



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

Diana Ortiz-Vallejo, Vincent Cellier, Violaine Deytieux, Alain Berthier, Antoine Savoie, Caroline Colnenne-David, Guillaume Audebert, Sébastien Darras, Ludivine Pirus, Rosemonde Devaux, et al.

► To cite this version:

Diana Ortiz-Vallejo, Vincent Cellier, Violaine Deytieux, Alain Berthier, Antoine Savoie, et al.. Pesticide-free agriculture: is a third way possible aside organic agriculture and conventional agriculture?. 2024. <hal-04786067>

HAL Id: hal-04786067

<https://hal.science/hal-04786067v1>

Preprint submitted on 15 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

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

Diana Ortiz¹⁻², Vincent Cellier³, Violaine Deytieux³, Berthier Alain³, Antoine Savoie⁴, Caroline Colnenne-David⁵, Guillaume Audebert⁶, Sébastien Darras⁷, Ludivine Pirus⁷, Rosemonde Devaux⁷, Tison Gilles⁸, Jean-Marc Valdrini⁹, Jordan Pirault⁹, Brigitte Montegano¹⁰, Valentin Deremetz¹¹, Marie-Hélène Robin¹¹, JP Deguine¹², Mark L. Gleason¹³, JN Aubertot¹.

¹ INRAE - UMR AGIR, chemin de Borde-Rouge, BP52627, F-31326 Castanet-Tolosan Cedex

² INRAE - UMR ABSys, 2 Place Viala 34060 Montpellier Cedex 2

³ INRAE - UE Domaine d'Epoisses, F-21110 Bretenière

⁴ INRAE - UE Physiologie Animale de l'Orfrasière, F-37380 Nouzilly

⁵ INRAE - UMR Agronomie, INRAE AgroParisTech, Université Paris-Saclay, 91123 Palaiseau

⁶ INRAE - UE FERLUS, 150 route le Chêne, F-86600 Lusignan

⁷ INRAE - UE GCIE Picardie, Estrées-Mons, F-80203 Peronne

⁸ INRAE - UE Domaine expérimental d'Auzeville, chemin de Borde-Rouge, BP52627, F-31326 Castanet-Tolosan Cedex

⁹ INRAE - UE DIASCOPE, Domaine de Melgueil, F-34130 Mauguio

¹⁰ INRAE - Domaine de la Motte au Vicomte, BP 35327, F-35653 Le Rheu Cedex

¹¹ Ecole d'Ingénieurs de PURPAN, 75 voie du TOEC - BP 57611, 31076 TOULOUSE Cedex 3

¹² JP Deguine

¹³ ML Gleason

Introduction session (6 pages en double interligne, Times new roman 12)

Pesticides: the 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 in order to achieve expected yields (Lamine et al. 2010). This high dependency is due, to some extent, to the low diversity and agroecosystem simplification that is often observed in conventional cropping systems. 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

naturally occur to prevent pest development cannot take place and constant external interventions and inputs are therefore required for crop survival. Nevertheless, after a recurrent exposure, pest populations often develop resistance to herbicides, fungicides, insecticides, or other pesticides (Hawkins et al. 2019). When this occurs, one of the most advocated solutions is to find new pesticides that accomplishes the same functions for an additional period of time. 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.

As a result, the pesticide-dependent agricultural model has been shown not only to be an inefficient way to provide sustainable crop protection, but also to 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, across each terrestrial matrix (soil, water and air), as well as in very remote areas such as deep waters or sub-polar regions. Furthermore, highly toxic pesticide molecules can persist in the environment for many years (Leenhardt et al. 2022). A precise quantification of the impact of pesticides on the erosion of biodiversity is particularly difficult to establish in a multifactorial context (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 (Brondízio et al. 2019; Sánchez-Bayo 2021; Boatman et al. 2004).

Unsurprisingly, agricultural areas are the most contaminated by pesticides (Leenhardt et al. 2022). Since a prolonged exposure of these substances is detrimental to the proper functioning of life processes and is incompatible with the sustainability of agroecosystems, there is an urgent need for a profound and radical change in the way we protect crops from damage caused

by pests. To date, several strategies have been explored to reduce pesticide use. Among the most encouraged strategies is Integrated Pest Management (IPM). IPM calls for “all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and maintain the use of plant protection products and other forms of intervention at levels that are economically and ecologically justified” (European Commission, 2017). Another 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, despite a wide range of efforts, pesticide use has continued to increase worldwide (FAOSTAT, 2020). Plausible explanations, concerning the solutions cited above, include the fact that farmers often partially adopt IPM practices and that in organic systems, yields tend to be lower than in conventional ones, which hinders wider adoption. Furthermore, both in IPM and organic agriculture, the use of harmful products is still permitted and they are still widely used in various cropping systems. For example, although copper accumulation in agricultural soils has also been shown to represent a major risk for the environment and crop health (Adrees et al. 2015; Navarrete et al. 2018), organic orchard and vineyard systems depend on copper sprays to prevent fungal and bacterial diseases (Andrison et al. 2018). To evaluate, identify, and effectively implement agricultural practices that ensure environmental and human health, while preserving optimal crop yields, is now a top priority in the agricultural sector worldwide (FAO 2018a, FAO 2018b; Mouhamed et al. 2023)

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

Public policies are developed to address societal issues such as agricultural practices, public health, and environmental preservation. The European Green Deal (2019), for example, forms part of a comprehensive plan by the European Commission that addresses interlinked policy

sectors in response to current environmental challenges. The Green Deal's two principal strategies, Farm to Fork and Biodiversity, provide guidelines and regulations concerning agriculture and food systems for 2030. Both strategies cover a 10-year plan with different measures and share common quantitative targets related to organic food production, nitrate losses and reduction of pesticide use. Concerning pesticides, the common aim of the Green Deal is a 50% reduction in the use of active pesticide ingredients per unit area of land by 2030.

At the worldwide level, 64 countries from all regions participated in the United Nations Summit on Biodiversity in September 2020, committing to address biodiversity loss caused by direct or indirect anthropogenic means, such as pesticide use (Pledge for Nature, 2021). The critical question now is the extent to which these goals can be achieved. Policies aimed at reducing pesticide use are not new, for instance DDT was banned in USA in 1972 (Keane 1972) and Denmark initiated the development of public policies for pesticide reduction as early as in 1980 (Pedersen and Nielsen 2017). Since then, similar policies have been gradually implemented in the European Union (EU), albeit without a clearly documented success. For example, EU Directive 2009/128/EC, established in 2009, set up a framework through national action plans aimed at reducing pesticide use. However, despite these efforts, an 11% increase in EU pesticide use from 2010 to 2018 was reported (FAOSTAT, 2020). Moreover, major concerns about the feasibility of attaining the goals stated in the Green Deal have been raised (Guyomard and Bureau 2020).

Although regulations on pesticides in EU agriculture have led to the elimination of a considerable number of dangerous and widely used pesticides from the market (Kudsk and Mathiassen 2020), a disruptive change, such as targeting completely pesticide-free agriculture, is necessary to achieve a profound agricultural transformation that requires considerable effort

in redesigning agroecosystems (Jacquet et al. 2022, Hatt and Döring 2023). One fundamental step in this process is to transition from a 'recipe' and input-based model, where curative crop protection with pesticides is a central part of the solution, to a process- and knowledge-based model where prophylaxis (a set of measures to prevent disease before it occurs) is at the core of the pest regulation management strategy (Fig. 1).

Agroecological crop protection: a way out of pesticide dependency

Despite 60 years of efforts to implement IPM, pesticide use has nonetheless continued to increase in most countries worldwide. Now, the orientation towards agroecology is proposed as a more holistic solution to develop a sustainable pesticide-free agriculture (Deguine et al. 2021). Agroecology has been commonly defined as “the application of ecological concepts and principles to the design and management of sustainable agroecosystems (Gliessman 2018)”. Furthermore, Wezel et al. (2009) considered agroecology in terms of three components, a set of scientific disciplines, a set of agricultural practices and a set of social interactions. Although agroecology embraces diverse definitions, three core principles have been defined. First, to produce according to ecosystem function. Second, to maximize the functional biodiversity. Third, to reinforce biological regulations in agroecosystems (Malézieux 2017). Agroecological crop protection (ACP) is therefore the application of the core scientific principles of agroecology to crop protection (Lucas et al. 2017) and is structured around two main management axes: the incorporation of plant diversity in time and space and the improvement of soil quality.

In the field, the implementation of ACP principles follows a systemic, orderly and ecologically based phytosanitary strategy. The first step is the application of preventive measures focused, on the management of plant populations; this includes a set of practices such as the use of

134 adapted varieties, crop sequences, crop rotation, cover crop management, direct seeding, and
135 sustainable irrigation and fertilization. On the other hand, pest population reduction and the
136 promotion of regulatory populations can be achieved through various methods. These include
137 establishing refuge areas, utilizing cultivar mixtures, practicing intercropping (species mixture),
138 implementing traps or repellent plants, managing field boundaries, and creating ecological
139 compensation structures such as corridors, hedgerows, and herbaceous and floral strips (Fig. 1).
140 In ACP, chemical pesticides are considered only as last resort after a careful assessment of the
141 phytosanitary risks. Different examples of successful pest control projects following ACP
142 principles have been documented (Deguine et al. 2015, 2018; Ratnadass 2017) demonstrating
143 that this is an efficient way to design multifunctional and productive pesticide-free cropping
144 systems.

145
146 To date, few examples exist of pesticide-free cropping systems for temperate arable crops and
147 they mainly concern organic agriculture (Jacquet et al. 2022). Hence, it is an open question
148 whether pesticide-free and non-organic cropping systems could: i) be technically feasible; ii)
149 reach acceptable levels of production; iii) preserve the environment and resources; iv) ensure
150 sufficient economic returns to farmers with acceptable workload. In this article, we present the
151 design and performance assessment of pesticide-free cropping systems in France. Nine different
152 cropping systems were set up in a national network called RésOPest. We describe the design
153 steps for locally adapted cropping systems, underlying agronomic principles, crop sequences,
154 and associated crop management plans implemented at each site. We present results on yields
155 of each cropping system and the net farm income. Finally, we discuss the relevance of
156 implementing systemic approaches following ACP principles to generate knowledge useful to
157 help design cropping systems that are less reliant on pesticide, even if not pesticide-free.

Description of the network, cropping system design and monitoring (6 pages double interline, Times new roman 12)

Research orientation and experimental approach

Rés0Pest is an experimental French network launched in 2012 as part of DEPHY EXPE, one of the main spearheads of the French national action plan concerning the reduction of pesticide use by 50% within 10 years (Anonymous 2015). In this network, we adopted a prospective research orientation with a high-risk, high-reward strategy to achieve breakthroughs in the technical feasibility, socio-economic, and environmental performance of pesticide-free cropping systems. 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 components.

Here, a cropping system is defined as a set of decision-making rules that govern the cropping management strategies implemented in a given crop sequence (Lechenet et al. 2017). 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 constraints related to work organization. Each rule serves a specific function: it aligns the decision with the overall objectives and limitations of the cropping system. For example, if a particular condition is observed ('if'), a corresponding set of actions may be taken ('then'). Finally, evaluating the outcomes ensures that 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 privileged for designing all cropping systems of Rés0Pest network because this approach focuses on ensuring agronomic consistency in the combination of management strategies to be tested. So, each cropping system is 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. Therefore, this method allows for evaluating the impact of the overall combination of techniques rather than the statistical effect of any specific technical choice (Fig. 2). This experimental choice differs from the classical factorial essays aiming to evaluate the effect 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 hinder the achievement of objectives and compromise the practical applicability for farmers in real-world settings (Boiffin et al. 2001).

In systemic 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 efficient 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 the 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. 2023). This iterative approach acknowledges that experimenters, akin to farmers, continuously learn 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 multi-performance of the cropping system through fine-tuning the management practices and associated decision rules. However, allowing the cropping system to evolve over time makes it difficult at the scientific level to identify the primary drivers of performance, thus posing a significant challenge for scaling up these practices.

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

We organized participatory workshops that included multiple actors, such as farmers, experimenters, advisors, technical engineers, and researchers, at each site (except for Lamothe), 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), Agogu   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 pilot of the experimental station.

During the creative part of the co-design process, participants were encouraged to propose innovative solutions according to specified guidelines. Initially, two constraints were established: the exclusion of all pesticides, including seed treatments, and the requirement to include arable crops representative of typical farms in each region. 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.

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

- At least 50% of the crops in the cropping sequence at each site had to be sown annually to ensure temporal repetitions and assess inter-annual variability.
- A minimum plot size of 0.48 hectares (minimum width: 48m, minimum length: 100m) 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 is obtained. Due to the size of the experimental unit, which restricts the number of possible replications, including a reference (i.e., 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 to particularly promote pest regulation.

Common data collection protocols were developed to monitor all cropping systems tested within the network. Key variables, including plant, pest, and auxiliary populations (organisms that aid in pest regulation), as well as soil physico-chemical and biological properties, and meteorological conditions were monitored during the study. Data concerning technical processes, such as date, number and type of intervention (e.g., tillage, sowing, harvesting), equipment (e.g., rotary hoe, spiked harrow, header machine), and input use (fertilizer, irrigation, seeds), were recorded on a shared online platform.

Finally, 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 the 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 progressively enhance the project's management.

Results session (6 pages en double interligne, Times new roman 12)

Description of pesticide-free cropping systems

The pesticide-free cropping systems of the network were established at nine sites with different French pedoclimatic and socio-economic conditions (Fig. 3). 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 preventive measures during the design process. Furthermore, Rés0Pest crop sequences were more diversified than typical French crop sequences, such as canola-wheat-barley. The diversification of crop succession by including new crops such as soybean and hemp, 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 graphic 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 Bretenièrre. 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 the assessment of the risk of 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 multi-performance.

Agronomical Performance of Rés0Pest Network

Yield and harvest quality are two of the indicators used to evaluate the agronomic performance of Rés0Pest crops each year. Since no reference for the expected yields of arable and livestock crops cultivated without pesticides and synthetic fertilizers was available during the time of the

experiment, yield objectives for Rés0Pest cropping systems were set by the designers based on information available in databases (e.g., FranceAgrimer, Agreste) of crops produced in conventional and organic systems for the relevant region. For uncommon crops, such as hemp, where official yield information was scarce or absent, yield targets were established mainly based on expert opinion from agronomists, researchers, and technicians with experience and knowledge in managing such crops. In both cases, yield targets were adjusted by the designers to account for the constraint of producing without pesticides, aiming for achievable yield objectives that were, in any case, lower than those reported for organic agriculture.

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 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.

Although the yield objectives were set by the designers based on information from official databases and expert knowledge, a bias linked to their lack of experience and knowledge gaps in managing pesticide-free cropping systems was observed. For example, the average yields obtained for hemp (grains), winter barley, fodder mixture, meadow (first and second year),

sugar beet, and potato were higher than the targets set by the experiment designers. One particularly interesting result illustrating this bias is the yield obtained for sugar beet.

Given that sugar beet is highly dependent on insecticides such as neonicotinoids (Hauer et al. 2017; Epstein et al. 2022), 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 minimum wages per human work unit, which is considered high in the French socio-economic context (Fig. 9). This result is particularly encouraging in France, where the use of neonicotinoids has been banned due to health risks. To date, almost no alternative has been found to replace their function (Hauer et al. 2017), so the agroecological principles used to produce pesticide-free sugar beet 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 analyzed the results for wheat, as it is the only crop in the network produced in eight different French regions over several years. Fig. 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 at Auzeville and Mauguio, and triticale at Estrées-Mons, Grignon, and Le Rheu (Fig. 8C). However, at the Lamothe site, bread wheat yields were even lower than those for organic bread wheat. Importantly, Lamothe was the only site included five years after the creation of the network without a formal design process involving multiple and external actors to the experimental station. The overall less satisfactory results observed at this site confirm the importance of following a well-structured process during the design of the cropping system and cropping management plans.

The quality of cereal harvests can be affected by the presence of mycotoxins. Mycotoxins are molecules produced by 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 (wheat, barley, and oats) or maize and can produce a type of mycotoxin called deoxynivalenol (DON). At Rés0Pest, the concentration of DON (ng/g) was monitored for each harvest of cereal crops (bread wheat, durum wheat, maize, sorghum, spring barley, triticale, winter barley). On average, the quantities of DON detected were below the European legislative limit of 1250 ng/g (Fig. 10). Exceptionally, for three harvests in ten years—triticale 2013 and bread wheat 2016 (Grignon), and triticale 2019 (Nouzilly)—DON levels were higher than what is permitted. High humidity during crop production was the most plausible explanation provided by experimenters for this result. Together, these results indicate that an increase in mycotoxin production in pesticide-free production systems does 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, an 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 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, an experimenter at Breteniére, 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."

The net farm income (€/ha/year) was calculated for each site and cropping system using data generated for at least one complete crop sequence under different pricing scenarios covering the years of the experiment (see supplementary information for calculation details). Overall, in Auzeville, Bretenière, Estrées-Mons, and Grignon, the net farm income was higher than one minimum wage per human work unit (MW/HWU) in all pricing scenarios from 2013 to 2022. Notably, the Estrées-Mons site showed very encouraging results, with a net farm income higher than three MW/HWU in most of the pricing scenarios (Fig. 9). In other sites like Le Rheu, Lusignan, Nouzilly, and Mauguio, the net farm income was lower than one MW/HWU. Interestingly, Le Rheu, Lusignan, and Nouzilly tested the feasibility of pesticide-free production in multi-crop-livestock systems (Fig. 9). These results may be influenced by multiple factors but indicate that special consideration needs to be given to the economic model when producing pesticide-free crops for animal feed. In the case of Mauguio, it is important to highlight that Rés0Pest plots were conducted in an experimental station focused on plant breeding trials with factorial experimental designs. This was a significant barrier, as experimenters reported difficulties in properly managing Rés0Pest plots due to a lack of time, given the other priorities of the experimental station. While this is certainly not the only reason for the less satisfactory results, it exemplifies that, beyond the technical feasibility of conducting pesticide-free cropping systems, other human factors, such as a lack of experimental support, were crucial determinants influencing the outcomes of the experiments in the network.

We conducted a socio-economic and environmental assessment of Rés0Pest cropping systems after 10 years of experimentation (Cellier et al. 2024, under revision) 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. The socio-economic contribution, however, is site-dependent. Mauguio, Lusignan, Nouzilly, and Le Rheu showed a low contribution to the economic component 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. Experimenters agree that better socio-economic results can be achieved primarily through better valorization of the price of pesticide-free crops and by an improvement of technical support, such as the development of plant varieties and machinery adapted to pesticide-free production modes.

Discussion & Conclusion (6 pages en double interligne, Times new roman 12)

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 has managed to work together for 10 years and complete one or two crop sequences across the sites. Overall, network members agreed that networking 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 was the first real opportunity for them to conduct an experiment where they had to learn to observe, exchange information with

organic and conventional farmers, bring basic knowledge into practice, test alternative solutions, and/or develop new solutions. This approach to conducting an experiment was very different from other experiments, where they followed predefined and less flexible crop management plans, resulting in less rich learning processes. Interestingly, experimenters mentioned that Rés0Pest profoundly modified the way they conduct other cropping systems. They often apply the knowledge gained from working in Rés0Pest to other experiments at the experimental station where no constraints on pesticide use exist. This shift is due to their experience using different cropping practices to manage pests and because they find it more pleasant to work without needing to use pesticides.

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 systems. Taking wheat as an example, we observed that 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). The fundamental strategy adopted at Rés0Pest to achieve higher yields compared to organic crops was to maintain a synthetic fertilization plan tailored to improve yields without increasing crop susceptibility to pests. In the case of wheat, the results of Rés0Pest are promising and confirm that mineral fertilization can indeed compensate for yield losses observed in organic agriculture. However, the use of synthetic fertilizers is known to be energetically costly, undermine soil health, and be a major source of water pollution. New methods of producing mineral fertilizers from innovative recycling processes have begun to emerge (Utai et al. 2022; Wald 2022; Smol 2019). The development of more sustainable mineral fertilizers, in combination with an optimal diagnosis of crop nutritional needs, constitutes an important step to ensure both the performance and sustainability of innovative systems such as pesticide-free crop production (Lemaire et al. 2021; Krüger 2016).

Data management plans: collecting, registering, and analyzing data was one of the major difficulties of Rés0Pest working as a network. First, the introduction of 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 a lack of feedback on 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 after 10 years of experimentation. 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 multi-performance of their systems and to see the importance of providing high-quality data.

Conclusion

Rés0Pest led to 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 multiple 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 of animal pest or pathogen populations 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 alleged to be highly dependent on pesticides, such as canola and sugar beet. For wheat, Rés0Pest results confirmed the hypothesis that yields of pesticide-free crops can achieve higher yields than organic crops by maintaining the use of mineral fertilizers. Ineffective weed management plans and drought were identified as the main factors threatening pesticide-free crop yields across sites and seasons, shedding lights on the more urgent avenues of improvement for this kind of systems.

Rés0Pest 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. 2017a). 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, under revision). 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 quite promising, especially considering that the network did not benefit from any price valorization for producing pesticide-free crops.

Since the Rés0Pest cropping systems aimed to test the feasibility of a proof of concept, the designers opted for a radical ban on the use 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 of the experimental unit either in 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 systems 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.

Acknowledgements

This work was financially supported by the French National Action Plan for pesticide reduction (ECOPHYTO DEPHY EXPE network), from 2012 to 2023, the European project PURE funded by the European Union Seventh Framework Program (FP7/2007e2013) under grant agreement no 265865 for Grignon trial, INRAE and the INRAE/Cirad IPM network. Marie-Hélène Bernicot. Serv0Pest (metaprogramme divecosys).

Adrees, M., Ali, S., Rizwan, M., Ibrahim, M., Abbas, F., Farid, M., et al. 2015. The effect of excess copper on growth and physiology of important food crops: a review. *Environmental Science and Pollution Research*. 22:8148–8162.

Agogu  , M., Hoo  , S., Arnoux, F., and Brown, I. 2014. *An introduction to innovative design: Elements and applications of C-K Theory*. Paris: Presses des Mines, coll. Economie et Gestion.

Andrade, C., Villers, A., Balent, G., Bar-Hen, A., Chadoeuf, J., Cylly, D., et al. 2021. A real-world implementation of a nationwide, long-term monitoring program to assess the impact of agrochemicals and agricultural practices on biodiversity. *Ecol Evol*. 11:3771–3793.

Andr  on, D., Bardin, M., Bertrand, C., Brun, L., Daire, X., Fabre, F., et al. 2018. *Can Organic Agriculture Give Up Copper As a Crop Protection Product ? Summary of the Scientific Assessment Report - June 2018*.

Anonymous. 2015. *Ecophyto plan II*.

Attoumani-Ronceux, A., Aubertot, J. N., Guichard, L., Jouy, L., Mischler, P., Omon, B., et al. 2011. *Practical guide for the design of cropping systems less reliant on pesticides*.

Berthet, E. T., Segrestin, B., and Hickey, G. M. 2016. Considering agro-ecosystems as ecological funds for collective design: New perspectives for environmental policy. *Environ Sci Policy*. 61:108–115.

Boatman, N. D., Brickle, N. W., Hart, J. D., Milsom, T. P., Morris, A. J., Murray, A. W. A., et al. 2004. Evidence for the indirect effects of pesticides on farmland birds. *Ibis*. 146:131–143.

Boiffin, J., Malezieux, E., and Picard, D. 2001. Cropping Systems for the Future. In *Crop science: progress and prospects*, eds. J N  sberger, H Geiger Hartwig, and P Struik. Hambour  h-Germany: CABI Publishing, p. 261–279. Available at: <https://cabidigitallibrary.org>.

Brond  zio, E. S., Settele, J., D    , S., and Ngo, H. T. (eds). 2019. *IPBES (2019), Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

Cellier, V., Ortiz, D., Colnenne-David, C., Deremetz, V., Darras, S., Deytieux, V., et al. 2024. Analyse de la durabilit   socio-  conomique et environnementale d'un r  seau de syst  mes de culture z  ro-pesticides (R  sOPest) apr  s 10 ans d'exp  rimentation. *Innovations Agronomiques*.

Coquil, X., Fiorelli, J. L., Blouet, A., and Mignolet, C. 2014. Experiencing organic mixed crop dairy systems: A step-by-step design centred on a long-term experiment. In *Organic Farming, Prototype for Sustainable Agricultures: Prototype for Sustainable Agricultures*, Springer Netherlands, p. 201–217.

Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J. M., Faloya, V., et al. 2009. Iterative design and evaluation of rule-based cropping systems: Methodology and case studies - A review. *Sustainable Agriculture*. 29:707–724.

Deguine, J. P., Atiama-Nurbel, T., Aubertot, J. N., Augusseau, X., Atiama, M., Jacquot, M., et al. 2015. Agroecological management of cucurbit-infesting fruit fly: a review. *Agron Sustain Dev*. 35:937–965.

Deguine, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A. G., and Ratnadass, A. 2021. Integrated pest management: good intentions, hard realities. A review. *Agron Sustain Dev*. 41.

Deguine, J.-P., Jacquot, M., Allibert, A., Chiroleu, F., Graindorge, R., Laurent, P., et al. 2018. Agroecological Protection of Mango Orchards in La R  union. In *Sustainable Agriculture Reviews*, eds. Sabrina Gaba, Barbara Smith, and Eric Lichtfouse. , p. 1–46.

651 Epstein, Y., Chapron, G., and Verheggen, F. 2022. What is an emergency? Neonicotinoids and
652 emergency situations in plant protection in the EU. *Ambio*. 51:1764–1771.

653 FAO. 2018a. *Catalysing dialogue and cooperation to scale up agroecology: outcomes of the*
654 *FAO regional seminars on agroecology*. Available at: www.fao.org/publications.

655 FAO. 2018b. *FAO's work on agroecology: A path- way to achieving the SDGs*. Rome, Italy.
656 Available at: <https://openknowledge.fao.org/items/efd8949e-ffba-4f5d-9ec5-472f0714fc2a>
657 [Accessed April 29, 2024].

658 Gliessman, S. 2018. Defining Agroecology. *Agroecology and Sustainable Food Systems*.
659 42:599–600.

660 Guyomard, and Bureau. 2020. Research for AGRI Committee – The Green Deal and the CAP:
661 policy implications to adapt farming practices and to preserve the EU's natural resources. :1–
662 162.

663 Hatt, S., and Döring, T. F. 2023. Designing pest suppressive agroecosystems: Principles for an
664 integrative diversification science. *J Clean Prod*. 432.

665 Hauer, M., Hansen, A. L., Manderyck, B., Olsson, Å., Raaijmakers, E., Hanse, B., et al. 2017.
666 Neonicotinoids in sugar beet cultivation in Central and Northern Europe: Efficacy and
667 environmental impact of neonicotinoid seed treatments and alternative measures. *Crop*
668 *Protection*. 93:132–142.

669 Hawkins, N. J., Bass, C., Dixon, A., and Neve, P. 2019. The evolutionary origins of pesticide
670 resistance. *Biological Reviews*. 94:135–155.

671 Jacquet, F., Jeuffroy, M. H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., et al. 2022.
672 Pesticide-free agriculture as a new paradigm for research. *Agron Sustain Dev*. 42:1–24.

673 Jeuffroy, M. H., Loyce, C., Lefeuvre, T., Valantin-Morison, M., Colnenne-David, C.,
674 Gauffreteau, A., et al. 2022. Design workshops for innovative cropping systems and decision-
675 support tools: Learning from 12 case studies. *European Journal of Agronomy*. 139.

676 Keane, W. T. 1972. Eliminate DDT? Quest for an advantageous benefit:Risk ratio. *Science of*
677 *the Total Environment, The*. 1:141–163.

678 Kudsk, P., and Mathiassen, S. K. 2020. Pesticide regulation in the European Union and the
679 glyphosate controversy. *Weed Sci*. 68:214–222.

680 Lamine, C., Barbier, M., Blanc, J., Buurma, J., Haynes, I., Lehota, J., et al. 2010. Reducing the
681 dependence on pesticides: a matter of transitions within the whole agri-food system.
682 *Transitions towards sustainable agriculture: from farmers to agro-food system*. :1943–1954.

683 Lechenet, M., Deytieu, V., Antichi, D., Aubertot, J. N., Bàrberi, P., Bertrand, M., et al. 2017.
684 Diversity of methodologies to experiment Integrated Pest Management in arable cropping
685 systems: Analysis and reflections based on a European network. *European Journal of*
686 *Agronomy*. 83:86–99.

687 Leenhardt, S., Mamy, L., Pesce, S., Sanchez, W., Achard, A., Amichot, M., et al. 2022. Impacts
688 des produits phytopharmaceutiques sur la biodiversité et les services écosystémiques.
689 *Synthèse du rapport d'ESCO, INRAE - Ifremer (France)*. :136.

690 Lucas, P., Ratnadass, A., and Deguine, J.-P. 2017. Moving from Integrated Pest Management
691 to Agroecological Crop Protection (ACP). In *Agroecological crop protection*, eds. Jean-
692 Philippe Deguine, Caroline Gloanec, Philippe Laurent, Alain Ratnadass, and Jean Noël
693 Aubertot. Editions Quae-Springer, p. 249.

694 Malézieux, E. 2017. Agroecology, a 21st Century Agricultural Revolution? In *Agroecological*
695 *crop protection*, eds. Jean-Philippe Deguine, Caroline Gloanec, Philippe Laurent, Alain
696 Ratnadass, and Jean-Noël Aubertot. Editions Quae-Springer, p. 249.

697 Meehan, T. D., Werling, B. P., Landis, D. A., and Gratton, C. 2011. Agricultural landscape
698 simplification and insecticide use in the Midwestern United States. *Proc Natl Acad Sci U S A*.
699 108:11500–11505.

700 Meynard, J. M., Cerf, M., Coquil, X., Durant, D., Le Bail, M., Lefèvre, A., et al. 2023a.
701 Unravelling the step-by-step process for farming system design to support agroecological
702 transition. *European Journal of Agronomy*. 150:126948.

703 Meynard, J. M., Cerf, M., Coquil, X., Durant, D., Le Bail, M., Lefèvre, A., et al. 2023b.
704 Unravelling the step-by-step process for farming system design to support agroecological
705 transition. *European Journal of Agronomy*. 150.

706 Mouhamed, R. S., Bicksler, A. J., Mottet, A., Lucantoni, D., and Barrios, E. 2023. The 10
707 Elements of Agroecology interconnected: Making them operational in FAO's work on
708 Agroecology. *Elementa*. 11.

709 Navarrete, M., Brives, H., Lefèvre, A., and Simon, S. 2018. Intertwining deterministic and
710 open - ended perspectives in the experimentation of agroecological production systems : A
711 challenge for agronomy researchers. In *Agroecological transitions, between determinist and*
712 *open-endend visions*, eds. Claire Lamine, Danièle Magda, Marta Rivera-Ferre, and Terry
713 Marsden. Library of Congress Cataloging-in-Publication Data.

714 Pedersen, A., and Nielsen, H. 2017. *Effectiveness of pesticide policies:experiences from*
715 *Danish pesticide regulation 1986-2015*. In: *Environmental Pest Management*. John Wiley.
716 eds. Moshe Coll and Eric Wajnberg. Chinchester, UK.

717 Rani, L., Thapa, K., Kanojia, N., Sharma, N., Singh, S., Grewal, A. S., et al. 2021. An extensive
718 review on the consequences of chemical pesticides on human health and environment. *J*
719 *Clean Prod*. 283:124657.

720 Ratnadass, A. 2017. Feedback and common approaches to agroecological crop protection:
721 Further examples. In *Agroecological crop protection*, eds. Jean-Philippe Deguine, Caroline
722 Gloanec, Philippe Laurent, Alain Ratnadass, and Jean Noël Aubertot.

723 Reganold, J. P., and Wachter, J. M. 2016. Organic agriculture in the twenty-first century. *Nat*
724 *Plants*. 2:1–8.

725 Sadok, W., Angevin, F., Bergez, J. E., Bockstaller, C., Colomb, B., Guichard, L., et al. 2009.
726 MASC, a qualitative multi-attribute decision model for ex ante assessment of the
727 sustainability of cropping systems. *Agron Sustain Dev*. 29:447–461.

728 Sánchez-Bayo, F. 2021. Indirect effect of pesticides on insects and other arthropods. *Toxics*.
729 9.

730 Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. 2009. Agroecology as a
731 science, a movement and a practice. *Sustainable Agriculture*. 2:27–43.

733 **References web sites**

734 Agreste. 2023a. Statistique agricole annuelle (SAA) - Séries longues depuis 2010
735 In: <https://agreste.agriculture.gouv.fr/agreste-web/disaron/SAA-SeriesLongues/detail/>

736 Agreste. 2023b. Des rendements en grandes cultures inférieurs en agriculture biologique à
737 ceux en conventionnel.
738 In: <https://agreste.agriculture.gouv.fr/agreste-web/disaron/Pri2308/detail/>
739

740 European Commission. 2017. Definition Integrated Pest Management (IPM).

In: Sustainable use of pesticides. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en Access: October 16th, 2022.

European Green Deal. 2019. https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf Access: November 10th, 2022.

EU Biodiversity Strategy for 2030. https://ec.europa.eu/info/sites/default/files/communication-annex-eu-biodiversity-strategy-2030_en.pdf . Access: November 10th, 2022.

EU Directive 2009/128/EC. 2009.
<https://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF>

FAOSTAT. 2020. Pesticide use. [http:// www. fao. org/ faost at/ en/# data/RP](http://www.fao.org/faostat/en/#data/RP) Access: October 19th, 2020.

Farm to Fork Strategy. https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pdf. Access: October 19th, 2020.

Pledge for nature. 2020. https://www.leaderspledgefornature.org/wp-content/uploads/2021/06/Leaders_Pledge_for_Nature_27.09.20-ENGLISH.pdf

765 **Figures**

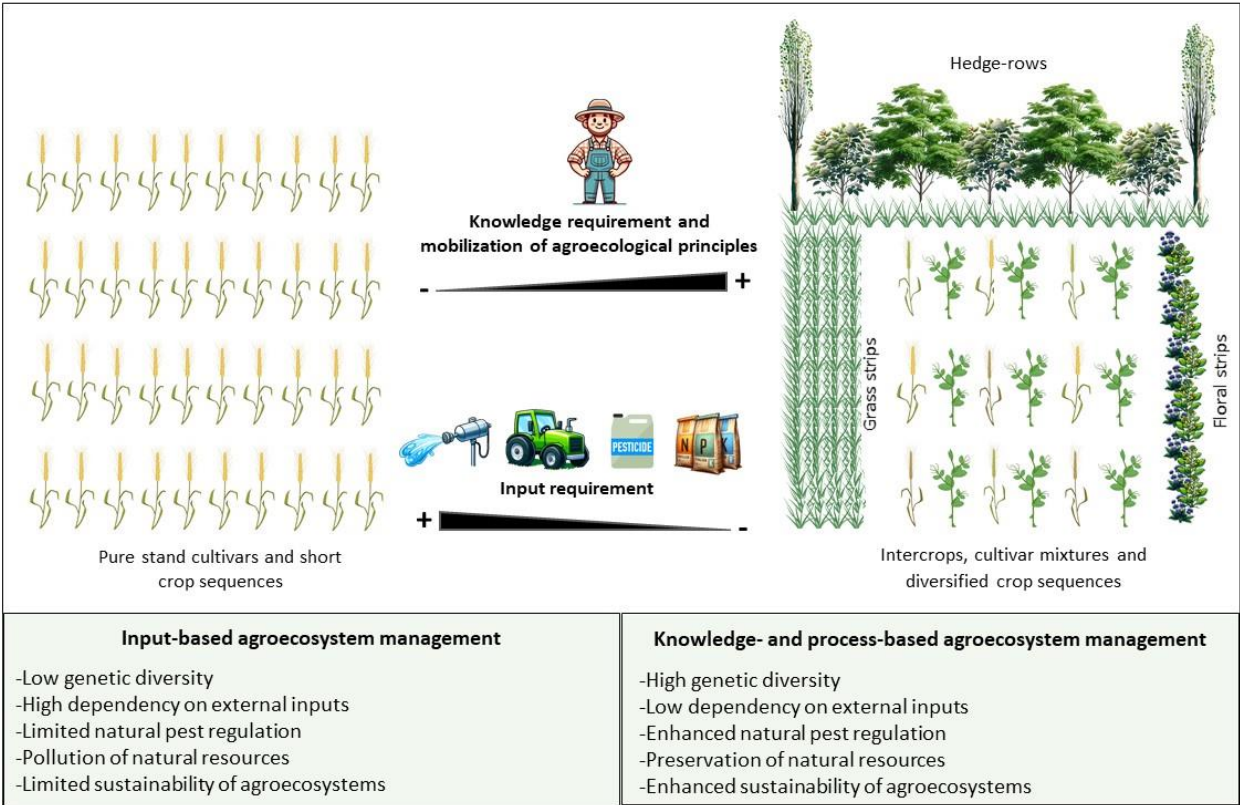


Fig 1. Redesign of crop systems by applying agroecological principles of crop protection.

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).

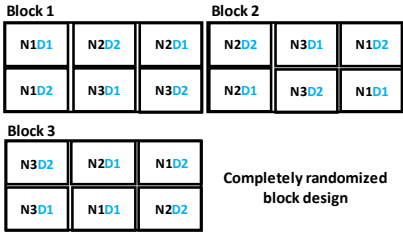
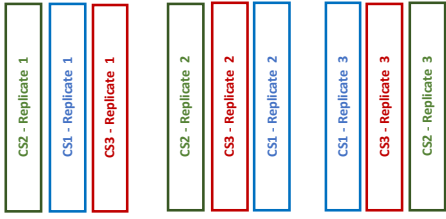
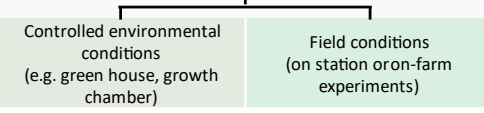
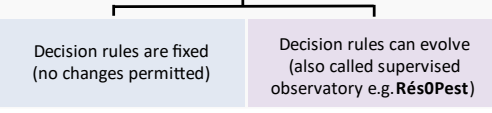
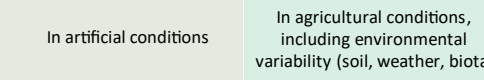
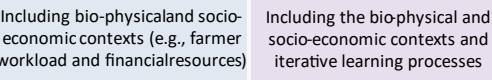
	Factorial experiment	System experiment
Aim of the experiment	Comparing the effects of one or several factor(s) (independent variables) on one or more dependent variables simultaneously.	Evaluating the ability of a system (e.g., cropping system, livestock farming system or production system) defined by 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	<p>Experimental unit: Plant organs, plant, pots or small plots.</p>  <p>Completely randomized block design</p>	<p>Experimental unit: Plot (minimal size compatible with the standard machinery), animal, farm.</p>  <p>Completely randomized design</p>
Experimental management	<p>Implementation</p> 	<p>Implementation only on field conditions of crop sequences and associated crop management plans ruled by decision rules</p> 
Evaluation	<p>Quantification of the individual effects of factors and their interactions</p> 	<p>Evaluation of technical feasibility and system performance</p> 
Applicability	-	+
Inference level	+	-

Fig 2. Main features of factorial and system experiments in agricultural research

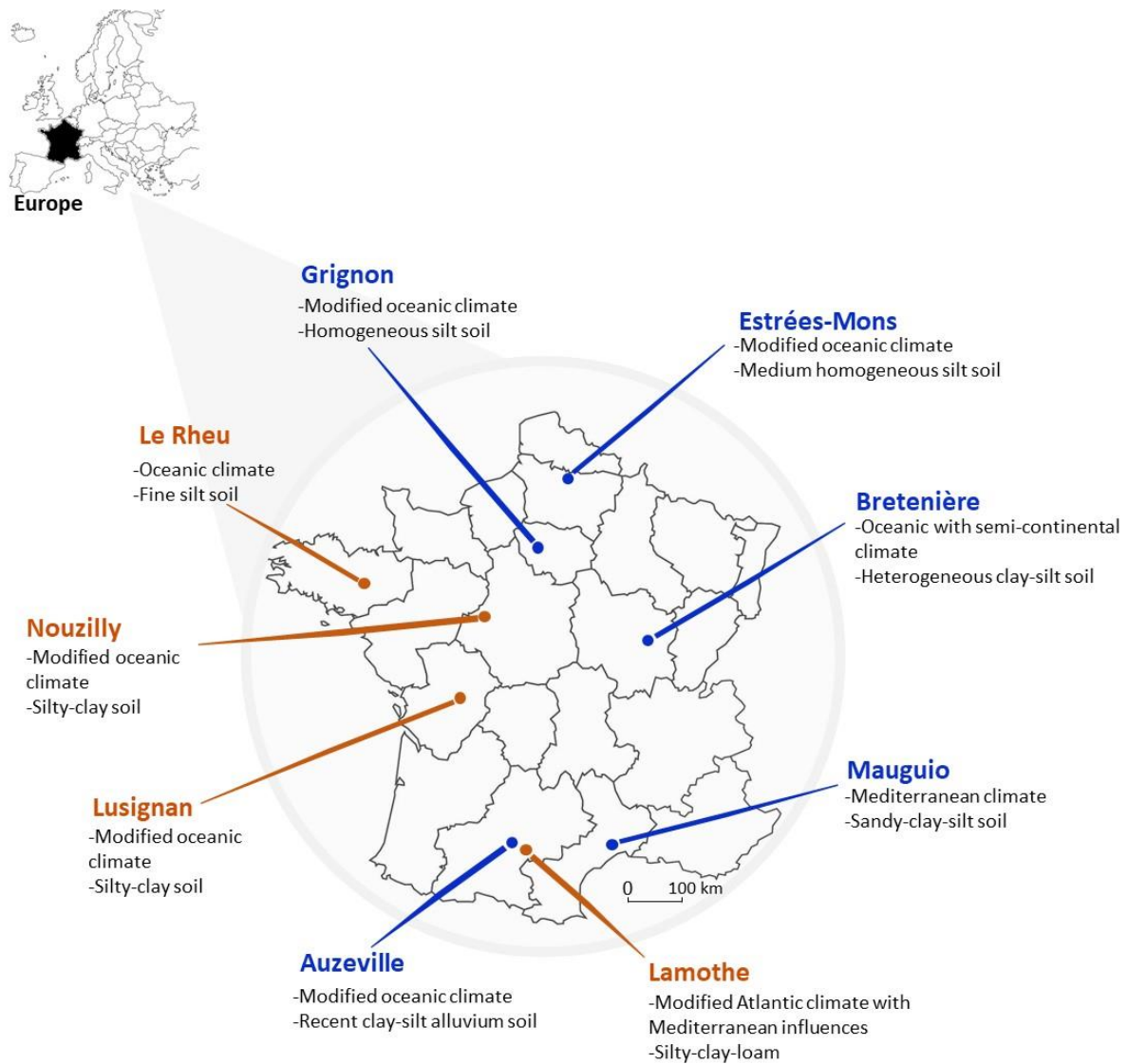


Fig. 3. Location of the nine sites of the Rés0Pest network spread in France. Names of experimental stations and main climate and soil features are indicated for each site. Colors represent cropping systems with arable crops (blue) and with multicrop-livestock (orange).

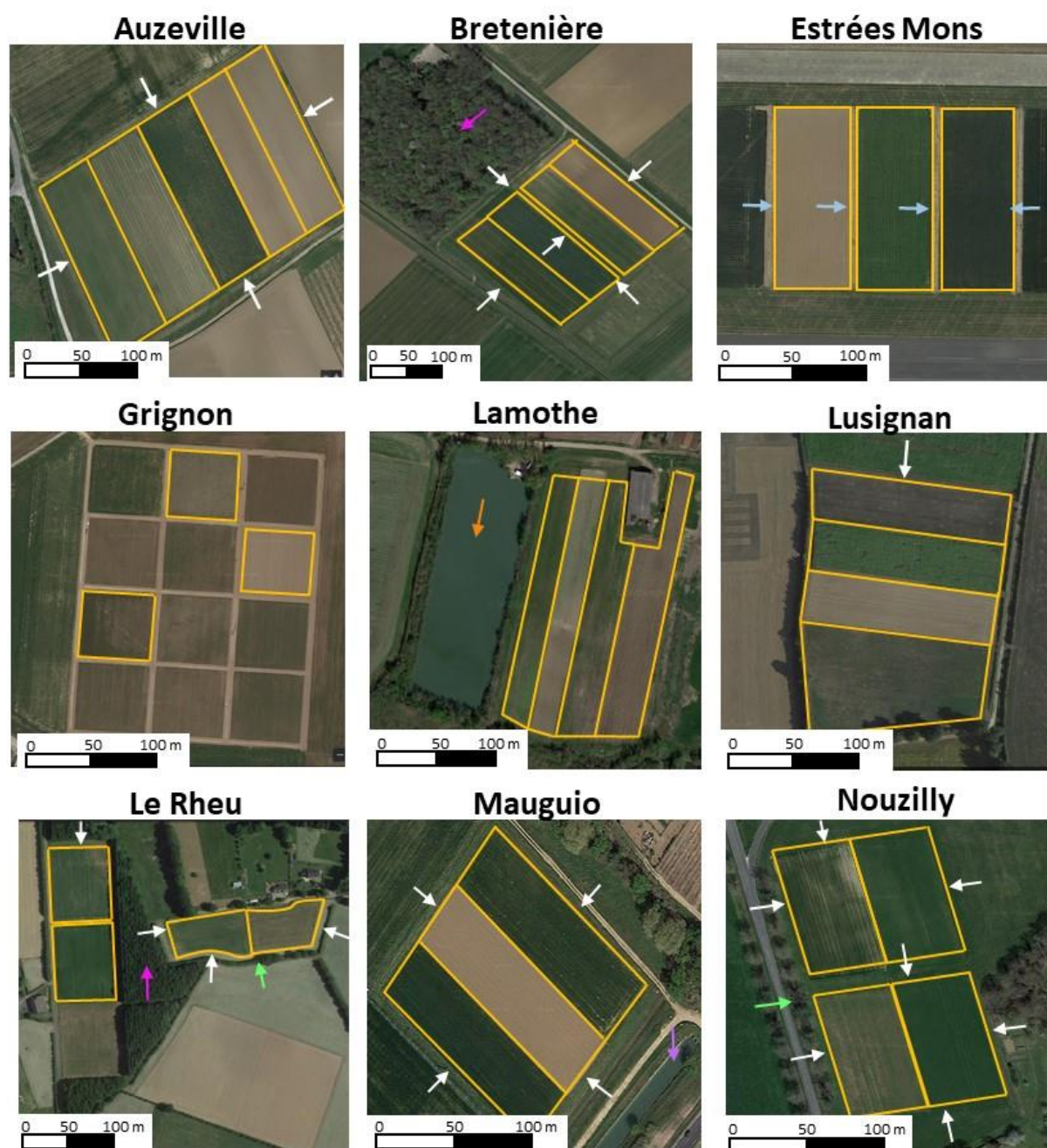
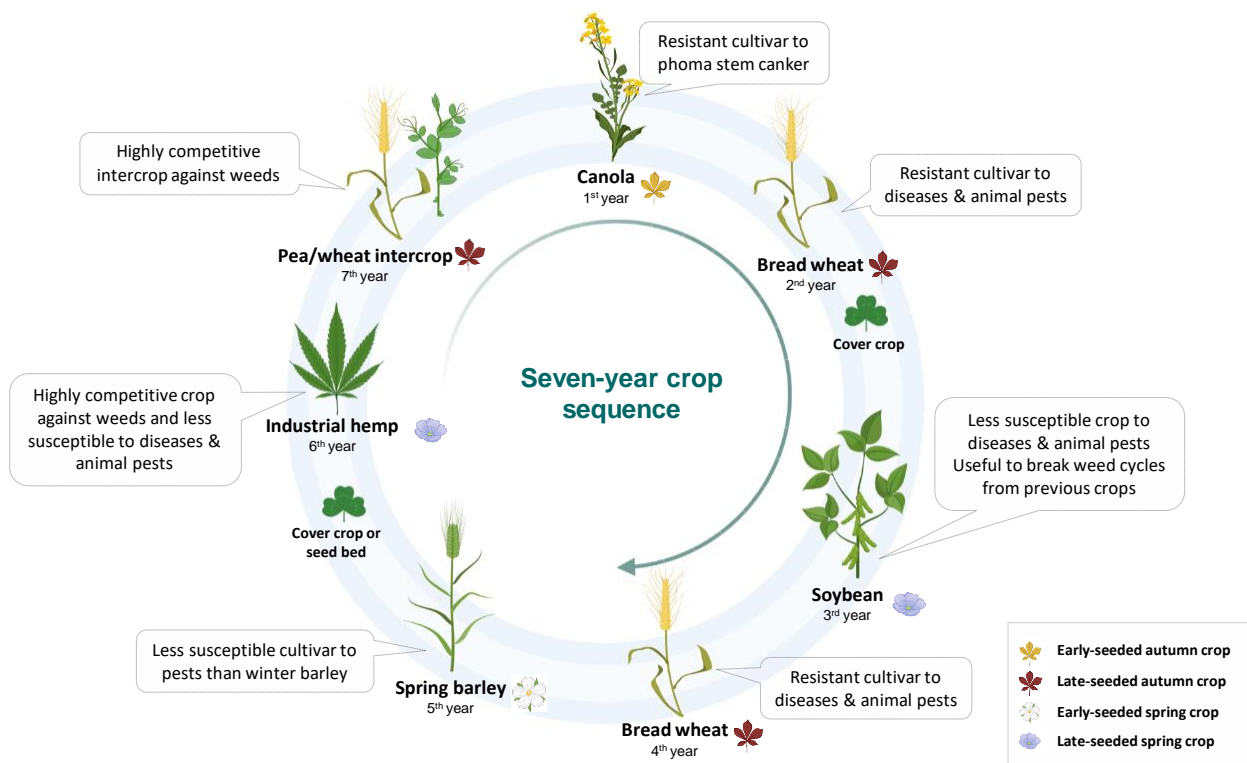


Fig. 4. Layout of the nine sites of the Rés0Pest network. Plots are highlighted by yellow frames. Agroecological infrastructures are indicated by arrows (white: grass strip; blue: grass strip + flower strip; pink: wood; light green: hedgerow; purple: river; orange: lake). Pictures are oriented with north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



796

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

802

803

804

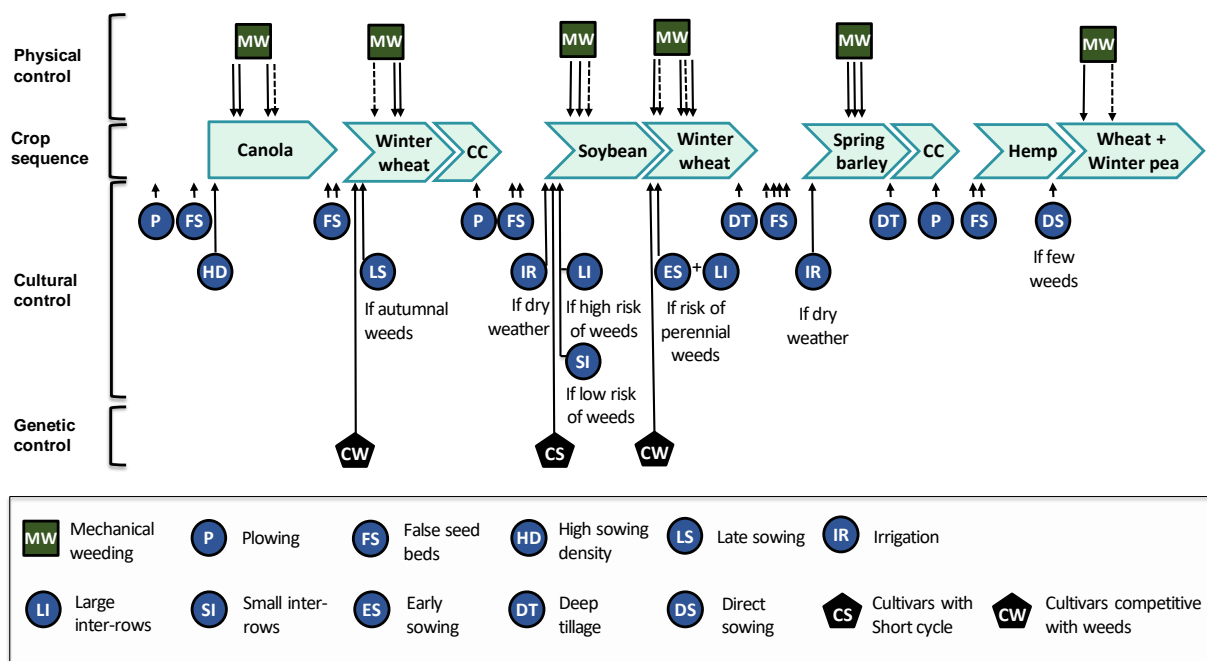


Fig. 6. Cropping practices used for the weed management plan in Bretenière. The green chevrons in the middle indicate the crop succession for the Bretenière cropping system. The squares, circles and pentagons indicate the set of cropping practices for physical, cultural, and genetic control, respectively.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

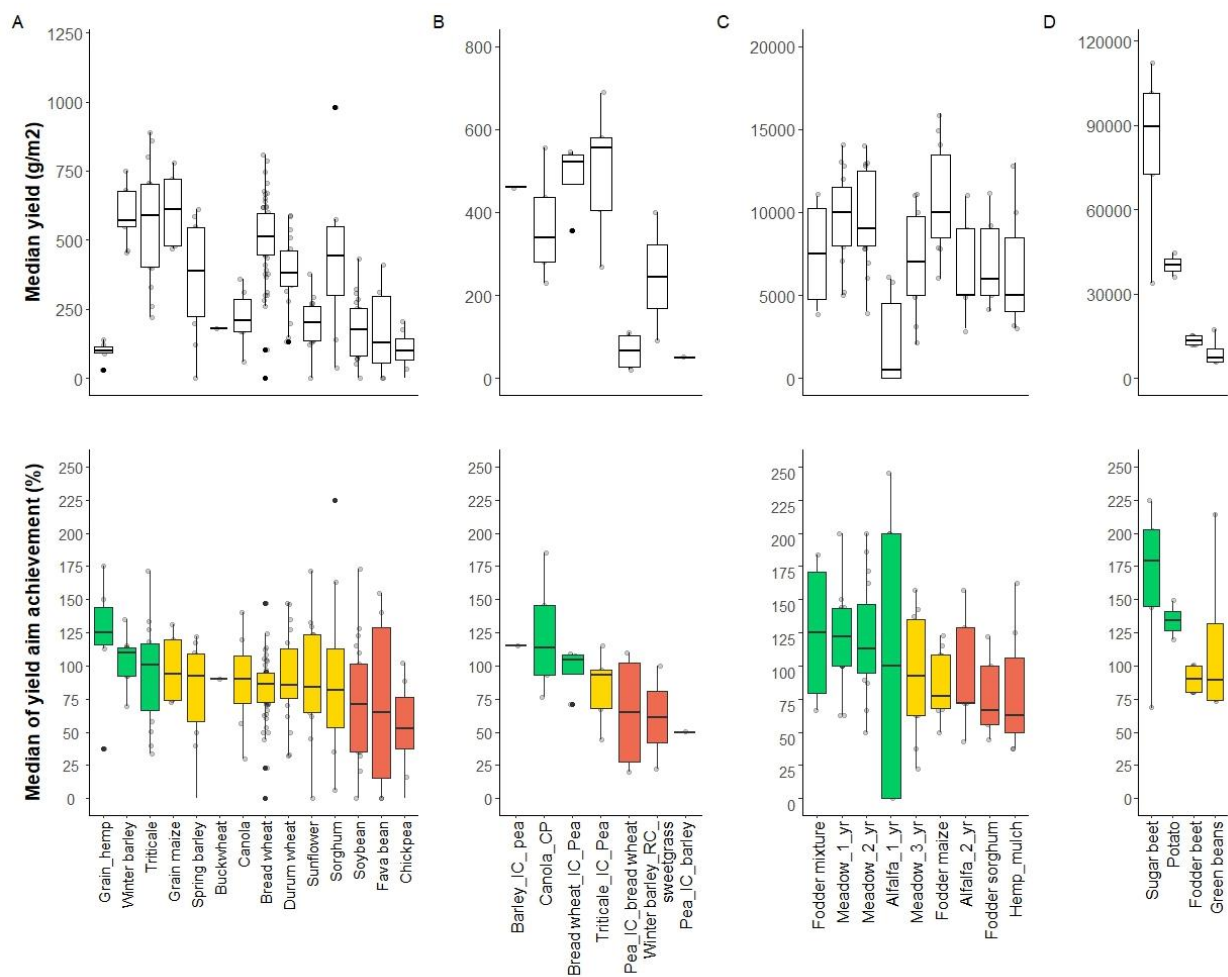


Fig. 7. Median yield performance of Rés0Pest crops across all sites and years. The panels are organized by groups of crops for better visualization and yield comparison as follows: A) Grain crops, B) Intercropping of grain crops, C) Vegetative parts, and D) Tubers and pods. The upper panels present the median yield obtained in grams per square meter (g/m²) 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.

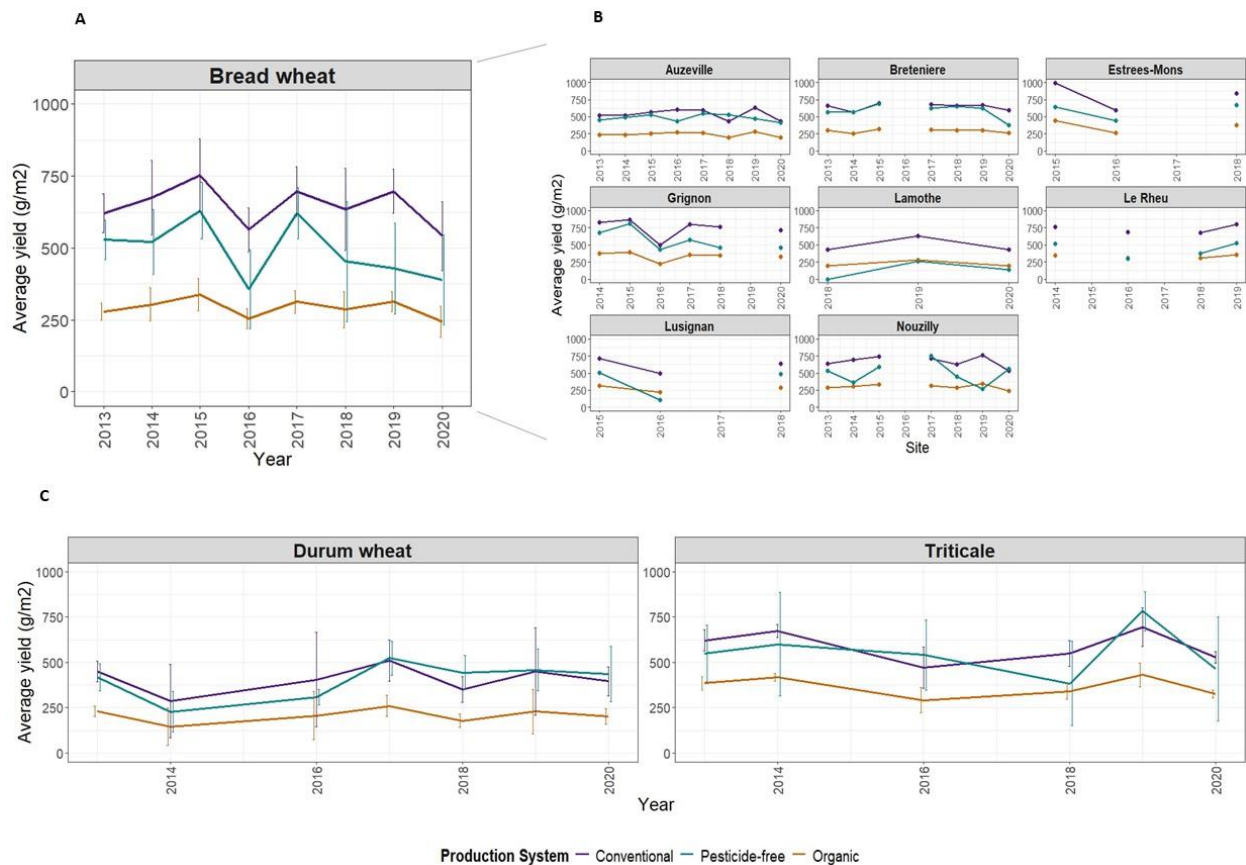


Fig. 8. Yield comparison of pesticide-free, conventional, and organic cropping systems.

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 (2023a) 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 (2023b). A) Shows the average yield of bread wheat for at least three Rés0Pest sites and regions per year. B) Shows the average yield of bread wheat for each Rés0Pest site-region for the corresponding year. C) Shows the average yields for durum wheat (Auzeville, Mauguio) and triticale (Estrées-Mons, Grignon, Le Rheu) across years.

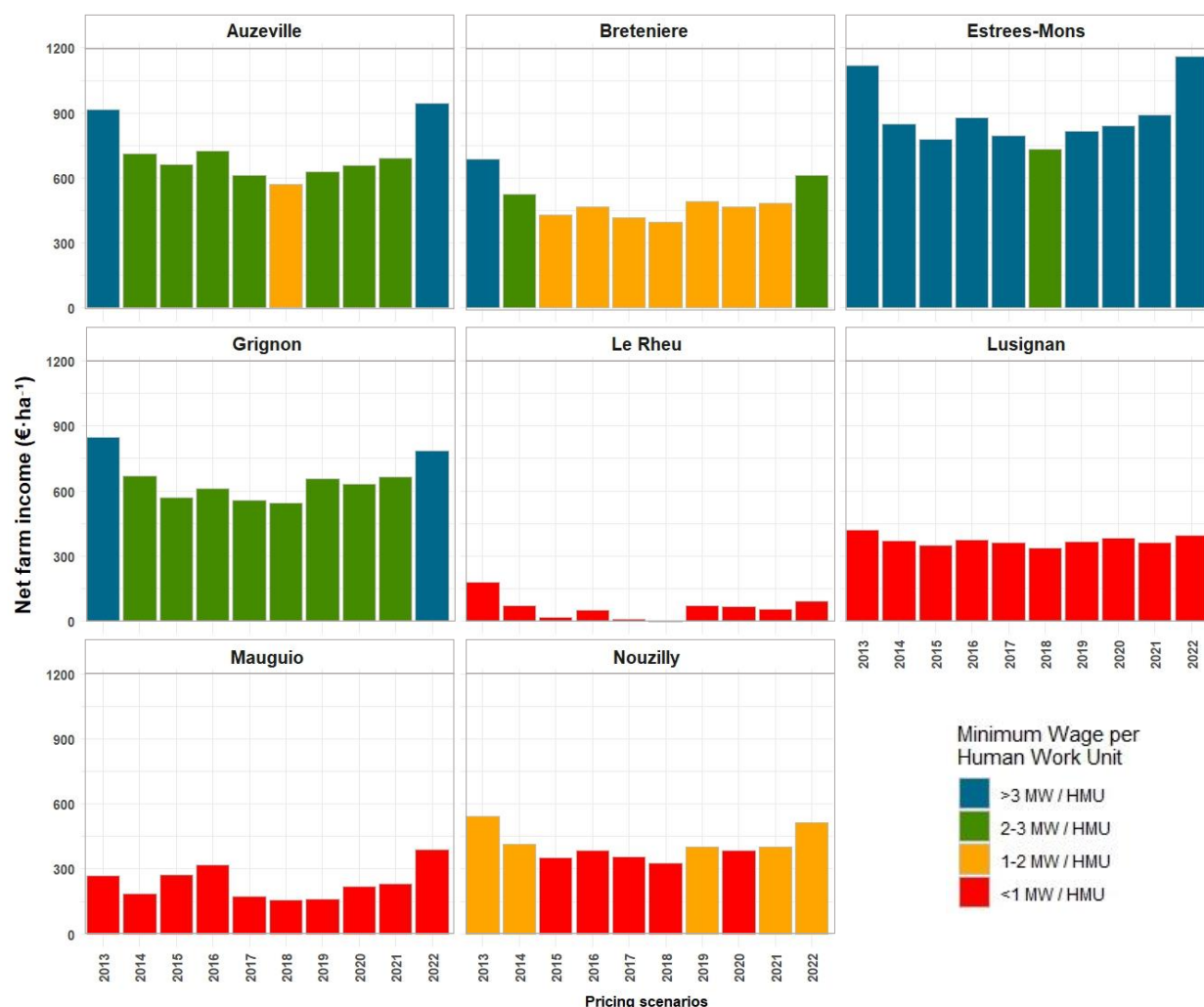


Fig. 9 Average net farm income of eight Rés0Pest cropping systems under a 10-year pricing scenario. Plots represent net farm income, which is calculated by subtracting the total operational and mechanization costs from the combined sum of the gross product (harvested quantity x sale price) and direct subsidies. The colors indicate the equivalence of farm income in terms of the minimum wage per human work unit in France. The net farm income values correspond to the average of the cropping system tested over at least one complete crop sequence (4-9 years) and were calculated under different pricing scenarios covering the period of the experiment.

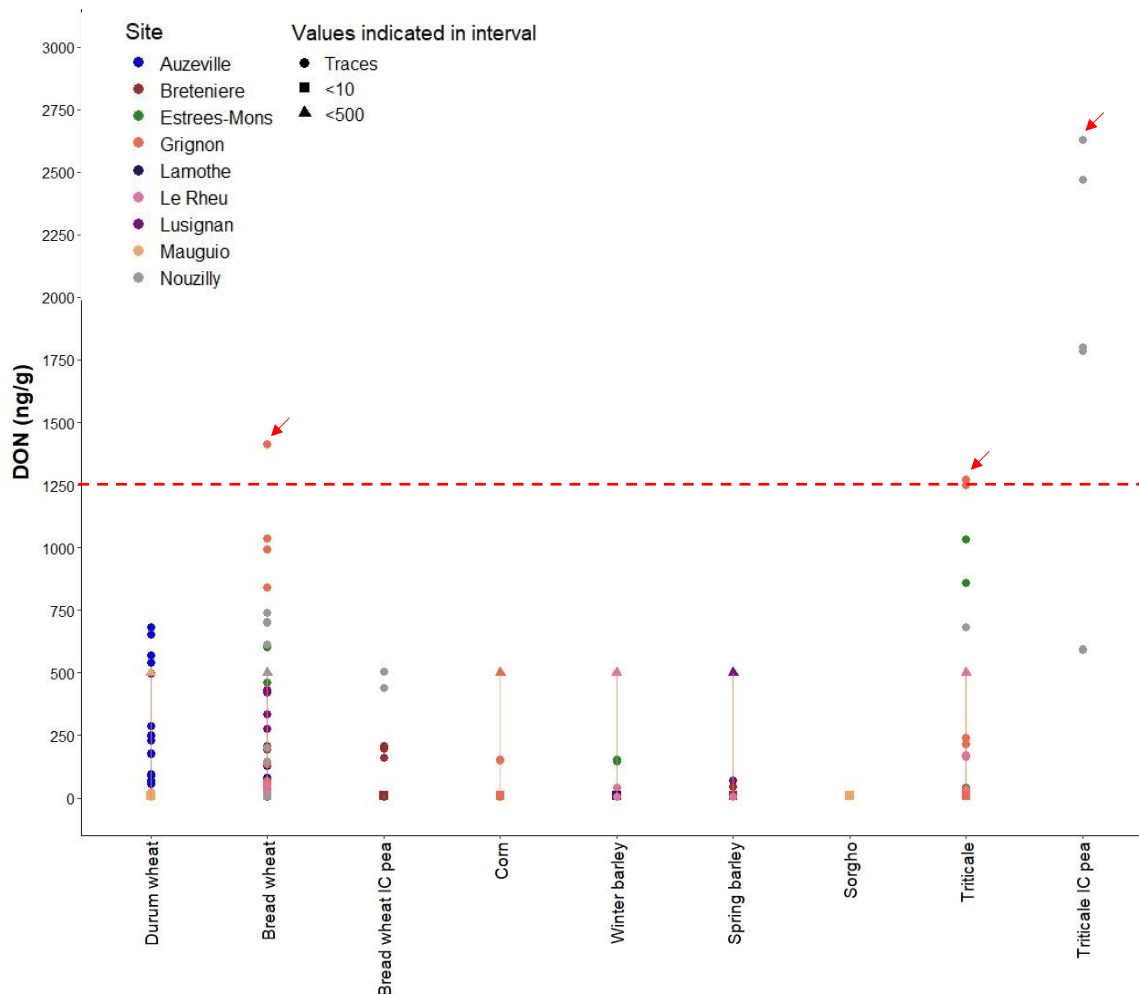


Fig. 10. Concentration (ng/g) of the deoxynivalenol (DON) mycotoxin measured from 2013 to 2020 in cereal crops in the network. The red dashed line indicates the tolerable limit for human consumption (1250 ng/g). Red arrows highlight cases where DON levels exceeded this limit. The figure plots the concentration of DON in various cereal crops over multiple years at different sites. Each point on the graph represents a measurement from a specific site. The shapes of some points (circle, triangle, and square) indicate values that were given as intervals by the measurement machine.

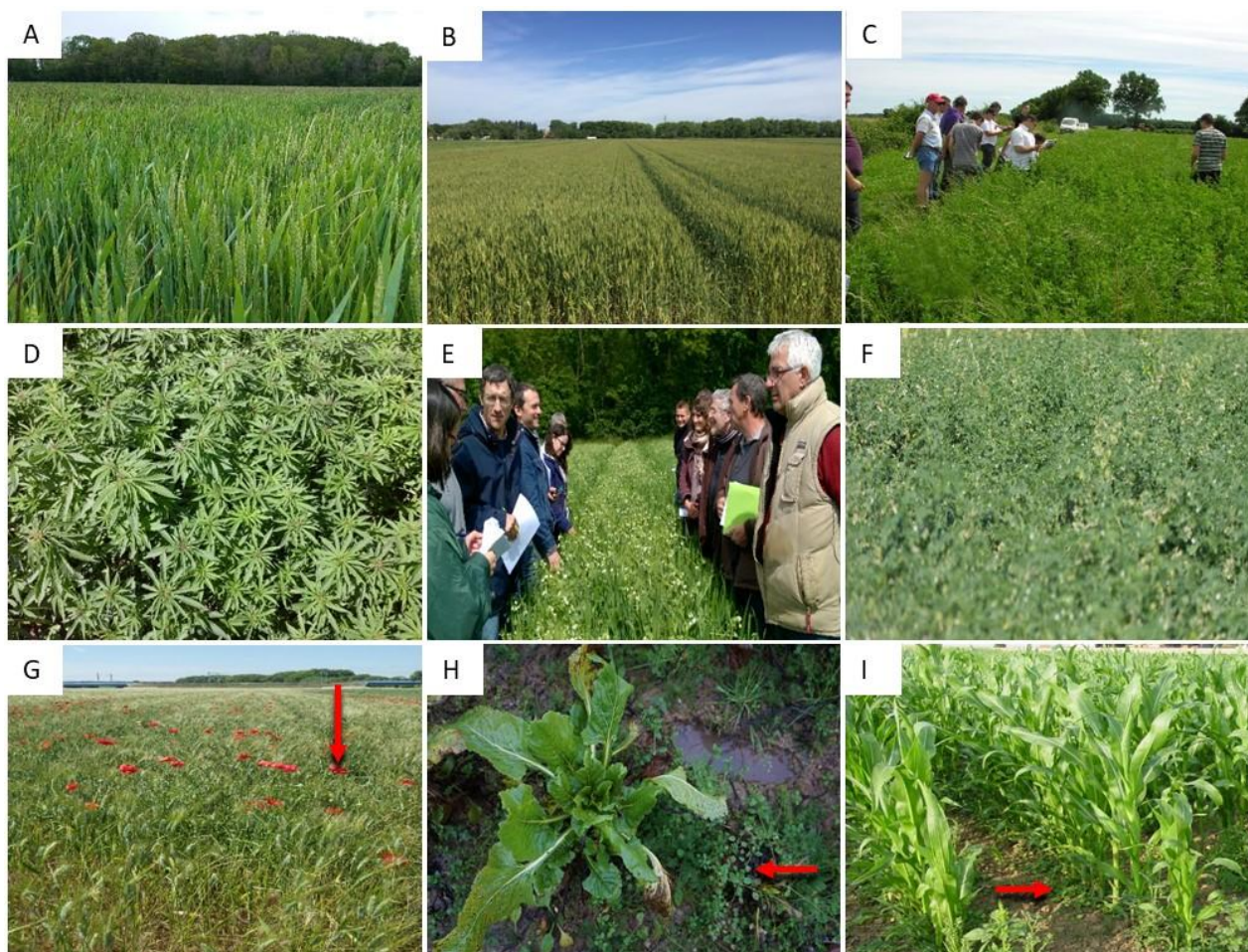


Fig. 11. Pictures showing examples of crops grown in Rés0Pest cropping systems. Red arrows indicate examples where weeds were a major limiting factor in crop management. A) Bread wheat, Bréteniere. B) Durum wheat, Auzeville. C) Meadow (Alfalfa + raygrass), Lusignan. D) Industrial hemp Grignon. E) Intercropping 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 (0-1-2) and why?	Feedback on the Implemented Technique	Deviation from target objective (0, 1, 2) 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	1: Late intervention with a different machine	Impossible to intervene earlier due to poor	2: 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		0: No excess canola, thus no hoeing planned		0: 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	0: Dose higher as planned	High insect pest pressure	1: 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		0: No confirmed risks		0: No sclerotinia observed on the canola
Harvest	250 g/m ² 9% moisture	Harvested with a combine harvester in good conditions	26/06/2018 Harvest Yield: 210g/m ²	0: Harvest was carried out as planned		2: The target yield was not reached

878 **Table 1. Objectives, decision rules and assessment of technical interventions.** A scale was established to evaluate the degree of deviation from
879 the decision rule and the technical objective, with '0' for conformity to the decision rule and technical objective, '1' for moderate deviation, and '2'
880 for major deviation

881

Site	Duration	Crop sequence
Auzeville	5 years	2012-2018: (CC) – Soybean – Durum wheat – (CC) – Grain Sorghum – Sunflower – Bread wheat
	4 years	2018-2023: (CC) Chickpea – Durum wheat – (CC) Soybean – Bread wheat
Bretenière	7 years	2012-2023: Canola – Bread wheat – (CC) – Soybean – Bread wheat – Spring Barley – (CC) – Industrial hemp – Barley or Bread wheat + Pea
Estrées-Mons	6 years	2012-2018: Sugar beet – Bread wheat – Barley – (CC) – Green Bean – Canola + companion plants – Triticale – (CC)
	7 years	2018-2023: Sugar beet – Bread wheat – (CC) – Potato – Barley – (CC) – Green Bean – Canola + companion plants – Triticale – (CC)
Grignon	6 years	2012-2020: Faba bean – Bread wheat – (CC) – Industrial hemp – Triticale (CC) – Grain maize – Bread wheat – (CC)
Mauguio	6 years	2012-2023: Alfalfa (2 years) – Durum wheat – Chickpea – Durum wheat – (CC) – Sunflower
Lusignan	9 years	2012-2023: Meadow (3 years) – Bread wheat – Canola + companion plants – (CC) – Sorgho + companion plants – Fodder mixture – (CC) – Soybean – (CC) – Barley
Lamothe	5 years	2017-2018: Alfalfa (3 years) – Sunflower – Bread wheat – Barley + alfalfa
		2018-2023: Sweetgrass (2 ans) – Sunflower – Bread wheat – Barley + Sweetgrass
Le Rheu	8 years	2012-2023: Meadow (2 years) – Fodder maize – Bread wheat – (CC) – Faba bean – Triticale – (CC) – Fodder beet – Barley
Nouzilly	8 years	2012-2018 : Meadow (3 years) – Bread wheat – (CC) – Fodder maize – Triticale + Pea – (CC) – Sunflower – Bread wheat
		2018-2023 : Meadow (3 years) – (CC) – Fodder maize – Bread wheat – Triticale + Pea – (CC) – Sunflower – Bread wheat

882

883 **Table 2. The duration and the specific crop sequences tested are indicated in columns two**
884 **and three, respectively.** Two different crop sequences in column three are shown for the sites
885 where crops or the duration of the crop sequence were modified. Dates correspond to the time
886 period during which the crop sequences were trialed.

887

888

889

890

899 **Net farm income calculation**

900 Short-term profitability is assessed based on the average annual net farm income (NFI) over the
901 crop sequence period (in €/ha/year). For each crop cycle, the net farm income is calculated by
902 subtracting the total operational and mechanization costs from the combined sum of the gross
903 product and direct subsidies.

904
$$NFI = \frac{[\sum i (GP_i + SA_i - OC_i - MC_i)]}{n}$$

905 Where:

906 **NFI:** Net farm income

907 **GP:** Gross Product (in €/ha) = Harvested Quantity x Sale Price

908 **SA:** Sum of Annual Subsidies received (in €/ha)

909 **OC:** Operational Costs (in €/ha) related each year of the succession to:

- 910 - the purchase of seeds, phytosanitary products, fertilizers
911 - fuel consumption on the plot
912 - occasional labor dedicated to the specific crop
913 - irrigation (water and necessary energy)

914 **MC:** Annual Mechanization Costs in €/ha (depreciation, repair, and maintenance of
915 equipment)

916 **n:** Duration of the crop sequence in years

917 **i:** year