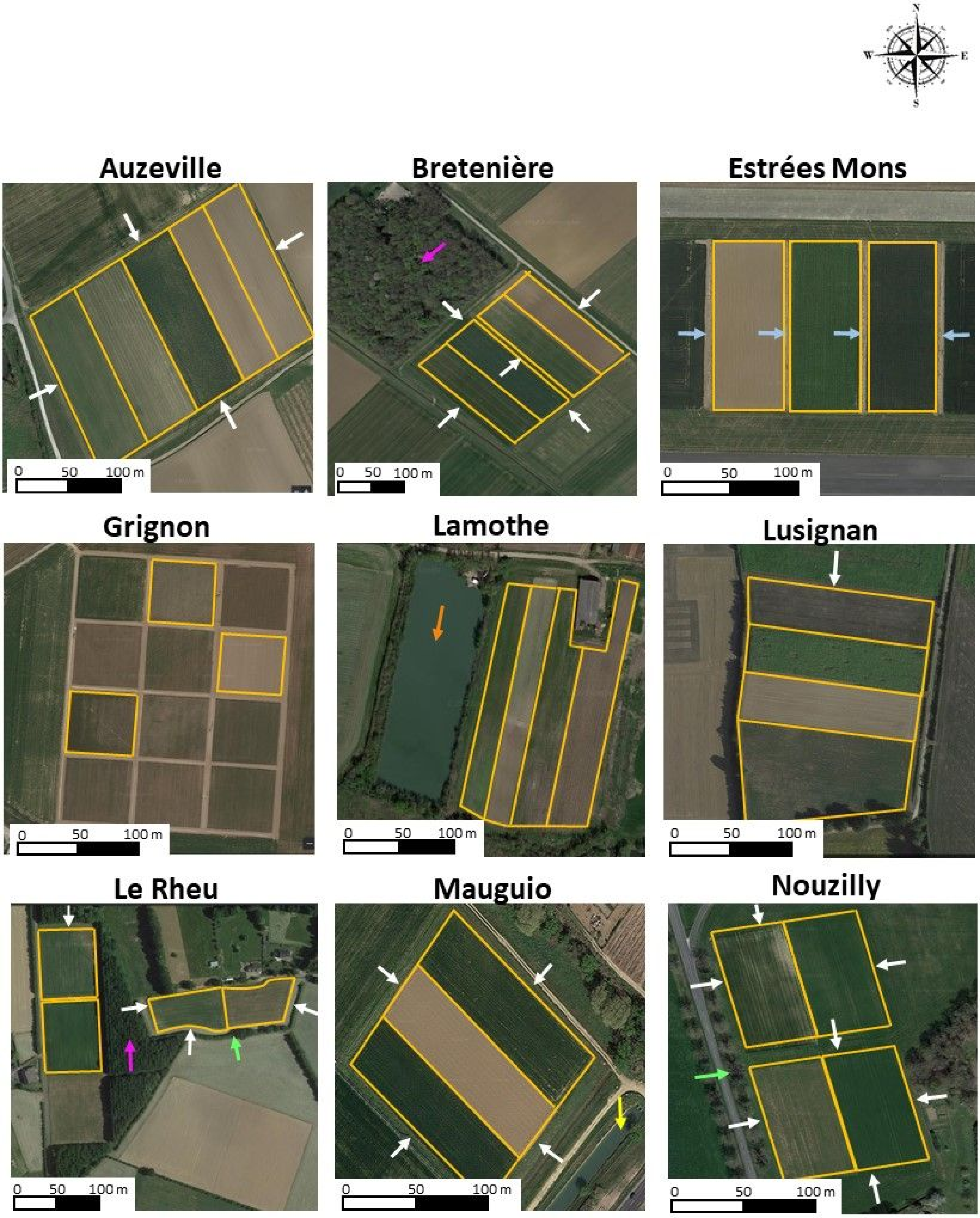


Fig. 4. Layout of the nine sites of the Rés0Pest network. Plots are highlighted by yellow frames. Agroecological infrastructures are indicated by arrows (white: grass strip; blue: grass strip + flower strip; pink: woodland; light green: hedgerow; yellow: river; orange: lake). Pictures are oriented with north at the top. Bars indicate distance (m).

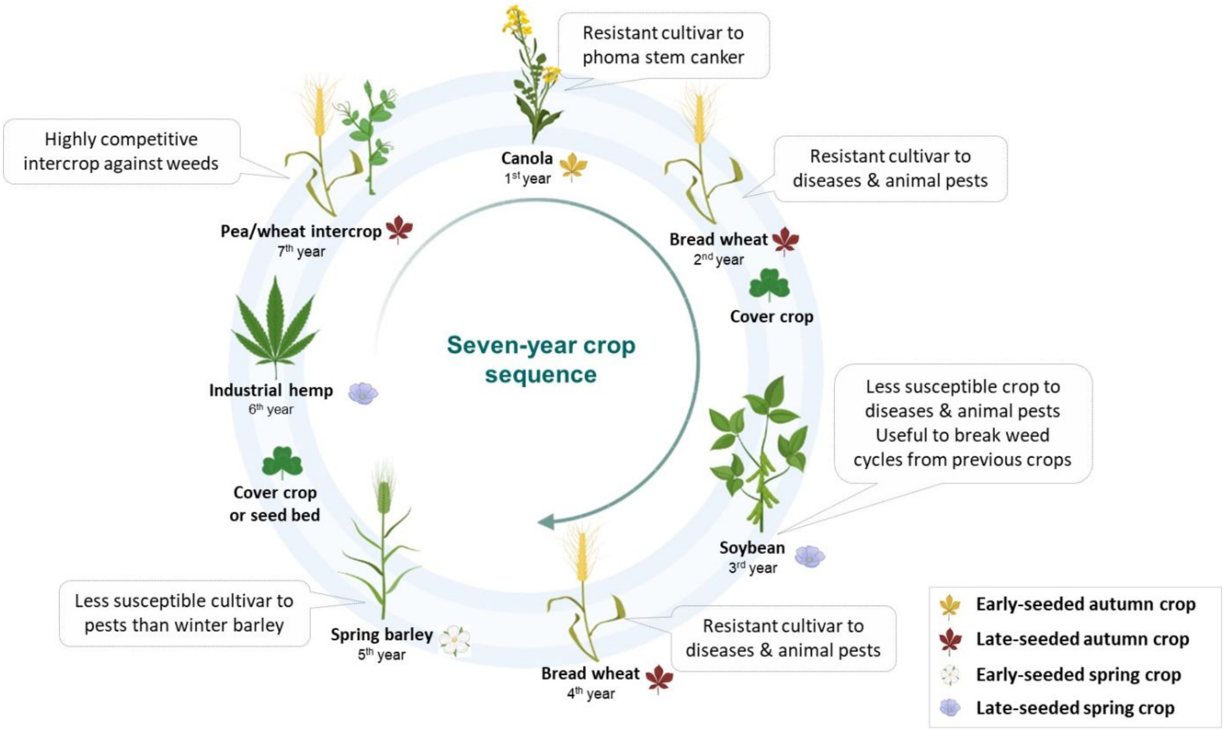


Fig. 5. Seven-year crop sequence designed for the Bretenière site, provided as an example of extended crop rotation sequences featured in *Rés0Pest*. The place of each crop in the succession is indicated by the number of the year. Cover crops are represented by a clover leaf. The leaf and flower icons indicate the alternating sowing dates of each crop. The most relevant feature of each cultivar or species to prevent pest damage is described in the gray rectangles.

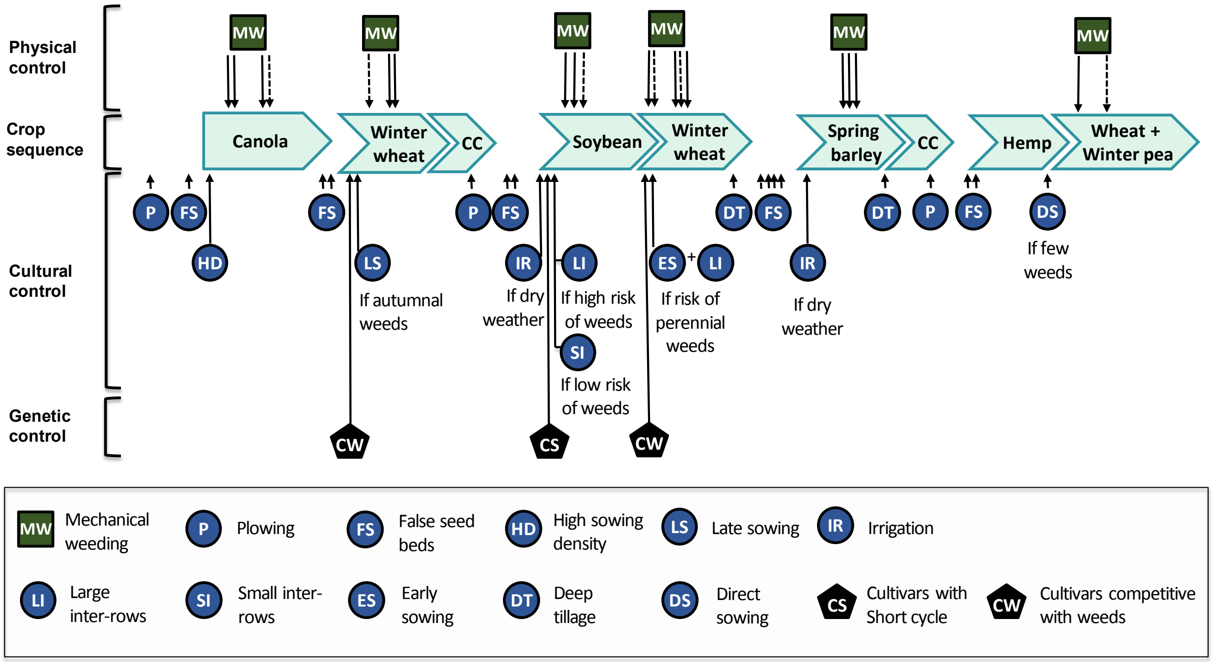


Fig. 6. Cropping practices used for the weed management plan in Bretenière. The green chevrons in the middle represent the seven-year crop succession designed for the Bretenière cropping system. The squares, circles, and pentagons indicate the set of cropping practices for physical, cultural, and genetic weed control, respectively. The timing of each intervention is shown by arrows; dashed arrows represent optional interventions. Mechanical interventions (MW, shown in the upper panel) were performed only when a high risk of weed density/competitiveness was observed, and weather conditions were suitable for mechanical work. Possible triggering situations are indicated by the word "if" followed by the icon of the relevant cropping practice (recommended solution).

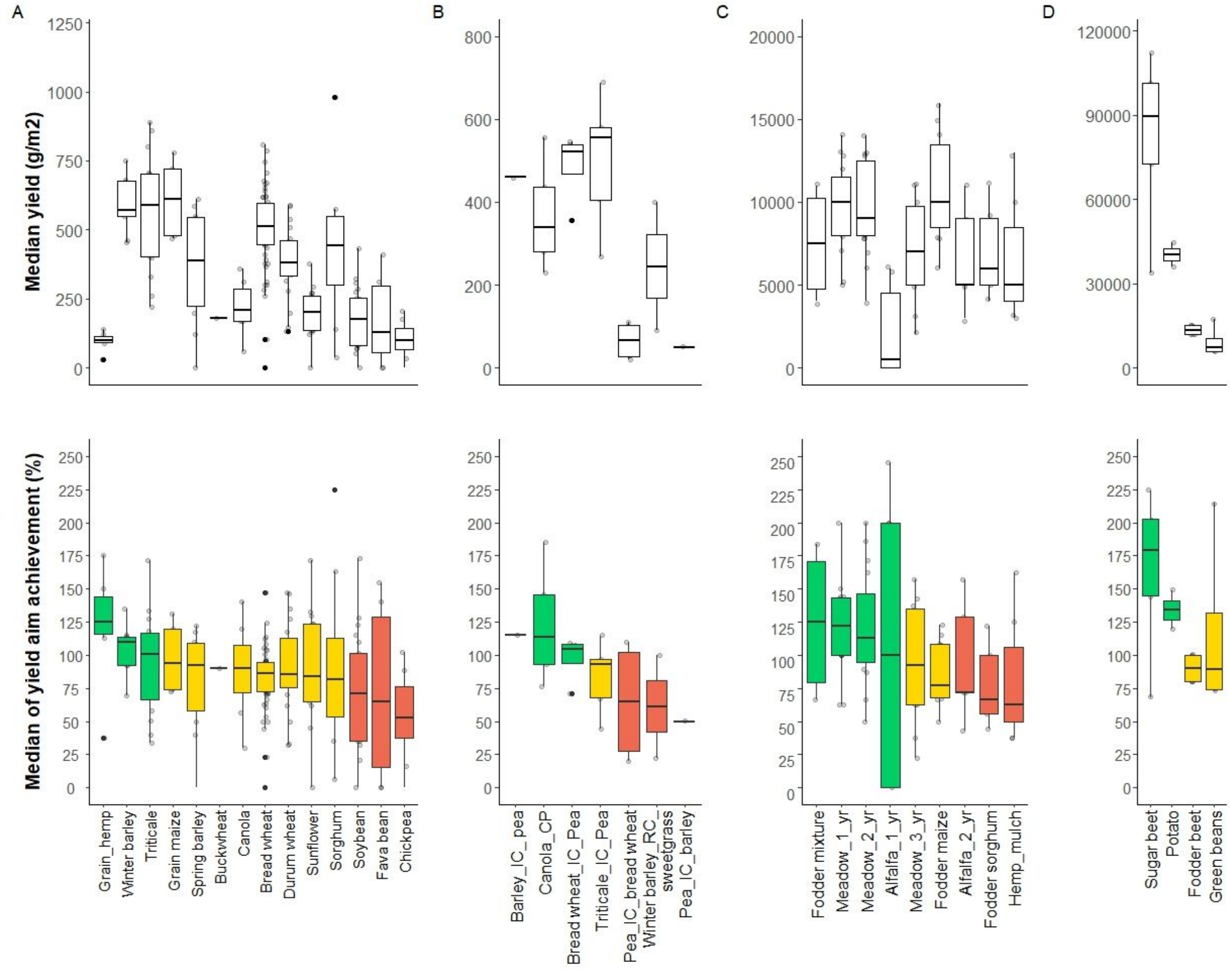


Fig. 7. Median yield performance of Rés0Pest crops across all sites and years. The panels are organized by groups of crops for better visualization and yield comparison as follows: A) grain crops, B) intercropping of grain crops, C) forage crops, and D) tubers and pods. The upper panels present the median yield obtained in grams per square meter ($g \cdot m^{-2}$) for each crop across all sites and years. The lower panels show the median percentage of the initially targeted yield achieved for each crop. A percentage equal to or higher than 100% indicates that the objectives were achieved (green). A percentage between 75% and 99% means the objectives were almost achieved (yellow). A percentage lower than 75% means the objectives were not achieved (red). IC: intercrop; CP: companion plant; Yr: year.

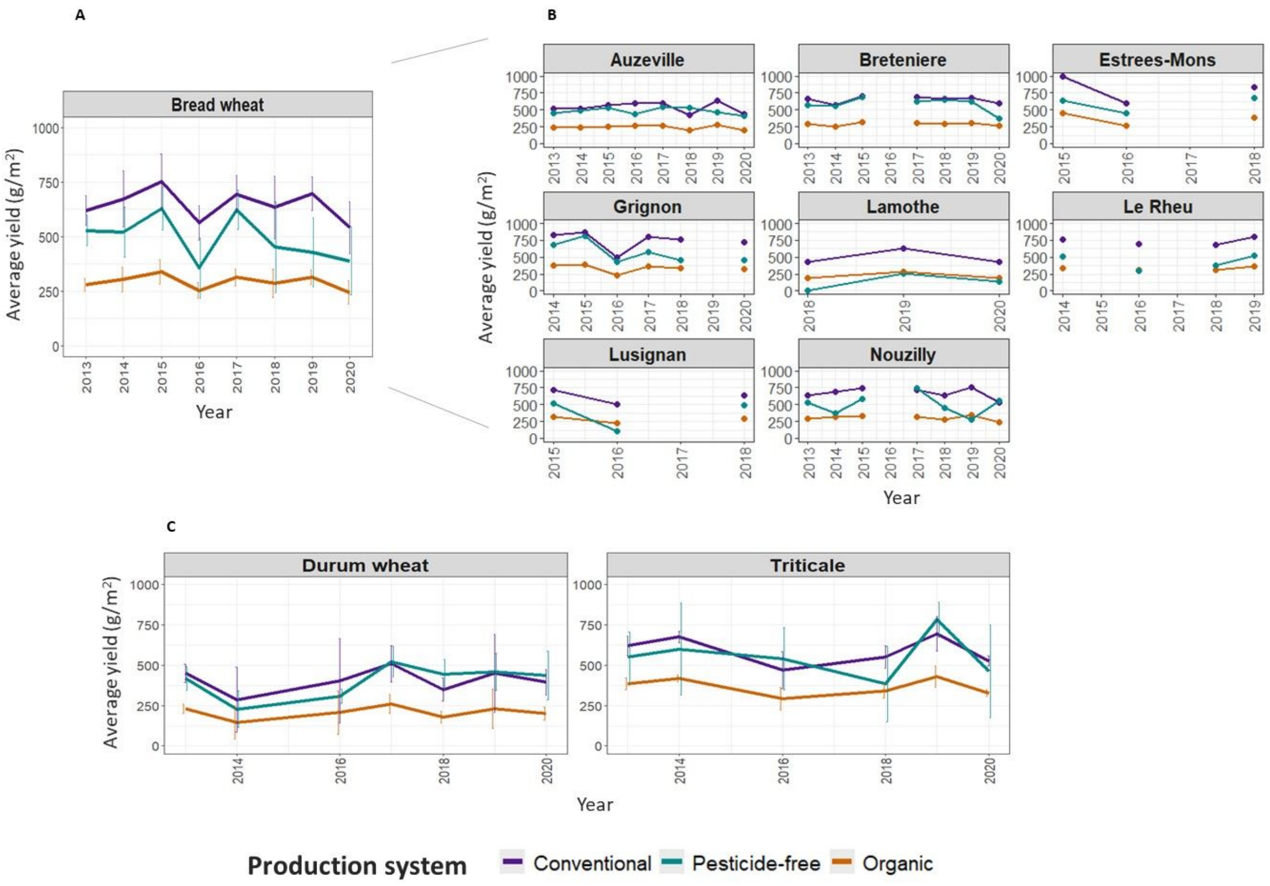


Fig. 8. Yield comparison of pesticide-free, conventional, and organic cropping systems. The average yield for pesticide-free production systems was calculated using yield data from at least three different Rés0Pest sites between 2013 and 2020 for bread wheat, durum wheat, and triticale. The average yield for conventional production systems corresponds to the yield reported in the French database (Agreste 2023b) for the same regions and the same crops of the Rés0Pest sites analyzed in a given year. The average yield for organic production systems was estimated by applying the percentage of the national production gap between organic and conventional production systems reported by (Agreste 2023a). A) Average yield of bread wheat for at least three Rés0Pest sites and regions per year, details on site/year are shown in panel B. B) Average yield of bread wheat for each Rés0Pest site-region for the corresponding year. C) Average yields for durum wheat (Auzeville, Mauguio) and triticale (Estrées-Mons, Grignon, Le Rheu) across years.

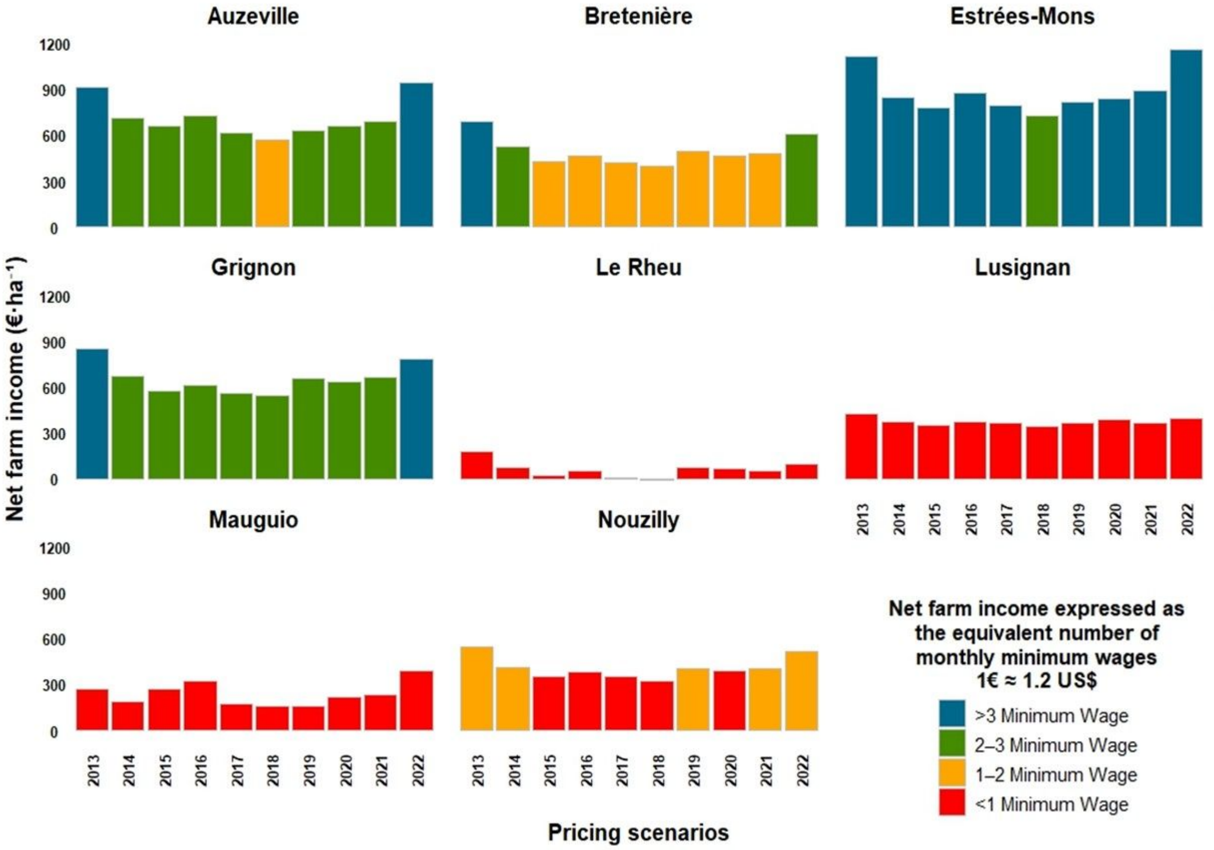


Fig. 9. Average net farm income of eight Rés0Pest cropping systems under a 10-year pricing scenario. Plots represent net farm income, which is calculated by subtracting the total operational and mechanization costs from the combined sum of the gross product (harvested quantity x sale price). Colors indicate the equivalence of net farm income in terms of multiples of monthly minimum wages in France. This equivalence was calculated per full-time human work unit (HWU), which refers to the average amount of land managed annually by one full-time worker. The net farm income values correspond to the average yield of each crop of the cropping system tested over at least one complete crop sequence (ranging between 4 and 9 years depending on the site) and were calculated under different pricing scenarios covering the period of the experiment.

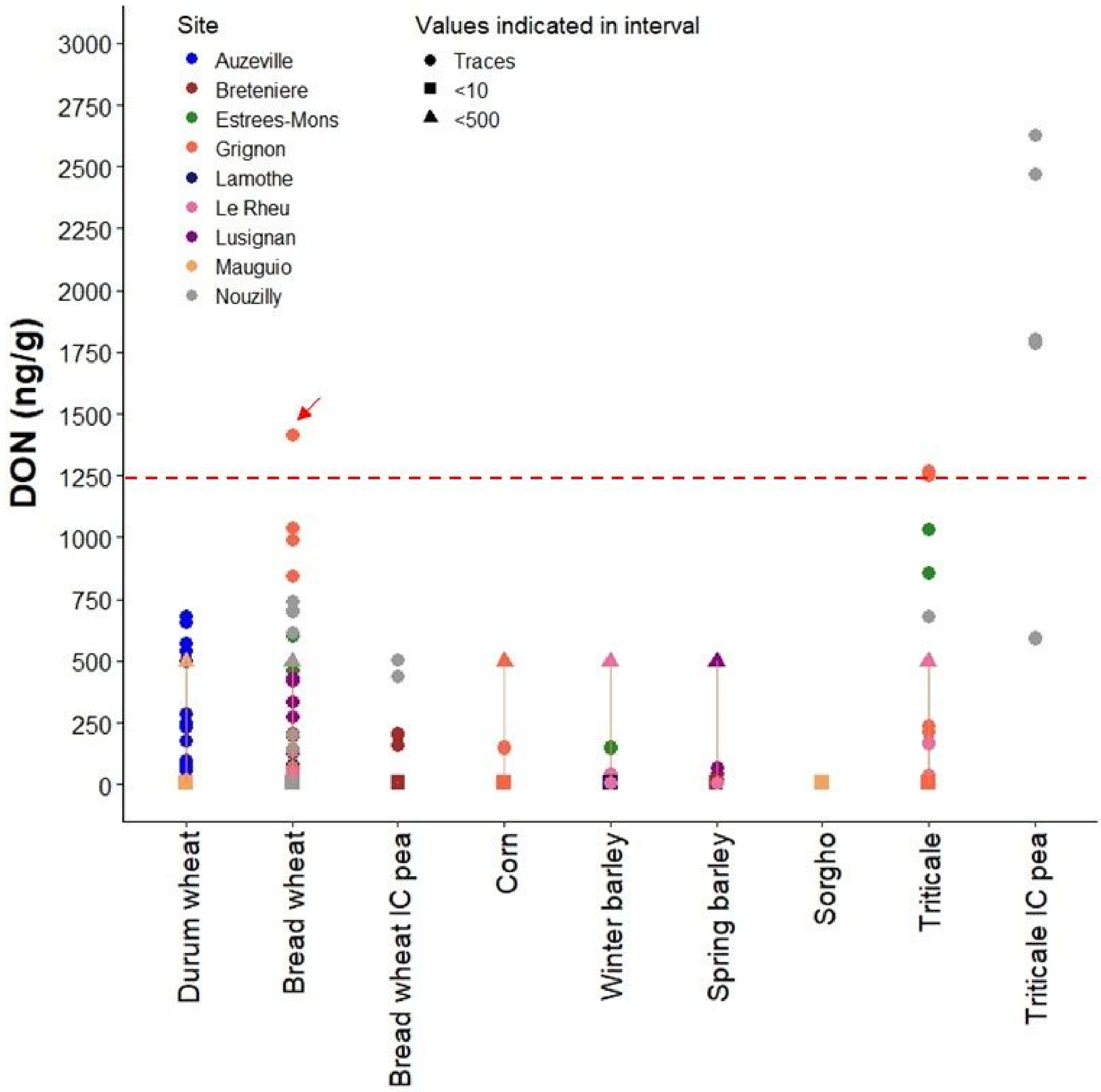


Fig. 10. Concentration (ng·g-1) of the deoxynivalenol (DON) mycotoxin measured from 2013 to 2020 in cereal crops in the Res0Pest network. The red dashed line indicates the tolerable limit for human consumption (1250 ng·g^{-1}) and red arrow highlight the only case where DON levels exceeded this limit. The figure plots the concentration of DON in various cereal crops over multiple years at different sites. Each point on the graph represents a measurement from a specific site. Circles, triangles, and squares indicate values that were given as intervals by the measurement device.

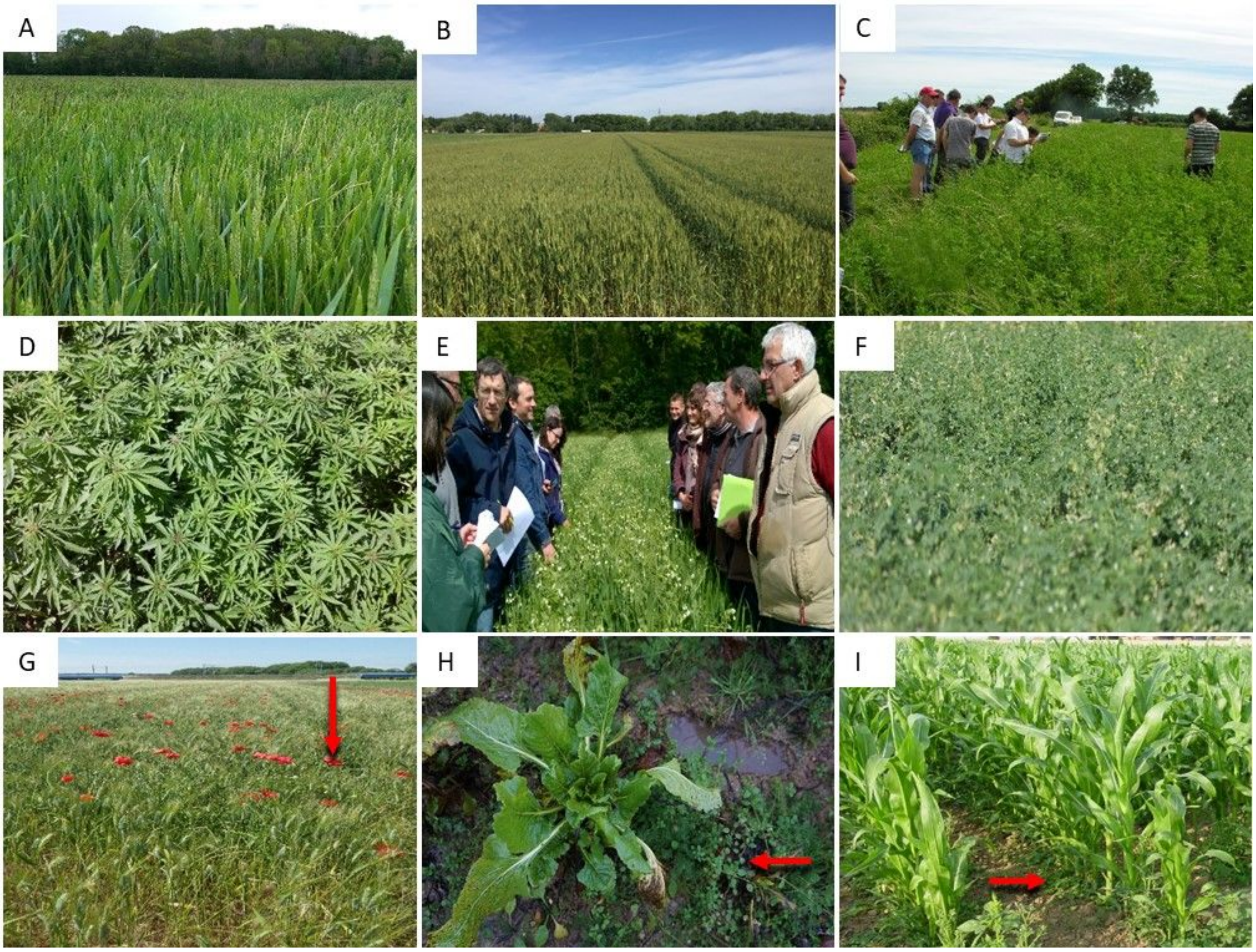


Fig. 11. Views of crops grown in Rés0Pest cropping systems. Red arrows indicate examples where weeds were a major limiting factor in crop management: A) bread wheat, Bréteniere; B) durum wheat, Auzeville; C) pasture (alfalfa + ryegrass), Lusignan; D) industrial hemp, Grignon; E) intercropping bread wheat and pea, Bréteniere; F) chickpea, Mauguio; G) durum wheat, Mauguio; H) fodder beet, Le Rheu; I) corn, Grignon.

Lever	Decision rule instruction		Implemented intervention (e.g., date, dose, equipment)	Deviation from the planned intervention (D0, D1, D2) and why?	Feedback on the implemented technique	Deviation from target objective (D0, D1, D2) and why ?
	Objective(s)	Planned Intervention				
Weeding	Destroy the weeds present in the crop	Rotary hoeing between the cotyledon stages and 2F, routinely done at the end of August	09/10/2017: passage of the tine harrow for the first mechanical weeding	**D1:** Late intervention with a different machine	Impossible to intervene earlier due to poor canola development	**D2:** Weeds were not destroyed as planned
		If canola density is very high, **then** use small hoes to remove only a small number of canola stalks (spacing of 25 cm) during autumn between stages 2-6F		**D0**: No excess canola, thus no hoeing planned		**D0:** No deviation from the planned objective
Pest and Insect Control	Avoid having to reseed canola in the fall due to excessive pest damage	Dense sowing with a cereal seeder at 140g·m^{-2}	21/08/2017 sowing on with a cereal seeder at 140g·m^{-2} 09/10/2017: Manual reseeding on the wooded side (1/4 of the plot) after the destruction of the canola by flea beetles	**D0**: Dose higher as planned	High insect pest pressure	**D1:** A small part of the plot was reseeded due to insufficient plants from the first sowing due to high flea beetle pressure
Disease Control	Limit the risk of sclerotinia in canola	Application of Contans® in case of sclerotinia risk		**D0:** No confirmed risks		**D0:** No sclerotinia observed on the canola
Harvest	250g·m^{-2} 9% moisture	Harvested with a combine harvester in good conditions	26/06/2018 Harvest Yield: 210g·m^{-2}	**D0:** Harvest was carried out as planned		**D2:** The target yield was not reached

Table 1. Example of objectives, decision rules, and assessment of technical interventions at the Bréteniere site. A scale was established to evaluate the degree of deviation from the decision rule and the technical objective: 'D0' indicates conformity, 'D1' indicates moderate deviation, and 'D2' indicates major deviation.

Site	Duration (years)	Crop sequence
Auzeville	5	2012-2018: (CC) – soybean – durum wheat – (CC) – grain sorghum – sunflower – bread wheat
	4	2018-2023: (CC) chickpea – durum wheat – (CC) soybean – bread wheat
Bretenière	7	2012-2023: canola – bread wheat – (CC) – soybean – bread wheat – spring barley – (CC) – Industrial hemp – barley or bread wheat + pea
Estrées-Mons	6	2012-2018: sugar beet – bread wheat – barley – (CC) – green bean – canola + companion plants –triticale – (CC)
	7	2018-2023: sugar beet – bread wheat – (CC) – potato – barley – (CC) – green bean – canola + companion plants – triticale – (CC)
Grignon	6	2012-2020: faba bean – bread wheat – (CC) – industrial hemp – triticale (CC) – grain maize – bread wheat – (CC)
Mauguio	6	2012-2023: alfalfa (2 years) – durum wheat – chickpea – durum wheat – (CC) – sunflower
Lusignan	9	2012-2023: meadow (3 years) – bread wheat – canola + companion plants – (CC) – sorghum + companion plants – fodder mixture – (CC) – soybean – (CC) – barley
Lamothe	6	2017-2018: alfalfa (3 years) – sunflower – bread wheat – barley + alfalfa
	5	2018-2023: sweetgrass (2 years) – sunflower – bread wheat – barley + sweetgrass
Le Rheu	8	2012-2023: meadow (2 years) – fodder maize – bread wheat – (CC) – faba bean – triticale – (CC) – fodder beet - barley
Nouzilly	8	2012-2018: meadow (3 years) – bread wheat – (CC) – fodder maize – triticale + pea – (CC) – sunflower – bread wheat
	8	2018-2023: meadow (3 years) – (CC) – fodder maize – bread wheat – triticale + pea – (CC) – sunflower – bread wheat

Table 2. Crop sequences and their duration at the nine Res0Pest sites. Two different crop sequences are shown for the sites where crops or the duration of crop sequence were modified. CC signifies use of a cover crop.

Type of control	Management strategy	Management options	AU	BR	GR	LA	LU	MA	MO	NO	RH
Cultural	**Extended crop sequence duration**	**From 4 to 9 years**	X	X	X		X	X	X	X	X
	Diversified crop succession	**Mixture of varieties**	X	X	X	X	X		X	X	X
		Intercropping		X			X			X	
		Crop less susceptible to diseases	X	X	X	X	X				
		Crop less susceptible to animal pests		X		X					
		Highly competitive crop against weeds		X	X			X	X	X	
		Multiannual crops				X					
		Cover crop	X	X			X	X	X	X	X
	Alternate sowing dates	**Late-seeded autumn crop**	X	X	X		X	X	X	X	X
		Early-seeded autumn crop		X			X	X	X	X	X
		Late-seeded spring crop	X	X	X		X	X	X	X	X
		Early-seeded spring crop		X	X		X		X		X
		Early sowing		X					X		
		Late sowing	X	X	X	X			X	X	X
	Sowing density	**High sowing density**	X	X	X		X		X	X	X
		Low sowing density		X							
	Inter-rows	**Large inter-rows**	X	X	X		X	X	X	X	X
		Small inter-rows		X	X	X			X		
	Adjustment of external inputs use	**Fertilization (N) adjusted to yield target**	X	X	X	X	X	X	X	X	X
		Exceptional use of irrigation		X				X			
	Mechanical interventions	**Alternating plowing and no-plowing**	X	X		X	X	X	X	X	X
		Frequent plowing			X						
		False seed beds	X	X	X	X	X	X	X	X	X
		Shredding of crop residues			X						
		Sowing under a vegetative cover				X					X
	Deterrence practices	**Bird scaring devices**					X	X			
Genetic		**Resistant variety to diseases**	X	X	X	X	X		X		X

	Resistance/Tolerance to biotic and abiotic factors	**Tolerant variety to diseases**	■ X	■ X	■ X	■ X	■ X	■ X	■ X	■ X	■ X
		Resistant variety to pest		■ X	■ X				■ X		
		Tolerant variety to pest					■ X			■ X	
		Resistant to lodging	■ X	■ X					■ X		■ X
		Resistant to frost		■ X							
		Tolerant to drought						■ X			
		Canopy competitiveness		■ X	■ X		■ X	■ X	■	■ X	■ X
Physical	**Mechanical weeding**	**Rotary hoe**	■ X	■ X	■	■ X	■ X	■ X	■	■ X	■ X
		Spiked harrow	■ X	■ X	■	■ X	■ X	■ X	■	■ X	■ X
		Hoeing	■ X	■ X	■		■ X		■ X	■ X	■ X
		Header machine	■ X	■ X							■ X
		Superficial cultivation					■	■ X		■	
	Hand weeding	**Hand weeding**			■				■ X		■ X
	Frequent harvesting	**Three to four cuts/year in the meadow**				■	■	■ X		■	■ X
Biological	**Release of natural predators**	***Trichogramma***			■						■
	Product spray	***Bacillus thurigiensis***						■ X			
		Contans® *(Coniothyrium minitans)*		■ X			■ X		■ X		

Table 3. Management strategies implemented in the Rés0Pest network. Management strategies for cultural, genetic, physical, and biological control are listed in the second column, and corresponding cropping practices are listed in the third column. The implementation of each practice by site (AU: Auzeville; BR: Bretenière; GR: Grignon; LA: Lamothe; LU: Lusignan; MA: Mauguio; MO: Estrées-Mons; NO: Nouzilly; RH: Le Rheu) is indicated by black cells.