

Reducing insecticide use in winter oilseed rape by in-field to landscape-scale agroecological pest management[☆]

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Abstract – Reducing insect pest damage in field crops while minimizing insecticide use poses a significant challenge for farmers in Europe. Initiated in 2019, the six-year territorial project R2D2 aimed to explore the effectiveness of an agroecological crop protection approach in the context of widespread resistance of winter oilseed rape (WOSR) autumn beetles to pyrethroid insecticides. Over an area of 1371 hectares, ten farmers collectively developed a generative experimentation based on modifying cultural practices and implementing conservation biological control to gradually phase out insecticide use. Two years later, these farmers had made significant shifts in their pest management strategies by implementing a coordinated array of pest control measures from the field to the landscape level. These changes led to a complete cessation of systematic insecticide applications on WOSR and a 37% reduction in the insecticide Treatment Frequency Index (TFI) for this crop. Despite these promising outcomes, the total TFI across all crops, as assessed at the territorial level, remained unchanged. One of the main reasons for this is the increase in aerial insecticide applications on winter barley following the ban on neonicotinoids, as well as on spring pea to combat rising pea beetle pressures across the territory. For these two crops, effective alternatives to insecticides must be identified. More time is needed to instigate fundamental changes in farming systems and to enhance natural pest regulation through conservation biological control. Farmers' support strategy should focus on identifying and overcoming barriers to the implementation of transformative systems.

Keywords: Insect pests / conservation biological control / area-wide pest management / generative experiment / farming systems

Résumé – Réduire les applications d'insecticides sur le colza d'hiver par la gestion agroécologique des insectes phytophages de l'échelle parcellaire à l'échelle du paysage. En grandes cultures, réduire les dégâts d'insectes tout en limitant l'usage des insecticides représente un enjeu majeur pour les agriculteurs européens. Initié en 2019 pour une durée de 6 ans, le projet territorial R2D2 a visé à mesurer l'efficacité d'une approche agroécologique de protection des plantes dans un contexte de résistance généralisée des insectes ravageurs d'automne du colza aux insecticides pyréthrinoïdes. Sur une surface agricole de 1371 ha, dix agriculteurs se sont engagés dans une expérimentation générative basée sur une modification de leurs pratiques culturales et sur les principes de la lutte biologique par conservation pour supprimer progressivement l'utilisation des insecticides. Deux ans après le démarrage du projet, ces agriculteurs ont modifié significativement leurs stratégies de gestion des insectes phytophages en déployant, de façon coordonnée, un ensemble de leviers de l'échelle parcellaire à l'échelle du paysage. Ces changements ont conduit à une suppression totale des traitements systématiques sur le colza d'hiver et à une diminution de 37% de l'indice de fréquence de traitement (IFT) sur cette culture. En dépit de ces résultats encourageants, l'IFT total mesuré pour l'ensemble du territoire, toutes cultures confondues est resté stable. Une des raisons à cela est l'augmentation des traitements insecticides par voie aérienne sur l'orge d'hiver à la suite de l'interdiction d'utilisation des insecticides néonicotinoïdes et aussi sur le pois de printemps pour

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lutter contre la bruche du pois dont les populations explosent sur le territoire. Pour ces deux cultures, des alternatives efficaces aux insecticides doivent être recherchées. Davantage de temps est requis pour engager des modifications profondes dans les systèmes de culture et pour augmenter le contrôle biologique des ravageurs grâce à la lutte biologique par conservation. La stratégie d'accompagnement des agriculteurs devra se concentrer sur l'identification et la levée des freins à la transformation des systèmes.

Mots-clés : insectes phytophages / lutte biologique par conservation / gestion territoriale des insectes phytophages / expérimentation générative / systèmes de culture

Highlights

- Farmers' support strategies based on territorial approaches and the principles of agroecological crop protection can contribute to reducing insecticide use in winter oilseed rape (WOSR).
- In the R2D2 project, WOSR yields increased by 78% between 2019 and 2021 while insecticide applications were reduced by 38%, and systematic insecticide treatments were eliminated

1 Introduction

Pest management generally poses a significant challenge for crop production (Waterfield and Zilberman, 2012). In Europe, and across most conventional farming systems, chemical insecticides remain the primary and most effective means to mitigate yield losses caused by pest damages. However, the use of insecticides brings about various adverse effects, prompting a thorough reconsideration of crop pest management strategies. One of the main concerns is the development of insect resistance due to repeated use of insecticides from the same family. This phenomenon occurs in many pests affecting Brassicaceae crops, particularly with pyrethroids insecticides, across several European countries, and its scope is continually expanding (Daum *et al.*, 2024; Højland *et al.*, 2015; Slater *et al.*, 2011; Willis *et al.*, 2020). Moreover, chemical pest control methods have adverse impacts on the environment and biodiversity, leading to diffuse pollution and unintentional harm to non-target organisms (Borsuah *et al.*, 2020; Desneux *et al.*, 2007; Thompson *et al.*, 2020). As a response, policymakers have implemented bans on certain active ingredients, such as neonicotinoids, which raises significant challenges for pest management in specific crops like sugar beet. Furthermore, the effects of climate change impose additional pressures on crops, emphasizing the urgent need for agricultural systems to adapt. Instances of water stress are becoming more frequent, particularly during crop establishment in autumn, while rising temperatures contribute to increased frequency and intensity of insect pest outbreaks (Skendžić *et al.*, 2021) and the introduction of new pathogens. These conditions highlight the importance of effective pest management strategies while complicating the adoption of alternative solutions, as they render the success of agronomic approaches more uncertain (Nash and Hoffmann, 2012). In France, the yield of winter oilseed rape (WOSR) is significantly impacted by insect pests, especially during autumn. The cabbage stem flea beetle CSFB

(*Psylliodes chrysocephala*) and the rape winter stem weevil RWSW (*Ceutorhynchus picipitarsis*) are coleopteran pests whose larvae cause considerable damage to WOSR. In certain regions, such as 'les plateaux de Bourgogne' in France, frequent applications of pyrethroids, the only approved family of active ingredients for controlling autumn coleopteran pests in WOSR, have led to the emergence of significant resistance in these pests around a decade ago (Robert *et al.*, 2019). With no effective means to mitigate insect damage to WOSR, exacerbated by severe autumn droughts on shallow soils, farmers faced dramatic yield losses. Consequently, there was a substantial reduction in WOSR cultivation, with acreage in the Burgundy region halving between 2016 and 2019 (Agreste, 2023). As WOSR served as one of the primary break crops in the region, this situation has disrupted the balance of crop rotations and the economic viability of farms. As outlined by Lewis *et al.* (1997), the transition needs creating conditions where insecticide treatments serve as a last resort, once all preventive measures have been taken. Consequently, cultural control, has emerged as pivotal components of agroecological pest management. These insights stem from a decade of research conducted by Terres Inovia, the technical institute for oilseed and protein crops, through long-term field trials and collaborations with innovative farmers' networks (Cadoux *et al.*, 2015; Robert *et al.*, 2021, 2022). This research has identified key indicators and associated practices that promote optimal oilseed rape growth and mitigate yield losses in the event of pest outbreaks. The concept of a "robust crop" encapsulates the critical stages and conditions necessary for WOSR success. Effective cultural practices to achieve a robust WOSR include: (i) early sowing, typically before mid-August to capitalize on rainfall opportunities and foster early autumn growth while avoiding flea beetle damage during vulnerable crop stages, (ii) precise nitrogen and phosphorus fertilization at sowing, (iii) integrating frost-susceptible legumes as companion plants to reduce larval abundance in WOSR, and (iv) selecting WOSR varieties with heightened early-stage growth capacities and/or reduced susceptibility to pests. By identifying physiological parameters and optimal stand characteristics, it became possible to adjust risk thresholds accordingly and minimize insecticide applications, particularly for WOSR stands exhibiting high biomass levels per plant at the onset of winter (Robert *et al.*, 2021, 2022). Enhancing crop robustness through cultivation techniques is a crucial stride in mitigating pest damage in WOSR, and several practices have been extensively adopted by French rapeseed growers. For instance, surveys conducted by Terres Inovia in 2022, encompassing 989 farmers and 22 591 hectares, revealed that 20% of WOSR acreage was planted alongside frost-susceptible legumes as companion plants. In addition to cultural

methods, ongoing research is concentrating on two complementary areas aimed at reducing the incidence of pest insects:

-Controlling pests' abundance on crops through behaviour manipulation involves influencing various aspects such as host location, feeding, and mating behaviour of pests. By utilizing plants, natural or synthetic semiochemicals, it becomes possible to manipulate the behaviour of pests or their natural predators to minimize their detrimental impact on crops. One effective technique among these methods is the implementation of trap crop strategies, which have proven successful in mitigating pollen beetle damage in WOSR and are presently employed in France. These strategies have also undergone testing on various weevil species and CSFB populations (Barari *et al.*, 2005; Büchi, 1990, 1995). This approach involves attracting and concentrating pests onto designated plants and/or areas to safeguard the primary crop of interest. This technique can be implemented in various ways and at different scales. At the field scale: the trap plants are sown directly in association with the crop of interest, as it is the case when incorporating 5% of an early-flowering oilseed rape variety to concentrate the first pollen beetles and reduce the damage on the main variety. At the landscape scale: strips or plots of trap plants are sown near the crops to be protected to divert pests away from them. Trap plants strategies open new perspectives for pest management in crops as they allow for a collective management of agricultural land parcels while considering various factors affecting pest activity: the spatial location of host crop fields from the previous year, semi-natural elements, etc.

-Boosting the abundance and diversity of beneficial arthropods through conservation biological control (CBC) involves expanding the acreage, diversity, and connectivity of semi-natural habitats to bolster populations of natural enemies. This approach provides them with essential food sources and shelter within the field surroundings. These habitats encompass hedgerows, meadows, and flower strips. CBC also advocates for farming practices that support beneficial insects throughout their life cycles while minimizing unintended adverse effects on these organisms. Reduced tillage practices are particularly beneficial for safeguarding predatory arthropods residing in the soil, such as Arachnidae and Carabidae, which inhabit field crops year-round (Patterson *et al.*, 2019). This practice also benefits coleopteran parasitoid wasps associated with WOSR, as their nymphal stage occurs beneath the soil surface (Williams, 2006). Parasitoid wasps play a crucial role as natural enemies of WOSR coleopteran pests, with around ten species exhibiting significant impact on pest populations and demonstrating high levels of specialization (Bonnemaïson and Jourdeuil, 1954; Robert *et al.*, 2019). For instance, *Tersilochus microgaster* regulates CSFB populations, while *Tersilochus heteroceris*, *Phradis interstitialis*, and *Phradis morionellus* target pollen beetles. Reducing insecticide application is essential to minimize adverse effects on beneficial arthropods, particularly flying insects like syrphids and parasitoids (Douglas *et al.*, 2015; Siviter and Muth, 2020; Stapel *et al.*, 2000). Disruption of biological control amplifies the susceptibility of farming systems to pests and escalates the dependency on insecticide applications. Regarding these two last approaches, implementation at a field scale is not pertinent. Strategies should be deployed at the landscape scale to: (i) consider the dispersal range of pests and their natural enemies, along with complex trophic interactions,

(ii) encompass the management of semi-natural habitats that serve as food sources and shelters for beneficial insects, and (iii) enable coordinated actions among farmers cultivating a shared territory. Like regional and concerted approaches for managing water resources, seen as a collective asset affected by agricultural practices at a watershed scale, crop pests, which pose widespread challenges, can benefit from Area Wide Pest Management (AWPM) strategies. AWPM has been successfully employed for certain rice and cotton pests (Elliott *et al.*, 2007; Pimentel, 2007; Smith, 1998) and relies on collective organization and synchronized interventions at the landscape scale across crop and non-crop habitats to promote beneficial organisms responsible for ecosystem services (Begg *et al.*, 2017). This approach facilitates the deployment of holistic pest management strategies, transitioning from individual and disconnected field-based approaches reliant mainly on insecticides to collective pest management organized around agroecology (Brévault and Clouvel, 2019). It brings the challenge of bridging the gap between agriculture and nature by understanding the ecological processes driving biological pest control. However, this approach remains rare in field crops and entirely unprecedented in oilseed rape. In 2019, Terres Inovia and six local partners launched the R2D2 project, embodying this holistic approach, in collaboration with ten farmers on the 'Plateaux de Bourgogne' covering a 1371-hectares area. The goal was to assist farmers in developing a territorial and agroecological pest management project integrating cultural pest control and conservation biological control. The primary objective was to reduce pest damage, particularly in WOSR, while progressively minimizing insecticide applications. The R2D2 project introduced a participatory approach for collective agroecological pest management with three main focuses: enhancing crop robustness through agronomic and cultivation techniques to mitigate plant damage, manipulating pest behaviour by attracting and trapping them in specific areas to protect crops, and reducing pest abundance at a territorial scale by enhancing natural regulation through conservation biological control. In 2022, two years after the project began, a first evaluation was conducted to assess changes in farming practices and decision-making processes related to pest management. The findings of this evaluation which are primarily aimed at marking a milestone and highlighting the early progress rather than providing a comprehensive evaluation are discussed in the context of cropping system performance, particularly environmental concerns, and input reduction.

2 Materials and methods

2.1 Study area and context

The R2D2 project started in 2019 on the 'Plateaux de Bourgogne', situated in Burgundy, Yonne, France. It engaged ten farmers who cultivated 1371 hectares of field crops, spread across 210 field plots, primarily concentrated in the municipality of Courson-Les-Carières. The predominant soils in the area are rocky superficial clay-limestone soils. Among the ten participating farms, two were organic farms, while the rest of them practiced conventional farming. Farm sizes within the R2D2 project ranged from 180 to 1200 hectares (with a mean of 400 ± 330 hectares), and all farmers had either all or a portion of their fields within the

Table 1. Data collection for parasitism rates on WOSR.

Monitoring	Species	Observation methods	Sampling	Frequency
Parasitism rates	<i>Psylliodes chrysocephala</i>	Molecular techniques (High Resolution Melting)	100 larvae per sample, each larva is analysed	3 times with an interval of 2 weeks (March)
	<i>Ceutorhynchus picitarsis</i>	Molecular techniques (High Resolution Melting)	100 larvae per sample, each larva is analysed	3 times with an interval of 2 weeks (March)
	<i>Brassicogethes aeneus</i>	Visual	50 larvae per sample	Every 15 days from the appearance of the first larvae, generally in March, until they pupate

study area (ranging from 9% to 100%). The project area was predominantly characterized by arable lands (65%) and woodlands (34%), with no surface waters due to the karstic nature of the subsoil. At the project's inception, twelve crops were cultivated, in order of importance in terms of acreage: winter wheat, winter barley, alfalfa, WOSR, and sunflower, with minor crops such as hemp and faba bean also present for diversification purposes. In 2019, farmers articulated a shared vision for the future of their agricultural activity within the territory, serving as a guiding principle for project implementation: "Improving the performance of cropping systems incorporating WOSR, while simultaneously reducing insecticide applications." Specifically, for WOSR, farmers aimed to cultivate 170 hectares with a target yield of 3 tons per hectare in the study area. Across all crops within the territory, the long-term aspiration was to achieve zero insecticide usage, with immediate attention focused on WOSR cultivation and pest management.

2.2 Supporting farmers to change their practices

Within the framework of the R2D2 project, farmers retained their role as decision-makers on their farms and were accountable for the changes implemented in their farming systems. The supporting strategy employed an adaptive management approach, as outlined by Klerkx *et al.* (2010), rather than a directive top-down approach. Its objective was to create conducive conditions that enabled farmers to envision, test, and progressively enhance solutions tailored to their specific needs and constraints through a process of co-innovation. This approach aligned with the concept of "generative experimentation" as elucidated by Ansell and Bartenberger (2016), which involved testing solutions in real-world conditions and iteratively refining them in response to successes and failures observed during the project's progression. To facilitate progress towards the project's objectives, an animation program was developed to foster the exchange of information, experiences, and ideas among farmers, as well as to provide them with technical support and scientific knowledge. Technical support was provided through monthly crop visits, enabling the project team to stay abreast of farmers' needs, address encountered issues promptly, and to share information on farming practices. Meetings were organized to equip farmers with the scientific and technical knowledge necessary to inform decision-making processes regarding

potential changes in practices and cropping systems. These sessions focused particularly on topics unfamiliar to farmers, such as biological control methods, the life cycle of main crop pests, and their natural enemies. Drawing from data in scientific literature, field trials conducted under controlled conditions, and proven cultivation techniques within networks of innovative farmers, thematic sessions were curated by the project team.

Furthermore, meetings with innovative farmers and other farmers' groups were arranged to stimulate curiosity, encourage the exploration of novel techniques and organizational approaches pertaining to pest management. Collective workshops were established to analyse, discuss, and propose enhancements to farmers' cropping systems, fostering a holistic and collective approach to pest management. This facilitated collaborative actions, such as the implementation of flower strips and trap cover crops, through joint planning efforts. Additionally, in-situ experiments were conducted in alignment with farmers' needs and constraints, ensuring practical relevance and applicability of the findings.

2.3 Monitoring of pest abundance and biological control of WOSR coleopteran pests by parasitoid wasps

The abundance of CSFB larvae on winter oilseed rape (WOSR) fields during early winter was obtained from the Burgundy epidemiological surveillance network "Vigiculture" which serves as the national official database for monitoring pest abundance in field crops. This parameter was assessed using Berlese tests, which involve drying WOSR plants collected from 1 m² per field above trays filled with water to collect coleopteran larvae that descend from them. The analysis considered 26 WOSR fields in 2019, 63 in 2020, and 64 in 2021. For each field, the maximum value of infestation was retained for analyses. Parasitism rates of *Psylliodes chrysocephala*, *Ceutorhynchus picitarsis*, and *Brassicogethes aeneus* larvae by parasitoid wasps were evaluated using High-Resolution Melting molecular analyses (see Tab. 1). High resolution melting methods are based on the specificity of the melting behaviour of PCR products during their transition from double-stranded DNA to single-stranded DNA with increasing temperature. The melting temperature of an amplicon depends on its length, GC content, sequence, and strand complementarity (Ririe *et al.*, 1997). High resolution

Table 2. Indicators calculated with Systerre© (performance) and from enquiries (practices and decision-making processes).

Category	Indicator	Description	Unit
Decision-making process	INFO_TYPE	Annual number of farmers' practices relying on each source of information mobilised	
Decision-making process	PEST_OPT_CROP PEST_SYST_CROP	Annual number of optional/systematic insecticide applications in farmers' decision-making process for the considered crop	
Practices	CROP_ACREAGE_YEAR	Acreage of the considered crop at territorial scale for the year considered	ha
Practices	CROP_NUMB	Mean number of crops species cultivated at territorial scale on the period 2019-2021	
Practices	EARLYSOW_CROP FERTI_CROP COMP_CROP ROB_CROP BCON_CROP BEHAV_CROP	Number of cultivation techniques alternative to insecticides (NUMB) or acreage (ACRE) covered with these techniques on the considered crop (early sowing, fertilisation, companion plants, measures to enhance biological control, or behaviour manipulation)	
Performances	CROP_YIELD_YEAR	Yield of the considered crop on the considered year	T/ha
Performances	GROSS_OPERATING_SURPLUS	GOS = products + CAP subsidies – operating costs (seeds, fertilizer, plant protection products, fuel, tenant farming and other annual inputs) – third-party work	€/ha
Performances	TOTAL_TFI	Annual value of Treatment Frequency Index at territorial scale (seed treatment not included)	
Performances	HERBICIDE_TFI	Annual value of herbicide Treatment Frequency Index at territorial scale	
Performances	FONGICIDE_TFI	Annual value of fungicide Treatment Frequency Index at territorial scale	
Performances	INSECTICIDE_TFI	Annual value of insecticide Treatment Frequency Index at territorial scale (seed treatments not included)	
Performances	INSECTICIDE_TFI_CROP_YEAR	Insecticide TFI value for the considered crop and year at territorial scale (seed treatments not included)	

melting analysis has often been used as a genotyping technique in medical fields, but also appears as an efficient species identification technique in the field of entomology (Oliveira *et al.*, 2020; Rugman-Jones *et al.*, 2020). Data collection involved two fields in 2019, three fields in 2020, three fields in 2021, and five fields in 2022. For each species and each sampled field, parasitism rates were assessed at least three

times. The retained value for each field was the highest parasitism rate recorded among the assessment dates.

2.4 Project evaluation

Farming practices were documented in 2019, 2020, and 2021, encompassing all crop management techniques such as

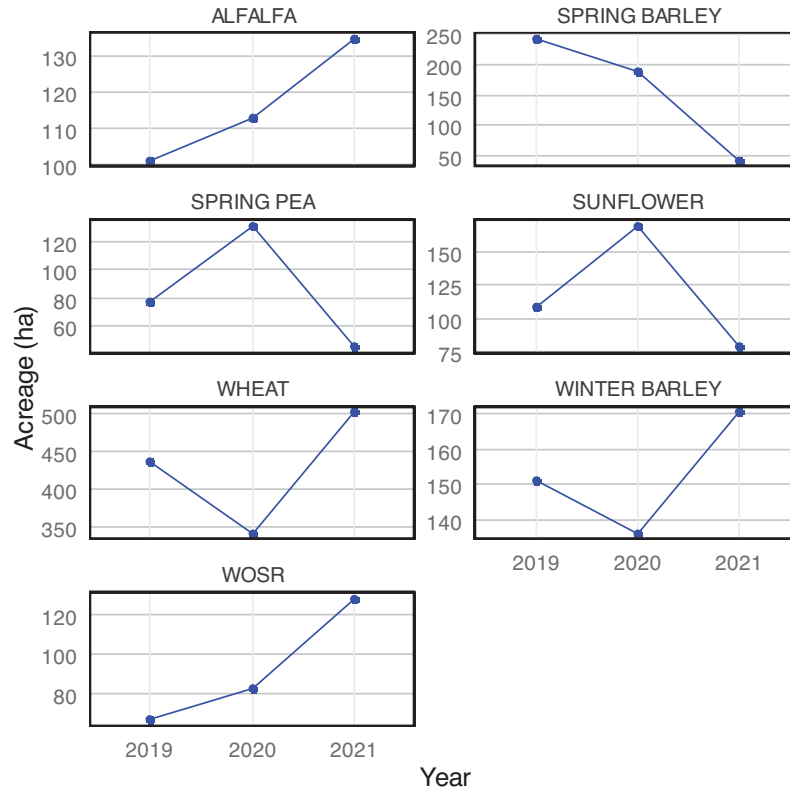


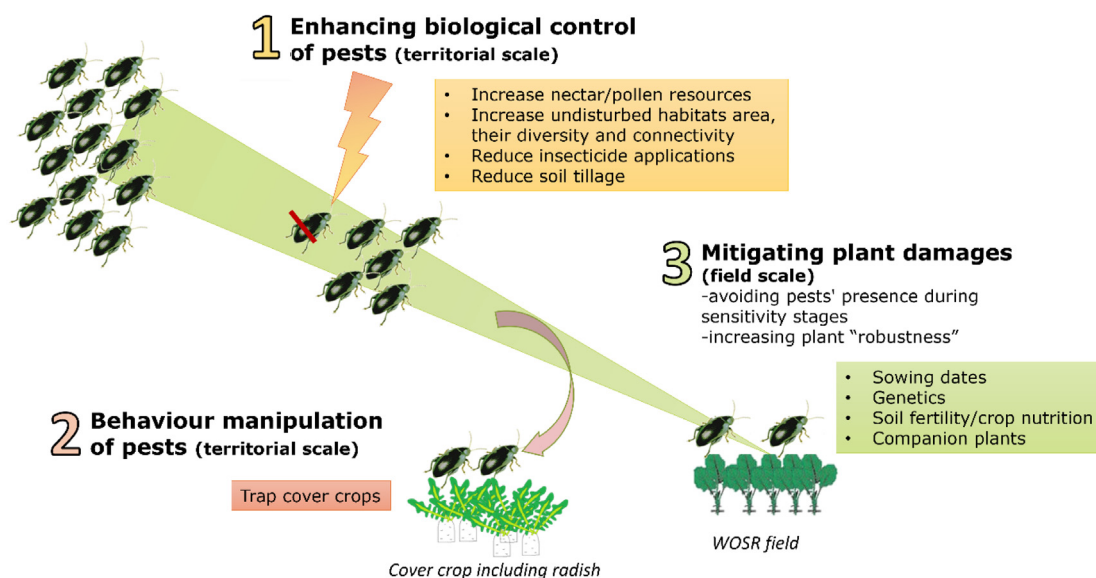
Fig. 1. Evolution of CROP_ACREAGE on R2D2 project territory from 2019 to 2021.

Table 3. Number of practices alternative to insecticides applications and their evolution in all crops between 2019 and 2021

Alternative practices categories	description	2019	2021
INCREASING CROP ROBUSTNESS	Companion plants	1	2
	Sowing dates	4	7
	Fertilisation	10	9
	Variety	1	2
<i>NUMB_ROB</i>	TOTAL	16	20
PEST BEHAVIOUR MANIPULATIONS	Companion plants	1	2
	Management of regrowth	5	7
	Crop residues management	5	6
	CSFB trap crops	0	6
	Mixing varieties	2	2
<i>NUMB_BEHAV</i>	TOTAL	13	23
INCREASING BIOLOGICAL CONTROL OF PESTS	Flower strips	1	4
	Flowering fallows	3	5
	Hedgerows	1	2
	Permanent crops	1	1
<i>NUMB_BCON</i>	TOTAL	6	12
TOTAL		35	55

Table 4. Acreage concerned by alternative practices to insecticides for WOSR between 2019 and 2021.

Alternative practices categories	Description	Indicator	2019	2021
INCREASING CROP ROBUSTNESS	Early sowing (before 15/08)	EARLYSOW_ACRE_WOSR	0	60
	Fertilization at sowing	FERTI_ACRE_WOSR	63	128
	Companion plants (Faba bean)	COMP_ACRE_WOSR	22	83
PEST BEHAVIOUR MANIPULATIONS	CSFB trap cover crops	BEHAV_ACRE_WOSR	0	272
INCREASING BIOLOGICAL CONTROL OF PESTS	Flower strips	BCON_ACRE_WOSR	0	8

**Fig. 2.** Agroecological strategy implemented on R2D2 project territory to reduce CSFB damage on WOSR.

sowing dates, insecticide, fungicide, and herbicide applications for each farm within the project territory. Within each farm, fields of the same crop species were assumed to have identical practices. Data were extracted from farmers' personal databases, and any missing information was obtained through interviews. Subsequently, the data were uploaded onto the Systerre[®] multiperformance assessment software and aggregated at the territorial scale for the calculation of performance indicators (see Tab. 2). The Treatment Frequency Index and yields were computed for all crops under conventional agriculture within the R2D2 study area and compared to reference values from fields within the Burgundy DEPHY farm network, a network of farms committed to reducing the use of phytosanitary products and receiving technical support to do so. These reference values were sourced from the Agrosyst database, with only practices from fields located in Burgundy considered for the analysis. Across all crops and years, the dataset extracted from Agrosyst comprised 948 fields, including 430 with winter wheat, 98 with WOSR, 166 with winter barley, 99 with spring barley, 20 with peas, and 65 with sunflower. To assess the economic performance of farms, gross operating surplus values calculated for the R2D2 project area were compared to values extracted for the Yonne

department from RICA France, the agricultural accounting information network. Semi-structured interviews were conducted with farmers to gather information on agricultural practices and decision-making processes related to pest management and to establish indicators (refer to Tab. 2). The objective was to detect changes in practices and modifications in how farmers approached crop pest management. Information collected included (i) the diversity of information sources consulted by farmers before implementing an action to manage pests (whether chemical intervention or alternative strategy), (ii) the alternative practices to insecticide applications that were implemented, and (iii) the rationale behind each potential chemical intervention outlined in farmers' decision-making processes. To explore this reasoning, farmers were asked to list all pests likely to be targeted by a chemical intervention for each main crop. They were also asked to indicate whether the pest was treated systematically or optionally, and the criteria they used to decide on an insecticide application, such as when a threshold was exceeded or based on damage levels. Alternatives to insecticide applications were categorized as follows: conservation biological control, manipulation of pests' behaviour, and cultivation techniques aimed at enhancing crop robustness.

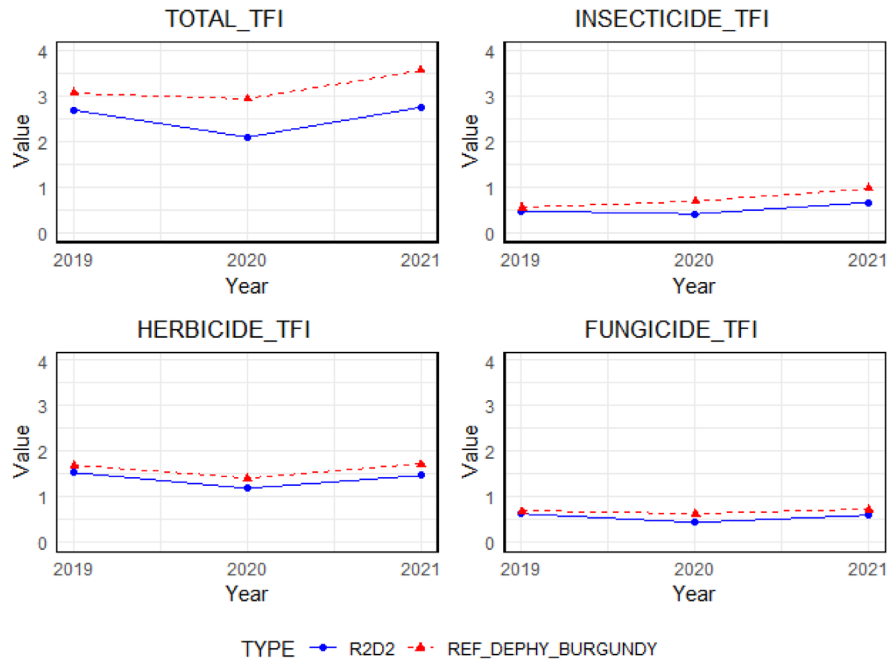


Fig. 3. Treatment Frequency Index (TFI) evolution at territorial scale between 2019 and 2021 on R2D2 project territory (R2D2) and the Burgundy DEPHY farms network (REF_DEPHY_BURGUNDY). Insecticide TFI does not include seed treatments.

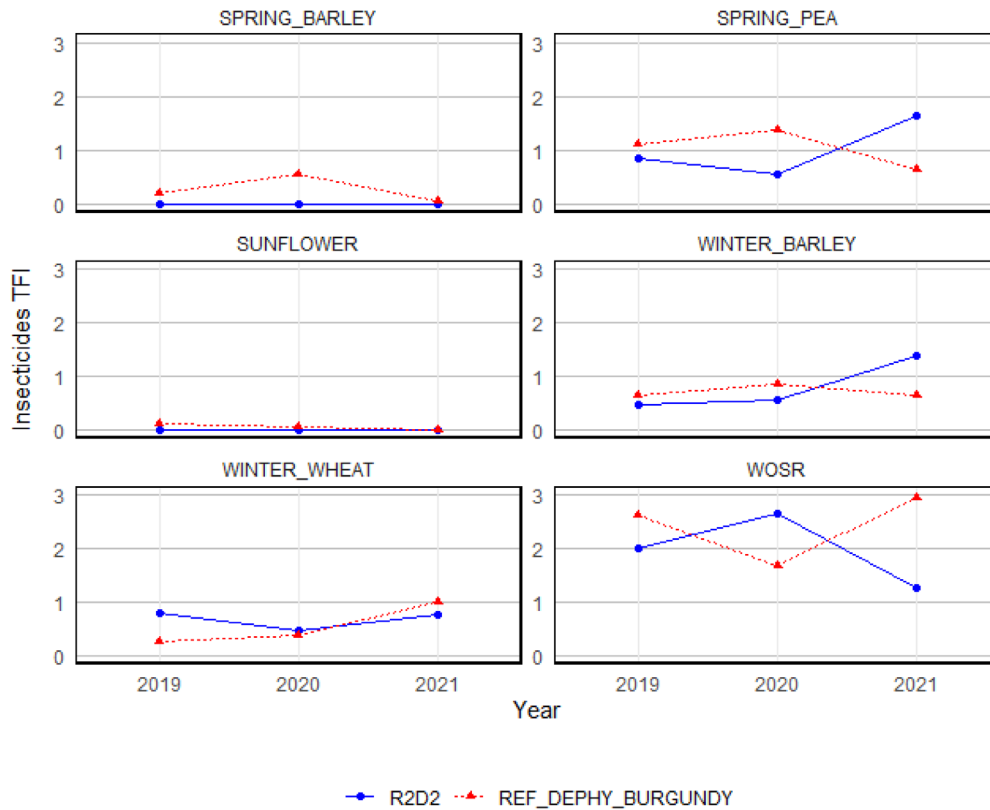


Fig. 4. Insecticide Treatment Frequency Index (TFI) for various crops from 2019 to 2021 on R2D2 project territory (R2D2), and on Burgundy DEPHY farms network (REF_DEPHY_BURGUNDY). NB: insecticide IFT does not include seed treatments.

Table 5. Farmers sources of information concerning pest management, expressed in % of all pest management practices implemented on R2D2 project territory.

INFO_TYPE	2019	2021
Other Farmers	8	20
Technical advisors	29	7
Other technical Institutes	25	17
Personal Observations	17	16
R2D2 Project	0	31
Other	21	9

3 Results

3.1 Crop composition

During the studied period, the average number of crops in the R2D2 project area was 12.3. Crop distribution remained relatively consistent from one year to the next, with cereals comprising most of the land use (56%): winter wheat (32%), spring barley (12%), and winter barley (12%). Other notable crops in the territory included sunflower (9%), alfalfa (9%), WOSR (7%), and spring peas (6%) (see Fig. 1). Minor crops such as chickpeas, hemp, faba beans, and buckwheat covered smaller areas (<15 ha each).

Winter wheat, winter barley, spring pea, and sunflower acreage experienced fluctuations but did not exhibit a specific trend over the period. In contrast, the acreage of spring barley decreased by 82% between 2019 and 2021, while the acreage of WOSR increased by 91%.

3.2 Alternative practices to insecticides

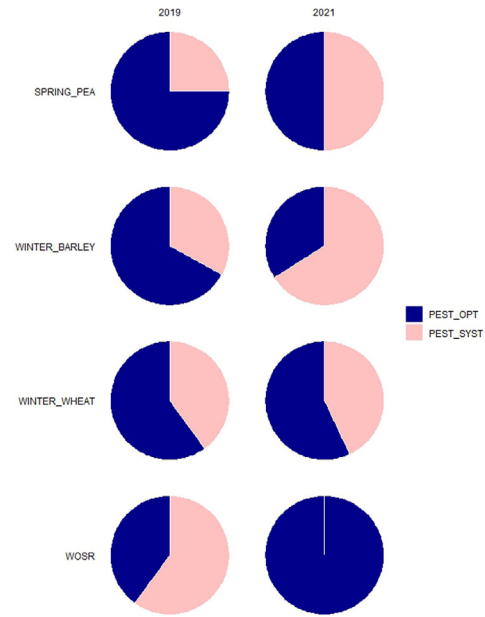
In 2021, farmers employed 55 alternative measures to insecticides across all crops, nearly double the number used in 2019 (35) (see Tab. 3). These practices were categorized into three groups: those aimed at enhancing crop robustness (NUMB_ROB) implemented at the field scale, measures deployed at the territorial scale to manipulate pest behaviour and mitigate pest-induced damages (NUMB_BEHAV), and practices focused on bolstering biological control of pests through the implementation of natural habitats (NUMB_BCON).

3.2.1 Practices to increase crop robustness

The implementation of practices to enhance crop robustness saw a notable increase in WOSR acreage from 2019 to 2021 (refer to Tab. 4). The association of WOSR with faba bean as a companion plant rose from 33% to 65% of the total WOSR acreage, while early sowing increased from 0% to 46%, and nitrogen and phosphorus fertilization at sowing reached 100% from 94%.

3.2.2 Techniques to manipulate pest behaviour

In 2021, CSFB trap crops were implemented on 272 hectares at the territorial level (BEHAV_ACRE_WOSR, see Tab. 4). This approach was first trialed in 2020 and was developed

**Fig. 5.** Percentage of systematic insecticide applications (PEST_SYST) and optional insecticide application (PEST_OPT) in farmers' decision-making schemes for major crops at territorial scale (sample: 8 farmers).

collaboratively with farmers during workshops. It involved incorporating Daikon radish (*Raphanus sativus longipinnatus*) seeds into farmers' cover crop mixes, targeting plant stands with 20–25 radish plants per square meter. Daikon radish was chosen due to its high attractiveness to CSFB, as demonstrated in field choice experiments (Terres Inovia, unpublished results). The implementation of this strategy led to a significant increase in Brassicaceae acreage on the territory during autumn, expanding from 128 hectares to 400 hectares of plants attractive to CSFB at the territorial scale in 2021 (including WOSR and cover crop mixes). Since 2020, approximately 250 hectares of Daikon radish-based cover crops have been sown annually.

3.2.3 Increasing biological control

Farmers in the studied area have implemented alternative practices to enhance natural pest regulation, specifically targeting CSFB and RWSW in their larval stages from early February to the end of April and aphids. To achieve this, they collectively organized the sowing of 8 hectares of multi-species flower strips. These strips were designed to provide food sources and habitats for beneficial arthropods for an extended period of time and starting in February to promote species such as *Tersilochus microgaster* and *Tersilochus obscurator*, parasitoid wasps involved in CSFB and RWSW regulations. The seed mix composition was tailored to the project's needs with input from specialists. The placement of these flower strips was collectively determined in workshops, considering the landscape structure and existing natural habitats, aiming to increase connectivity across the territory.

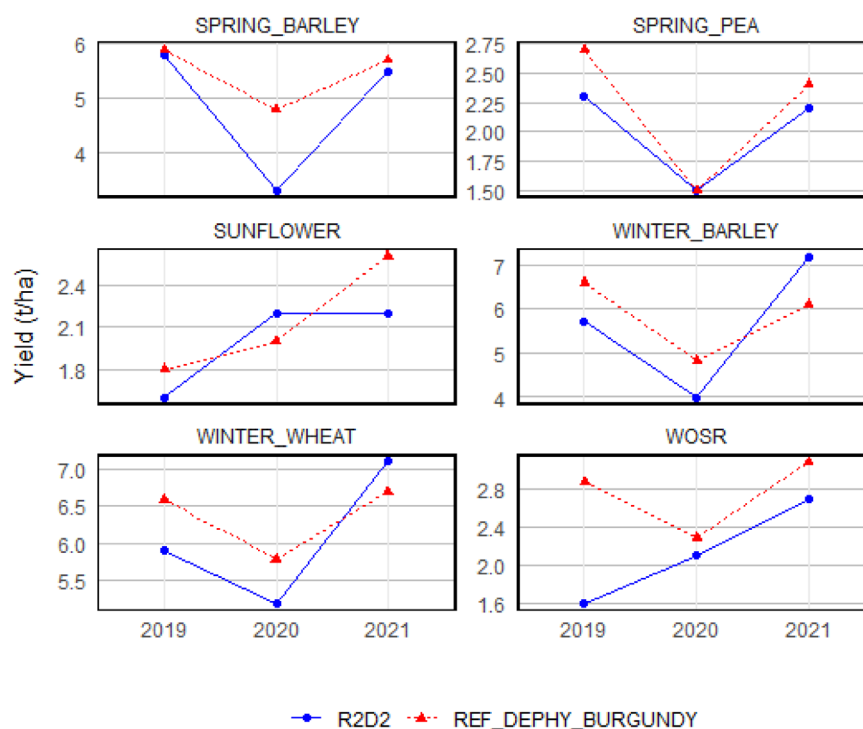


Fig. 6. CROP_YIELD values from 2019 to 2021 on R2D2 project area (R2D2) and on DEPHY Burgundy farm network (REF_DEPHY_BURGUNDY).

Table 6. GROSS_OPERATING_SURPLUS (GOS) values for R2D2 project area and Yonne department (RICA Database, agricultural accounting information network). $GOS = \text{products} + \text{CAP subsidies} - \text{operating costs (seeds, fertilizer, plant protection products, fuel, tenant farming and other annual inputs)} - \text{third-party work}$

GROSS_OPERATING_SURPLUS (€/ha)	R2D2 territory mean	REF_RICA Yonne mean	Δ (%)
2019	296	353	-16
2020	249	366	-32
2021	630	647	-3

Regarding the CSFB, the combination of partial-effect measures from the field scale to the landscape scale led to the development of a coordinated agroecological management strategy at the territorial level, detailed in [Figure 2](#).

3.3 Insecticide applications

The Total Treatment Frequency Index (TFI) remained relatively stable between 2019 and 2021, with values ranging from 2.69 to 2.76 ([Fig. 3](#)). These values consistently stayed below those recorded in the Burgundy DEPHY farms network used as a reference during this period. However, there was a 49% increase in the insecticide TFI on the R2D2 project territory, while herbicide and fungicide applications remained stable. A similar trend was observed in the Burgundy DEPHY farm network, where the insecticide TFI increased by 73%. In the R2D2 project territory, the overall increase in insecticide TFI masked differing trends among individual crops. For

winter barley and spring pea, insecticide TFI values saw substantial increases of 191% and 96%, respectively, between 2019 and 2021. In contrast, the insecticide TFI for WOSR decreased by 37% during the same period ([Fig. 4](#)). This sharp increase in TFI for pea and barley was not observed in the DEPHY farm network, where insecticide TFI values for these crops decreased. Notably, the significant decrease in WOSR's insecticide TFI between 2019 and 2021 on the R2D2 territory stands in stark contrast to a 12% increase in the same value within the Burgundy DEPHY farm network.

3.4 Decision-making process relative to pest management

In 2019, the primary sources of information for farmers regarding pest management were technical messages provided by advisors from the 'chambres d'agriculture' and local cooperatives. By 2021, the R2D2 project had become the

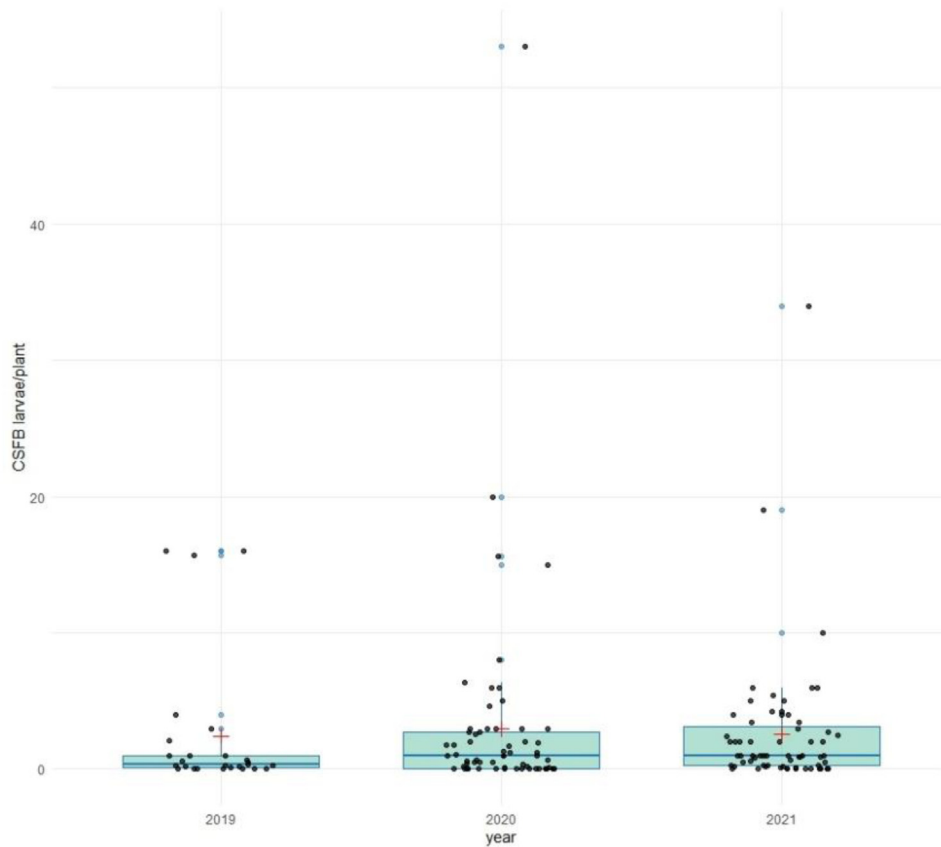


Fig. 7. CSFB larvae per plant in early winter within the Burgundy epidemiological surveillance network “vigiculture”.

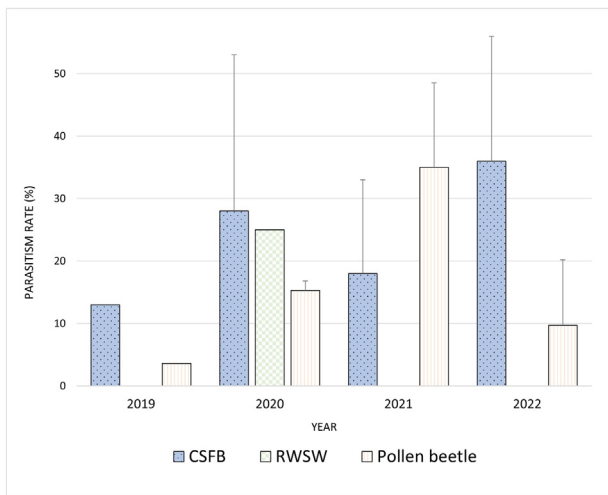


Fig. 8. Parasitism rates on cabbage stem flea beetle (CSFB), rape winter stem weevil (RWSW) and pollen beetle on R2D2 project territory from 2019 to 2021. Mean values plus Standard Deviations. The absence of error bars reflects situations where only a single field was measured due to insufficient pest infestation in the other fields.

leading source of information for insect pest management, accounting for 31% of total practices (Tab. 5). In 2019, insurance insecticide applications on WOSR constituted 60% of the treatments recorded in farmers’ decision-making schemes (Fig. 5). These systematic treatments were completely suppressed by 2021. Conversely, systematic insecticide applications on winter barley and spring pea doubled between 2019 and 2021, likely contributing to the increased insecticide TFI for these crops in 2021 (Fig. 4).

3.5 Performance of farming systems

For WOSR, yield values continuously increased on the R2D2 project territory, rising by 78% between 2019 and 2021. This trend contrasts with the Burgundy DEPHY farms network, where similar yield improvements were not observed (Fig. 6). As previously mentioned, this yield increase was accompanied by a significant expansion in WOSR acreage at the territorial scale and a reduction in the insecticide TFI.

Table 6 presents the economic performance of farms involved in the R2D2 project. Over the studied period, mean values of GROSS_OPERATING_SURPLUS (GOS) were

3 to 32% lower than the reference values for Yonne. GOS trend profiles were quite similar for the farms within the R2D2 project area and Yonne, with higher GOS values in 2021 than in the two previous years. GOS values were notably low in 2020, particularly within the project area, where there was a 32% disparity. It was linked to summer water shortages, with potentially greater impacts in the project area due to the prevalence of stony soils with low water reserves. In 2021, the GOS value for the R2D2 project area nearly reached the reference value. Notably, the implementation of the project did not negatively affect the economic performance of the participating farms.

3.6 Biological control of WOSR pests

At the regional scale, the number of CSFB larvae per plant on WOSR fields in early winter remained stable from 2019 to 2021, averaging approximately 2 larvae per plant (Fig. 7). This level is relatively moderate and below the indicative risk thresholds.

Parasitism rates for CSFB, RWSW, and pollen beetles showed significant variability between fields and years, without indicating a clear trend over the period (Fig. 8). The absence of data in 2019 and 2021 for RWSW was due to the low abundance of this pest during these years. Notably, for this pest, larvae were never detected in plants before winter.

4 Discussion

Significant changes in agricultural practices and decision-making processes related to the management of WOSR pests have been measured, marking a crucial first step toward reducing insecticide use. In 2019, the limited acreage of WOSR in the studied area reflected the significant challenges faced by farmers in cultivating this crop, particularly due to the autumn drought conditions compounded by CSFB abundance, which severely hampered WOSR establishment. Through participatory workshops with farmers' group and technical support, new techniques were successfully deployed to enhance crop resilience and biological control and to create unfavourable conditions for pests over extensive areas, laying the groundwork for a collective and area-wide strategy to improve pest management. Since 2019, performances of WOSR cultivation have improved. WOSR yield, reached 2.7 tons per hectare in 2021, nearing the crop's yield potential for the region. Furthermore, the insecticide TFI value decreased by 37% in 2021 compared to 2019, as opposed to the trend observed in the Burgundy DEPHY farm network. This deviation from the reference value suggests a positive effect of the support provided within the project framework on the reduction of insecticide applications and farmers' motivation to do so. The shift in the reasoning behind insecticide applications on this crop, as evidenced by the total suppression of systematic insecticide treatments in 2021, further strengthens this hypothesis. Results obtained on WOSR were proportional to the support efforts focused on this crop, considering the challenges faced by the producers at the beginning of the project. The remarkable progress was also achieved thanks to previous research innovations, which identified effective strategies for enhancing crop robustness

(Cadoux *et al.*, 2015). Further consolidation of these trends will be necessary in subsequent years.

However, there was a significant increase in insurance insecticide applications on other crops, particularly on winter barley and spring peas in 2021, which contrasts with the positive results mentioned earlier. Regarding winter barley, the rise in insecticide TFI value in 2021 was primarily due to a bias related to the exclusion of seed treatments from the TFI calculation. Prior to the ban on neonicotinoids (NNI) in 2018, a significant portion of the barley acreage was safeguarded through NNI seed treatments. Following the ban, these seed treatments were gradually replaced by aerial treatments with the same preventive objective, and thus contributed to the TFI score. Moreover, effective alternatives to insecticides have not yet been identified or made available to farmers for both pea and barley crops, except for genetic tolerance to yellow dwarf disease in barley, which has recently emerged as a possibility. This lack of viable alternatives appears to be one of the primary reasons why alternatives to insecticides have not yet been widely adopted on these crops.

Regarding the economic results calculated for the entire territory, it appeared that they had not been adversely affected by the implementation of the R2D2 project. However, they were lower than the reference values calculated for the Yonne department. This is because the project area comprised stony soils with low water reserves, resulting in significantly lower yield potentials compared to the average soils in Yonne. The low gross operating surplus value recorded in 2020 on the R2D2 territory was primarily due to summer water deficits that penalized winter and spring crops, relatively low selling prices for crops, and high fertilizer costs. A more thorough evaluation, incorporating all available data to date, is underway to truly assess the progress enabled by the implementation of the project and its sustainability over time. Indeed, agriculture is strongly influenced by economic conditions and also by climatic uncertainties. These factors influence both the pressures from pests and the growth of plants, and lasting changes in system performance can only be appreciated over the medium term.

The introduction of flower strips and CSFB trap cover crops across an entire territory marked the early stages of area-wide pest management for field crops in France. The CSFB trap cover crop was designed to achieve two objectives: firstly, to reduce the presence of CSFB and RWSW adults in WOSR fields by diverting a portion of the populations to adjacent cover crops during autumn flights, and secondly, to decrease adult pest emergence the following spring by mechanically destroying the cover crop in winter. The implementation of this strategy involved consultations among farmers to synchronize the growth stages of WOSR and radish and ensure spatial proximity. Cover crops destruction was synchronized when cabbage stem flea beetle larvae were at their peak (L3 stage), monitored using Berlese tests (Seimandi-Corda *et al.*, 2024). Since 2020, this technique has been evaluated in several French regions to determine its efficacy under various conditions, such as the optimal sowing date, radish density, and the ratio of WOSR/cover crop acreage to achieve the best results at the territorial level. The evaluation of this strategy is ongoing. It represents a significant innovation within the R2D2 project and holds great promise for the future. However, the comprehensive redesign of the landscape to favour biological

regulation and deter pests requires time to implement and yield observable results. This may explain why levels of biological control did not increase significantly. Additionally, certain initiatives, such as flower strips, will likely need to be implemented on a larger scale to truly benefit the entire territory (Tscharntke *et al.*, 2016).

Experience with farmers highlighted the challenges they face in working on a landscape scale to enhance biological pest control. Such practices are unfamiliar to many and may seem disconnected from their daily concerns. Additionally, the restoration of natural habitats conflicts with a prevailing trend spanning over 50 years, where hedgerows, bushes, or wetlands are viewed as competing spaces with monoculture cropping, and potential sources of nuisance such as weeds and pests. Even among those who recognize the benefits of augmenting resources and habitats for beneficial insects, birds, or mammals, the lack of financial support hinders significant changes in practice. Furthermore, the provision of contextualized data to quantify the benefits brought to agriculture by ecological infrastructure is particularly crucial. This is because the subject remains poorly documented, with results from various studies with sometimes contradictory findings.

5 Conclusion

Two years on, the R2D2 project provided a framework that facilitates the testing of innovative solutions and offers technical support to farmers, empowering them with the confidence and knowledge to conceive and implement alternative strategies to reduce insecticide usage on a territorial scale. Significantly, changes in farmers' practices and decision-making processes have ensued. For CSFB management, farmers have adopted flower strips and experimented with the innovative concept of trap cover crops. This promising technique aims to divert a portion of the cabbage stem flea beetle populations from WOSR fields and reduce pest populations at the territorial level. At the field scale, cultivation techniques have been combined to mitigate pest damages by promoting fast and continuous crop growth during early development stages. These changes, coupled with a 37% reduction in the frequency of insecticide treatments in 2021 and the complete cessation of insurance insecticide applications. Under a stable CSFB pressure, WOSR yield increased by 78% between 2019 and 2021, probably due to better crop establishment in autumn. Despite these positive outcomes in WOSR, significant disparity between crops was observed. On pea and winter barley, levels of systematic insecticide applications experienced a substantial increase in 2021, resulting in a 49% rise in the insecticide TFI value within the R2D2 project territory (excluding seed treatments). For these crops, alternative preventive measures to insecticide applications are limited, while the potential risk of pest damage remains high. To progress towards the zero-insecticide target, deeper changes in farming systems are imperative, yet the two-year timeframe proved insufficient for the comprehensive implementation of such changes. Additionally, it is likely that more time will be required to translate into measurable results, particularly concerning biological

control, as the dynamics are complex and not yet well understood. At present, the lack of financial and technical support for the implementation of agroecological infrastructures by farmers remains a major obstacle to increasing semi-natural habitats on farms.

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Conflicts of interest

The authors declare that there are no conflicts of interest related to this article.

Author contribution statement

Nicolas Cerrutti: conceptualization, data curation, formal analysis, methodology, project administration, supervision, visualization, writing original draft. Noémie Cadeddu: conceptualization, data curation, formal analysis, methodology. Julien Carpezat: supervision, methodology. Sylvie Clerget: investigation. Michael Geloën: conceptualization, investigation. Domitille Jamet: data curation, formal analysis, review. Céline Robert: conceptualization, data curation, formal analysis, methodology, review. Antoine Lauvernay: investigation. Stéphane Cadoux: conceptualization, supervision, review.

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