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# Working Group Landscape Management for Functional Biodiversity

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# Preface

In recent years, we have witnessed significant progress in both the visibility and practical relevance of landscape ecology and functional biodiversity. Agroecological principles are increasingly reflected in agricultural policy, and there is growing recognition that collective, landscape-scale action is essential for building resilient food systems. At the same time, advances in biodiversity monitoring – through remote sensing, automated image analysis, bioacoustics and AI-driven species identification – are rapidly expanding the quality and scope of ecological information available to researchers and practitioners. Together, these developments are creating new opportunities to connect scientific insight with coordinated management strategies that operate effectively at the scales where ecological processes unfold.

Yet considerable challenges remain. Implementing biodiversity-based solutions across landscapes requires not only sound ecological understanding but also practical tools, long-term monitoring capacity, and mechanisms that enable cooperation among farmers, advisers and regional stakeholders. The urgency of responding to the biodiversity crisis and strengthening climate resilience adds to this imperative. Looking ahead, we see strong potential in approaches that integrate multiple data sources, support adaptive management, and link biodiversity patterns more directly to ecosystem functions. Such innovations will help move us from describing the ecological structure of landscapes to designing and evaluating interventions that deliver tangible ecosystem services.

It is within this context that we welcome you to the 11th Meeting of the IOBC-WPRS Working Group “Landscape Management for Functional Biodiversity” (LMFB26), held in Avignon, France, from 11-13 March 2026. This year’s meeting has attracted a large and diverse group of participants, reflecting the growing interest in landscape-scale approaches to biodiversity conservation and sustainable agricultural management. The scientific programme is rich and wide-ranging, organized around four themes central to current research and practice – Monitoring agrobiodiversity, Ecosystem services, Management of floral resources, and Landscape management of the agricultural mosaic. We are also very pleased to host keynote presentations from Sandrine Petit-Michaud and Séverin Hatt, whose work spans agroecology, landscape management, and applied conservation.

As always, the strength of this Working Group lies in its openness, collaboration and community spirit. We greatly value the participation of early-career researchers, the exchange of ideas across disciplines, and the contribution of new perspectives and methodologies. We warmly encourage all participants – and anyone with an interest in these themes – to join us in the ongoing work of the group, whether through future meetings, collaborative initiatives or informal exchange.

We would like to express our sincere thanks to the local organizing team at INRAE and Avignon University – Pierre Franck, Claire Lavigne, Bertrand Gauffre, Alan Kergunteuil, Armin Bischoff and Olivier Blight – for their dedication, hospitality and hard work. We also thank the scientific committee, authors, reviewers and contributors whose effort has made these proceedings possible.

We hope that this instalment of the Working Group’s proceedings will inspire new insights, fruitful collaborations and continued progress in advancing landscape-scale management for functional biodiversity.

Graham Begg and Daniela Lupi
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# Session Management of floral resources

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# From margins to in-field: strategic deployment of flowering service plants for biological control

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**Abstract:** Flowering service plants are critical for biological control because their (extra-)floral nectar and pollen are key food resources for many predators and parasitoids, in addition to hosting alternative prey. However, their beneficial effects may depend on their spatial deployment at the field scale. We present cases in Europe, Pakistan and China where flowering service plants are deployed within fields, compared to implementations at field margins. In Belgium, in-field flower strips sown every 27 m consistently reduced *Aphis fabae* abundance in sugar beet. In Pakistan, row intercropping of oilseed rape with wheat significantly reduced wheat aphid abundance through natural enemy enhancement. In China, *Tagetes erecta* deployed as clustered patches between tea tree rows significantly favored pest control compared to sowing around the field. In Germany, flowering weeds maintained at an acceptable level through intercropping attracted natural enemies at the crop vicinity, interacting with flower strips sown at field margins. The way to use flowering service plants may depend on the cropping systems and the socio-cultural and economic context. Overall, maximizing the benefits of flowering service plants to biological control invites not to leave them at margins and instead to insert them within the field.

**Key words:** conservation biological control, agroecosystem diversification, functional agrobiodiversity, functional plants, flower strips, intercropping

## Introduction

Service plants are used in agroecosystems for biodiversity conservation (Haaland et al., 2011), improve the aesthetics of farmlands (Hatt, 2024), and provide regulating ecosystem services (Moreau et al., 2025). Among these objectives, which are not mutually exclusive, flowering service plants can be sown or preserved to attract and support natural enemies of crop pests. Their strategic spatial deployment in agroecosystems may determine their effectiveness at enhancing biological control. In this review, we take benefit of four worldwide case studies to consider the benefits of service plants whether they are used as non-crop habitats (Belgium), harvested intercrops in annual crops (Pakistan), clustered patches within perennial crops (China) or combinatory approach with non-crop habitats at field margins and spontaneous biodiversity at interrow (Germany).

## Service plants used as non-crop habitat

Flower strips are one of the efficient tools to enhance biological control in agroecosystems. The availability of nectar and pollen is a key functional trait supporting natural enemies of crop pests (Hatt et al., 2019). In addition, the presence of alternative prey and hosts, such as aphids, increases natural enemies' abundance and diversity, and decreases their evenness in flower strips (Coppi, 2025). In Europe, flower strips are usually sown as mixtures of annual and/or perennial forbs and grass species (Hatt et al., 2020). In wheat adjacent to annual flower strips sown at field margins in Belgium, the abundance of aphid pests was reduced by 73 % on average at 5 m compared to 50 m from the flower strips (Coppi, 2025).

The distance-decay effect of flower strips in enhancing biological control is well known (Albrecht et al., 2021). A solution lays in deploying flower strips at regular distances within field. In sugar-beet, 3 m-wide annual flower strips implemented every 27 m reduced the abundance of the aphid *Aphis fabae* by 5-10-fold, compared to control fields with flower strips or hedgerows at margins only. However, this beneficial impact was not consistently observed against the aphid *Myzus persicae* (Maenhout, 2025).

## Service plant used as intercrop

A major limitation for implementing flower strips in field crops is the retraction of land from production. In Europe, subsidies aim at compensating the economic loss for farmers. In regions where subsidies are lacking, a solution may lay in intercropping with one of the partner crops being a flowering species. In Pakistan, alternating rows of wheat and oilseed rape increased the abundance of aphid natural enemies by 45-170 % and reduced the abundance of wheat aphids by 20-25 % compared to wheat with oilseed rape rows set at margins (Saleem et al., 2025).

## Valorizing available space

In perennial cropping systems, the interrow space between trees can be valorized with intercrops or flower strips. In tea plantations in China, *Tagetes erecta* (Asteraceae) was especially effective at supporting the abundance and diversity of natural enemies (Ichneumonidae and Braconidae parasitoids, Coccinellidae and Phytoseiidae predators) and reducing the abundance of key pests (Thripidae, Cicadellidae, and aphids) compared to clean tillage and other service plant species (Gong et al., 2024). Evaluation of spatial arrangements revealed that sowing *T. erecta* as clustered patches between each tea tree rows enhanced natural enemy abundance by 34 % and reduced pest abundance by 32 % compared to deployment at the field surrounding (Wang et al., 2026).

## Taking advantage of spontaneous biota

Beyond sowing service plants, spontaneous vegetation can be significant providers of food resources for natural enemies. Within fields, weeds are generally unwanted because they compete for resources against the crops. However, if maintained at an acceptable level, they may contribute to attracting and supporting natural enemies at crop vicinity. A field trial in Germany combined intercropping with flower strips at margins. In intercropping, weed biomass was reduced by 60 % compared to the respective monocultures over two cropping seasons, and the remaining weeds had no significant impact on crop yield. Among the remaining flowering weeds, *Matricaria recutita* (Asteraceae) was especially attractive to flower visiting insects, and was up to four-times more often visited by predatory Syrphidae in intercropping fields with adjacent flower strips, compared to fields without flower strips (Hatt and Döring, 2025).

## Perspectives

There are various ways to use flowering service plants to enhance biological control in agroecosystems. They may depend on the cropping systems and the socio-cultural and economic context. Flowering service plants should not be left at margins. Their in-field deployment can be determinant to effectively support natural enemies and reduce crop pests. Future research will need to continue developing tailored plant diversification tactics enhancing functional agrobiodiversity, in collaboration with farmers to favor adoption and wide scale implementation.

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# Association and abundance of insect taxa in response to floral strips in an apple orchard

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**Abstract:** In Canadian apple orchards, floral strips are typically established along borders, where they are known to increase arthropod diversity near them. To evaluate whether we could extend this benefit within orchards, strips of native perennial flowers were established in the alleyways of four plots in an experimental, unsprayed orchard in Québec, Canada. Their effects on the abundance of different arthropod taxa were compared with four unmanaged control plots. Arthropod communities were sampled weekly over three growth seasons using pitfall traps (2021-2023), and over two growth seasons using aspiration (2021-2022). Across the three years of pitfall trap sampling, carabid beetles were almost twice as abundant in floral strips compared to controls. Across both sampling years, the aspiration data revealed that floral strips were associated with more Heteroptera, and non-Coccinellidae Coleoptera, and with less Homoptera. Additionally, Coccinellidae were more abundant in floral strips in 2021, and Brachycera in 2022. Our results support the use of alleyway floral strips as a useful habitat management strategy to promote and diversify beneficial arthropods in apple orchards.

**Key words:** indigenous plants, habitat manipulation, functional diversity, predators, agroecology

## Introduction

The project sought to enhance functional biodiversity by establishing native perennial floral strips in orchard alleyways, exploiting available space while reducing edge effects associated with peripheral strips. Flowering plants within or adjacent to apple orchards attract a diverse assemblage of arthropods, including beneficial, antagonistic, and functionally neutral arthropod taxa (Haaland et al., 2011; Pfiffner et al., 2019). The objective was to evaluate and compare arthropod assemblages and abundances between orchard plots with alleyway floral strips and unmanaged plots.

## Materials and methods

### *Experimental plots*

This study was conducted in an acaricide- and insecticide-free experimental orchard at the Research and Development Institute for the Agri-Environment in Mont-Saint-Bruno, Québec, Canada. Eight experimental plots were established, each comprising eight apple trees rows, 38 m long, covering 0.1 ha. Two treatments – floral strips and unmanaged controls – were randomly assigned to the plots, with four replicates per treatment. The floral strips were established in 2020 using thirteen native perennial plant species, forming 40-cm-wide strips in the center of each of the seven alleyways. Unmanaged control plots consisted of a standard orchard ground cover maintained as regularly mowed grass.

Twelve species of plants were sown, *Daucus carota*, *Achillea millefolium*, *Cichorium intybus*, *Euthamia graminifolia*, *Leucanthemum vulgare*, *Lotus corniculatus, Medicago lupulina*, *Trifolium pratense*, *Prunella vulgaris*, *Glechoma hederacea*, *Festuca rubra* and *Poa pratensis,* while *Mentha canadensis* was planted. The seed mixture consisted of 56 % forbs and 43 % grasses (expressed as seeds/m²).

### *Pitfall traps*

To monitor the presence of edaphic predators, three pitfall traps were installed per experimental plot at the interface between the ground cover and the apple tree row (Labrie et al., 2003). The traps were checked weekly from the beginning of June until the end of August in 2021, 2022, and 2023. Captured specimens were filtered and preserved in 70 % ethanol and were later identified. For each year, the abundances of Carabidae adults, Staphylinidae adults, non-identified Carabidae and Staphylinidae larvae, Araneae, and Chilopoda (both adults and juveniles) were analysed by fitting generalized linear mixed models (GLMM) with a negative binomial distribution and selecting the model with the lowest Akaike Information Criterion (AIC; Akaike, 1974). Treatment, plot identity, and the interaction treatment × plot were used as fixed effects, whereas rows and date of sampling were used as random effects in the models. Community composition of adult Carabidae, pooled across all sampling years due to low abundances or absence of certain species in individual years, was compared between treatments using a PERMANOVA based on Bray – Curtis dissimilarities.

### *Aspiration*

The effect of floral strips on the abundance of pollinators, predators, pests and parasitoids was assessed by aspiration sampling with a motorized D-Vac (Dietrick, 1961). Sampling was performed for one minute along the central 13 meters of three alleyways per plot, weekly from June to August in 2021 and 2022 (McCabe et al., 2017). Floral strips and unmanaged alleyways were aspirated by moving the D-Vac to collect both upper- and lower-dwelling arthropods. The number of Nematocera, Brachycera, Syrphidae, Apoidea, Vespoidea, other Hymenoptera, Homoptera, Heteroptera, Neuroptera, Coccinellidae, and other Coleoptera was recorded. Aspiration data were Hellinger-transformed prior to analysis. Redundancy analyses (RDA) were used to assess the effect of floral strips on the assemblages of recorded arthropod taxa and were implemented via the *capscale* function in the vegan package using chord distance. Species were considered associated with a treatment when their RDA scores were oriented toward, and closer to, the centroid of that treatment in constrained ordination space.

Yearly data from pitfall traps and aspiration were analyzed separately due to the temporal evolution of floral strips.

## Results and discussion

### *Pitfall traps*

Across the three seasons, cumulative captures were higher in floral strips for adult Carabidae (5,638 *vs.* 3,062), adult Staphylinidae (1016 *vs.* 785), undetermined Staphylinidae and

Carabidae larvae (231 *vs.* 104), Araneae (2,732 *vs.* 2129), and Chilopoda (275 *vs.* 241). Forficulidae (55 *vs.* 103) and Diplopoda (8 *vs.* 8) were also captured, but the numbers were too low to be analysed.

Model estimates showed consistently higher Carabidae abundance in floral strips than in unmanaged plots, with an expected increase in mean abundance of approximately 82 % in 2021 ($\beta = 0.60 \pm 0.10$ SE, $z = 6.27$, $p < 0.0001$; IRR = 1.82), 77 % in 2022 ($\beta = 0.57 \pm 0.14$ SE, $z = 4.09$, $p < 0.001$; IRR = 1.77), and 75 % in 2023 ($\beta = 0.59 \pm 0.24$ SE, $z = 2.48$, $p = 0.01$; IRR = 1.81). For all the other taxonomic groups, treatment effects on abundances were weak or inconsistent across years.

Although floral strips supported higher abundances and a greater number of Carabidae species than the unmanaged control strips (23 *vs.* 21), community composition remained largely similar between treatments (Figure 1, PERMANOVA based on Bray – Curtis dissimilarities, $R^2 = 0.047$, $p = 0.37$). The most abundant species in both treatments were *Harpalus rufipes* and *Harpalus affinis*, which are two natural enemies known to predate on aphids, slug eggs, codling moth larvae, apple maggot pupae and weed seeds (El-Danasoury and Iglesias, 2017; Hagley et al., 1982; Saska et al., 2010). Floral strips mainly enhanced Carabidae abundance of dominant species rather than promoting community turnover.

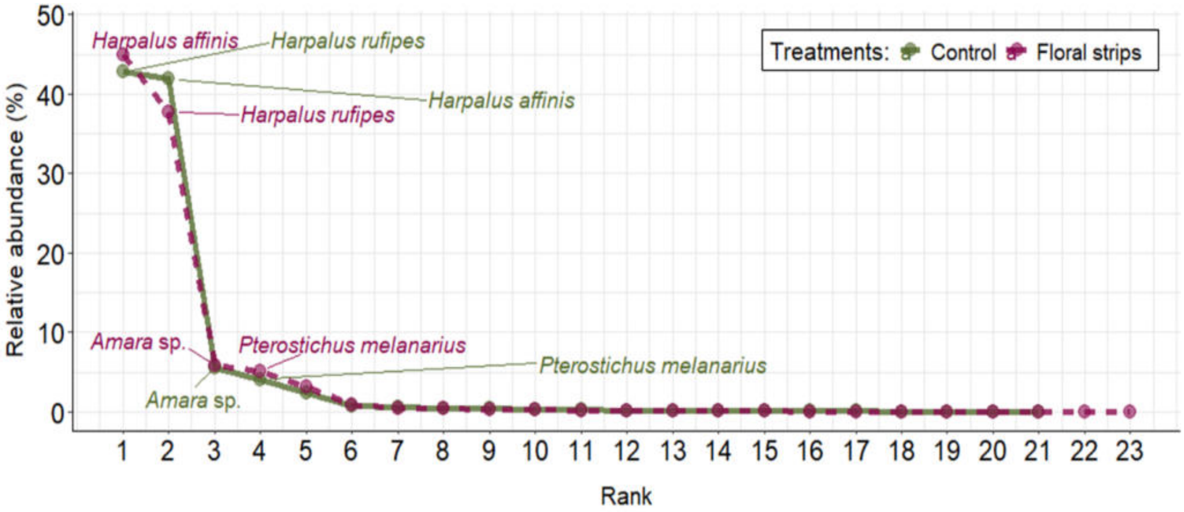

Figure 1. Species evenness of total Carabidae sampled in pitfall traps. Ranks represent the position of species in the community ordered from most to least abundant. Only the names of the four most abundant species of each treatment are shown.

### *Aspiration*

Across two seasons, a total of 44,529 arthropods were captured in floral strips compared with 74,673 in unmanaged plots. Cumulative captures were higher in floral strips for Heteroptera (4,656 *vs.* 1,483) and Apoidea (32 *vs.* 5), whereas unmanaged plots had more Nematocera (20,151 *vs.* 11,262), Homoptera (29,869 *vs.* 9,859), and Hymenoptera other than Vespoidae and Apoidae (11,142 *vs.* 7,572). Other taxa showed minor differences between treatments.

In 2021, the redundancy analysis showed that floral strips were associated with more Heteroptera, Coccinellidae and other Coleoptera, and less Homoptera and Nematocera (Figure 2). The constrained ordination explained 69 % of the total community variation (adjusted R² = 0.55). In 2022, floral strips were mainly associated with more Heteroptera, Brachycera and other Coleoptera, and less Homoptera (Figure 2). The constrained ordination explained 82 % of the total community variation (adjusted R² = 0.78).

Because sampled insects were identified only to the highest taxonomic levels (families or order), their functional roles are difficult to predict. Floral strips support many predator and parasitoid taxa that can contribute to biological control but also taxa that may have neutral or detrimental effects for the orchards (e. g., phytophagous Coleoptera, Brachycera, and Heteroptera). Nematocera and Homoptera taxa were mostly associated with unmanaged plots and function mainly as decomposers, prey for other arthropods or phytophagous pests, and have limited potential for direct pest suppression.

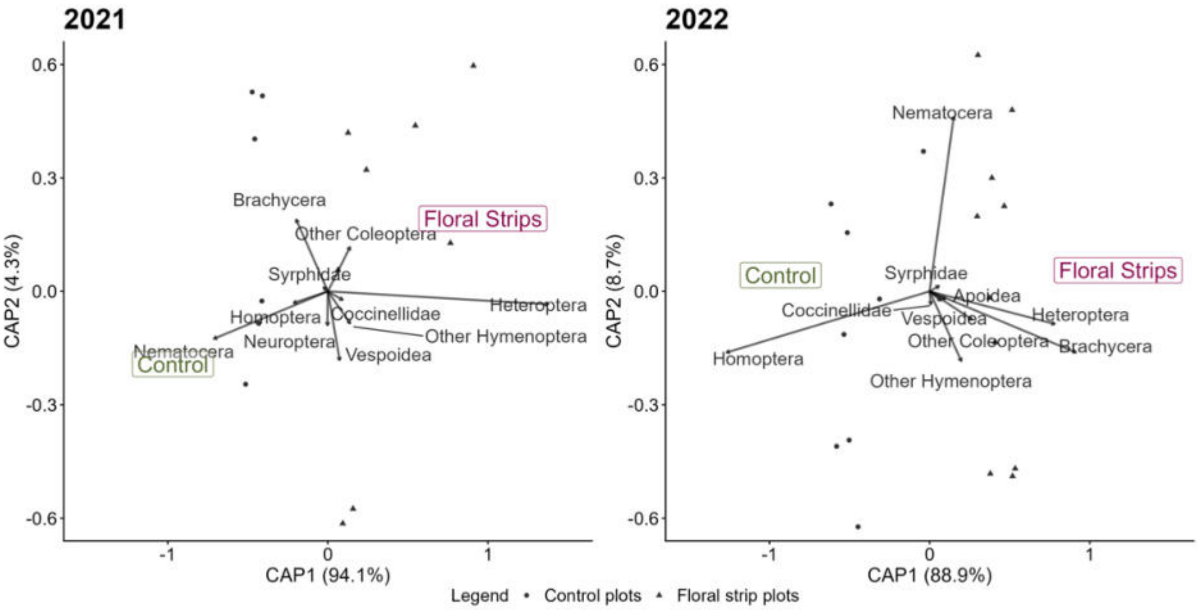

Figure 2. Redundancy analyses of aspirated insect community composition (Hellinger-transformed) for both sample years. Axis labels indicate the percentage of constrained inertia explained by each canonical axis. Treatment centroids were located at CAP1 = −0.39, CAP2 = −0.09 (control) and CAP1 = 0.39, CAP2 = 0.09 (floral strips) in 2021, and at CAP1 = −0.42, CAP2 = −0.02 (control) and CAP1 = 0.42, CAP2 = 0.02 (floral strips) in 2022. Treatment labels were slightly displaced using label repulsion to improve readability and therefore do not exactly match centroid coordinates.

In conclusion, floral strips increased the abundance of Carabidae, which are key edaphic predators beneficial to orchards, and promoted a more functionally diverse insect community, while unmanaged plots were mainly associated with decomposers, phytophagous pests and insects serving as prey for other arthropods.

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# Comparison of the morphological and biochemical traits of four companion plants interplanted in an apple orchard and their consequences on the natural enemies involved in the control of rosy apple aphid

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**Abstract:** Sustainable aphid management is a major challenge in fruit production as pesticide use and efficacy continue to decline. Introducing companion plants (CPs) into orchards is a promising but understudied strategy, especially in apple systems. Some CPs emit volatile organic compounds (VOCs) that may repel aphids or attract natural enemies (NEs), yet their effectiveness under orchard conditions remains poorly documented. We investigated how four CP species (*Ocimum basilicum*, *Tagetes patula*, *Mentha × piperita* and *Foeniculum vulgare*) interplanted in the tree row influence the regulation of the rosy apple aphid *Dysaphis plantaginea*. Over two years, we monitored plant phenology, VOC emissions, NE communities on CPs, and NEs occurring within aphid colonies. The four species showed marked functional divergence and strong seasonal and interannual variability. These differences resulted in contrasting NE attractivity and, in some cases, differences in aphid colony dynamics. Overall, investigating CP functional traits and their seasonal dynamics appear essential to optimise their use as ecological infrastructures in apple orchards.

**Key words:** service plants, *Dysaphis plantaginea*, functional traits, volatile organic compounds

## Introduction

Apple orchards are among the most pesticide-dependent fruit systems in Europe, and sustainable control of *D. plantaginea* remains difficult (Blommers et al., 2004; Rousselin et al., 2017). Companion plants (CP) have been proposed as a promising tool to enhance biological control (Djian-Caporalino and Lavoir, 2024). CPs may directly affect aphid behaviour and reproduction (bottom-up effects) or attract NEs favouring top-down control. Morphological and phenological traits, such as flowering and plant height, determine plant attractiveness to NEs (Hatt et al., 2019; Kopta et al., 2012), as well as VOCs emission which has been less studied (Ben-Issa et al., 2017).

Previous studies have shown the influence of flower strips and inter-row vegetation on NEs abundance and pest regulation (Gontijo et al., 2013; Laffon et al., 2024), but intra-row CPs remain poorly documented, despite their potential (Rizzi et al., 2025; Song et al., 2010). Our objectives were (1) to compare the attractiveness of four CP species in relation to their functional traits, and (2) to assess their potential effects on the regulation of *D. plantaginea*. We hypothesized that CP morphological and biochemical traits modulate both NE abundance in the vicinity of CPs but also in the aphid colonies and consequently aphid colony dynamics.

## Materials and methods

### *Experimental site and design*

The study was conducted in 2024-2025 in a multispecies orchard (apple cvs. Ariane and Akane; peach cv. NectarLove) at INRAE Avignon (1.2 ha). Four CPs (*Ocimum basilicum, Tagetes patula, Mentha × piperita and Foeniculum vulgare*) were planted in intra-row strips around Ariane trees and compared with a grass control (2024) or bare soil (2025). Six replicate plots per treatment (4 × 2 m; three trees) were monitored. Plants were transplanted in early April and irrigated by micro-sprinklers (2024) or drip irrigation (2025).

### *Functional traits*

Plant height and flowering were recorded weekly. VOCs were collected in April and June using an active enclosure system and analysed by TD-GC-MS.

### *Natural enemies and aphid colonies*

NEs were monitored weekly on CPs (Araneae/Opiliones, Cantharidae, Coccinellidae, Forficulidae, parasitoids, Syrphidae). In 2024, the first four aphid colonies per tree were marked and monitored for aphid and NE abundance.

## Results and discussion

### *Functional traits*

CPs showed strong divergences in phenology and growth. *T. patula* flowered earliest (from early April) and longest (100 % of flowering plants in June and later); *O. basilicum* and *F. vulgare* flowered later (from mid-May), while *M. × piperita* did not flower in Spring while the aphids were present in apple trees. *T. patula* and *F. vulgare* reached larger heights (up to 70 cm), whereas *O. basilicum* and *M. × piperita* remained below 30 cm height. VOC profiles differed strongly among species and varied significantly with month and year (Table 1), with more abundant and diverse emissions in June. These patterns align with known effects of plant phenology on VOC production (Stefanakis et al., 2022).

Table 1. PERMANOVA results testing the effects of sampling period (year × month) on VOC blend composition of companion plant species.

| Companion plant | p-value | Pseudo-F-value | Degrees of freedom | $R^2$ |
|---|---|---|---|---|
| *O. basilicum* | 0.001 | 3.48 | 3 | 0.35 |
| *T. patula* | 0.001 | 10.22 | 3 | 0.61 |
| *M. x piperita* | 0.001 | 11.62 | 3 | 0.66 |
| *F. vulgare* | 0.001 | 9.28 | 3 | 0.59 |

### *CPs' attractiveness to natural enemies*

Seasonal increases in NE abundance were positively associated with flowering and plant height, in agreement with previous observations following the installation of flower strips in another orchard (Jacobsen et al., 2022).

*F. vulgare* was the most attractive species, especially to floricolous predators such as Cantharidae, reflecting the well-documented role of Apiaceae in supporting beneficial arthropods (Kopta et al., 2012). *O. basilicum* mainly hosted generalist predators (Araneae, Opiliones, Forficulidae), likely due to its dense architecture (Orpet et al., 2019). *T. patula* attracted Syrphidae early in the season, whereas *M.* × *piperita* attracted very few NEs which could be related to its vegetative stage in Spring.

### *Aphid colony dynamics*

Overall, the succession of NE observed during the aphid infestation in 2024 was similar across treatments, consistent with typical successional patterns (Dib et al., 2010). Aphid infestation levels were too low to support statistical analyses; however, several trends emerged (Figure 1). Syrphidae appeared first and seemed associated with reductions in aphid numbers on *T. patula*, *O. basilicum* and *L. multiflorum*. Coccinellidae were present from mid-May onwards, coinciding with the peak aphid infestation. Across all treatments, Coccinellidae presence on 22 May appeared to correlate with a decline in aphid numbers the following week. These patterns remain strictly correlative due to insufficient colony numbers for statistical testing. Mummified aphids, both black and golden, were mostly observed in the vicinity of *O. basilicum*, with a marked peak around 22 May. Forficulidae, Miridae, Cantharidae and, less frequently, Araneae were recorded later in the season, predominantly during the infestation peak or during the subsequent aphid decline, whatever the CP.

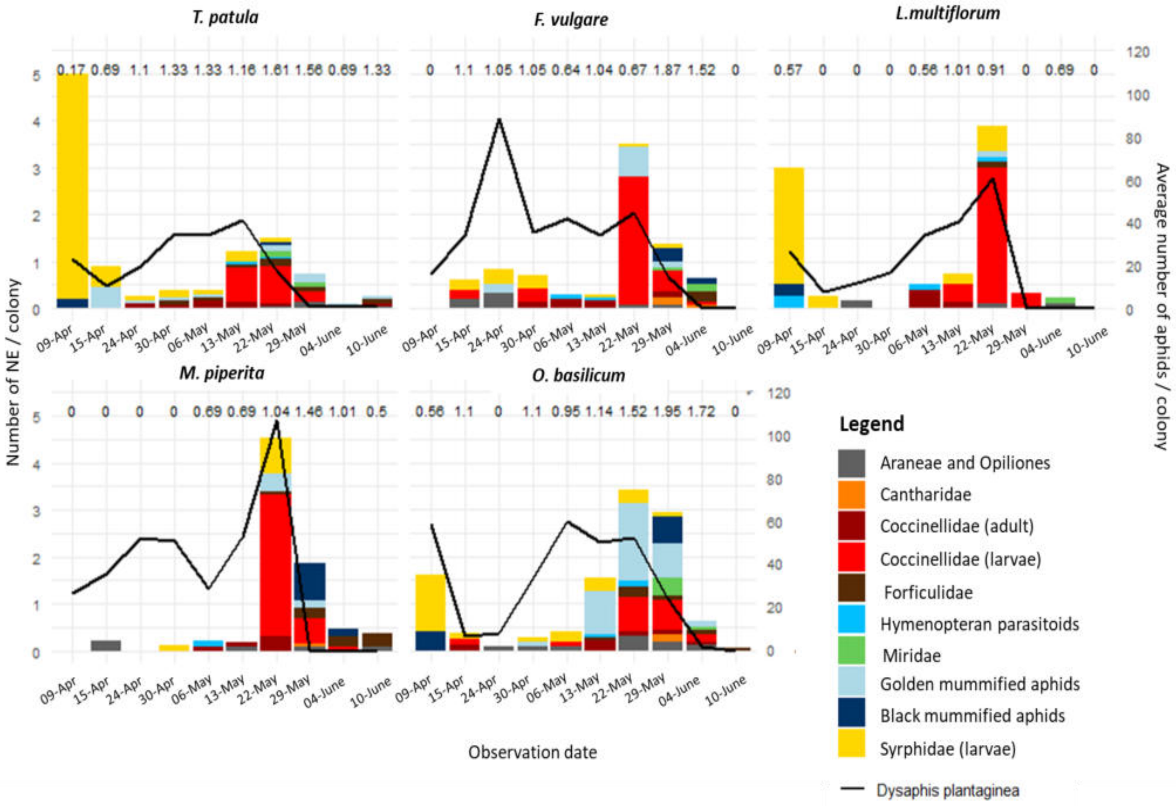

Figure 1. Evolution of the composition of natural enemies present in aphid colonies according to the companion-plant treatment in 2024. Stacked bars represent the mean abundance per colony for each functional group of natural enemies. The black line indicates the mean number of aphids (*Dysaphis plantaginea*) per colony (secondary axis).

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# Effects of wildflower resources on the survival of *Ganaspis kimorum*, an Asian parasitoid of *Drosophila suzukii*

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**Abstract:** Classical biological control programs exploiting the Asian parasitoid *Ganaspis kimorum* (Hymenoptera: Figitidae) against *Drosophila suzukii* (Diptera: Drosophilidae) are currently ongoing. Their success depends on the establishment and spread of the parasitoid in new environments. Beyond climatic suitability and landscape composition, the availability of suitable floral resources within crop areas may play a key role in parasitoid survival and activity. In this study, we evaluated under laboratory conditions the effect of ten wildflower species commonly found near cherry orchards on the survival of *G. kimorum*. Unfed males and females were exposed to fresh flowers for three days. After this period, parasitoids were deprived of the different floral resources and provided only with tap water. Mortality was recorded daily. Negative control received only water, whereas the positive control consisted of a sucrose solution (5 g/100 ml). Parasitoid survival was positively influenced by floral resources. *Taraxacum officinale*, *Daucus carota*, *Pastinaca sativa* and *Sambucus nigra* significantly increased parasitoid longevity compared to the negative control. In contrast, negligible benefits were observed with *Trifolium pratense*, *Centaurea* sp. and *T. repens*. These findings provide valuable insights for habitat management aimed at enhancing the presence and persistence of *G. kimorum* within agricultural landscapes. Practical implications include the management of mowing regimes to preserve flowering resources for natural enemies, as well as the selection of suitable plant species for flower strips or hedgerows.

**Key words:** habitat management, conservation biological control, non-crop habitats

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# Functional plants to conserve green lacewings *Chrysoperla carnea* (Neuroptera: Chrysopidae) in greenhouses

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**Abstract:** Evaluation of flowers to conserve green lacewings has focused on adult feeding. Nevertheless, plants can offer benefits besides floral resources, such as shelter and oviposition sites. Moreover, flower resources may also benefit the larvae as a complementary food. Here we assessed *C. carnea* larval survival on isolated floral resources, as pollen. The refuge and oviposition effect of plants were also tested, along with sweet pepper with release-recapture experiments in cages inside the greenhouse. In release-recapture experiments *C. carnea* adults Insects showed a significantly higher probability of selecting *Cochlearia officinalis* and *T. kolibri* relative to *C. arvensis* and *R. sanguineus*. We didn't find significant differences in egg numbers laid between companion and crop plants. The larval survival experiment revealed significant differences in survival among treatments. Compared with the negative control (water), treatments pollen + sugar-water, sugar-water, and pollen + water exhibited significantly improved survival, while pollen alone did not differ from water. These results suggest that *C. carnea* larvae may benefit from access to sugar resources in natural environments in case of a shortage of prey, whereas pollen alone does not appear to support larval survival. A wider study would be needed to understand *C. carnea* preference for refuge and oviposition, but in general, in our study the adult lacewings show a preference for resting in the sweet pepper plants.

**Key words:** conservation biological control, lacewings survival, companion plants

## Introduction

Lacewings (Insecta: Chrysopidae), generalist predators commonly found in natural environments, play a significant role in controlling agricultural pests in greenhouses (Fang et al., 2022; Ntalia et al., 2022; Mani et al., 2022). Conservation biological control practices, such as incorporating (extrafloral) nectar and pollen, can enhance their effectiveness by promoting their establishment and even attracting naturally occurring lacewings to greenhouse surroundings (Li et al., 2021; Messelink et al., 2014; Messelink et al., 2021). Evaluation of flowers to conserve green lacewings has so far mainly been focused on adult feeding (Alcalá et al. 2020; Gonzalez et al. 2016; Villa et al. 2016). Nevertheless, plants can offer benefits besides floral resources, such as shelter and oviposition sites. Moreover, flower resources may also benefit the larvae as a complementary food (Limburg et al., 2001).

Here we aim to determine *C. carnea* larval survival on isolated floral resources such as pollen and sugar. The refuge and oviposition effect of plants will also be tested, along with sweet pepper as our crop of interest, with release-recapture experiments in cages inside the greenhouse. This will be the first step for designing functional plant islands to conserve *C. carnea* in greenhouses to control sweet pepper pests.

## Materials and methods

### *Insect rearing*

*Chrysoperla carnea* eggs were supplied by Bioline Agrosciences. Eggs were individualized in Elisa plates until hatching and then the larvae were transferred to Petri dishes and fed *ad libitum* with *Ephestia kuehniella* eggs obtained from Koppert. The resulting adults were used in the release-recapture experiment, and eggs laid by these adults were collected and reared until hatching to perform the larval survival experiment.

### *Release-recapture experiment*

To assess the attractiveness for refuge and oviposition sites of companion plants versus sweet pepper plants to *C. carnea*, we performed a series of release-recapture experiments (Batista et al., 2017) in a greenhouse on average 20 °C and 60 % RH. We tested the effect of the following companion plants: *Rumex sanguineus*, *Cochlearia officinalis*, *Calendula arvensis* and *Tagetes kolibri.* Each plant was placed in a cage together with a sweet pepper plant, with a total of four cages per companion plant. Adult green lacewings were kept in couples for 10 days in plastic cups with pollen and a sugar-water solution as food, and five couples were released in each cage. After 15 minutes we aspired as much as possible adults and recorded the place where they were. Then lacewings were released again and the process was repeated 4 times every two hours. After the last release the lacewings were kept in the cages for two days for a final recapture, then the plants were taken to the laboratory and the eggs laid on them were counted.

### *Larval survival experiment*

To assess the *C. carnea* larval survival on isolated flower resources, first instar larvae were placed in small cups covered with lids with a hole with fine mesh, placed in a climate chamber at 25.0 ± 1.5 °C, 70 ± 10 % RH, and a 16:8 h L:D photoperiod. The larvae were fed with the following diets: *Typha angustifolia* pollen, *T. angustifolia* pollen above a piece of cotton with a sugar-water solution, cotton with sugar-water solution, cotton with water and, *E. kuehniella* eggs as a control. The food was replaced when needed and the larval survival was recorded at least every other day.

### *Statistical analysis*

Plant preferences were analyzed using generalized additive mixed models with a quasibinomial error distribution and logit link. Companion plant species and recapture round were included as fixed effects, with cage included as a random effect to account for repeated measures. Because sampling hours differed among treatments, recapture time was converted to recapture round within each cage to standardize temporal comparisons across treatments. Models were fitted using restricted maximum likelihood, and post hoc estimated marginal means were used to summarize effects on the response scale. For each treatment, paired Wilcoxon signed-rank tests were used to assess whether the difference in egg counts (Companion − Crop) differed from zero, with Holm correction applied to adjust for multiple comparisons. Differences in larval survival among treatments were assessed using the log-rank test. When the global log-rank test indicated significant differences, pairwise comparisons between treatments were performed using pairwise log-rank tests with adjustment for multiple testing. All analyses were conducted in R (version 4.5.1).

## Results and discussion

***Release-recapture and oviposition preference***

Conditional on being located on a plant, insects showed significant differences in plant preference among companion plant species (quasibinomial generalized additive mixed model; deviance explained = 29.7 %; Figure 1). Insects showed a significantly higher probability of selecting *C. officinalis* and *T. kolibri* relative to *C. arvensis* and *R. sanguineus*. Recapture round did not significantly affect plant preference, indicating that conditional choice was temporally consistent.

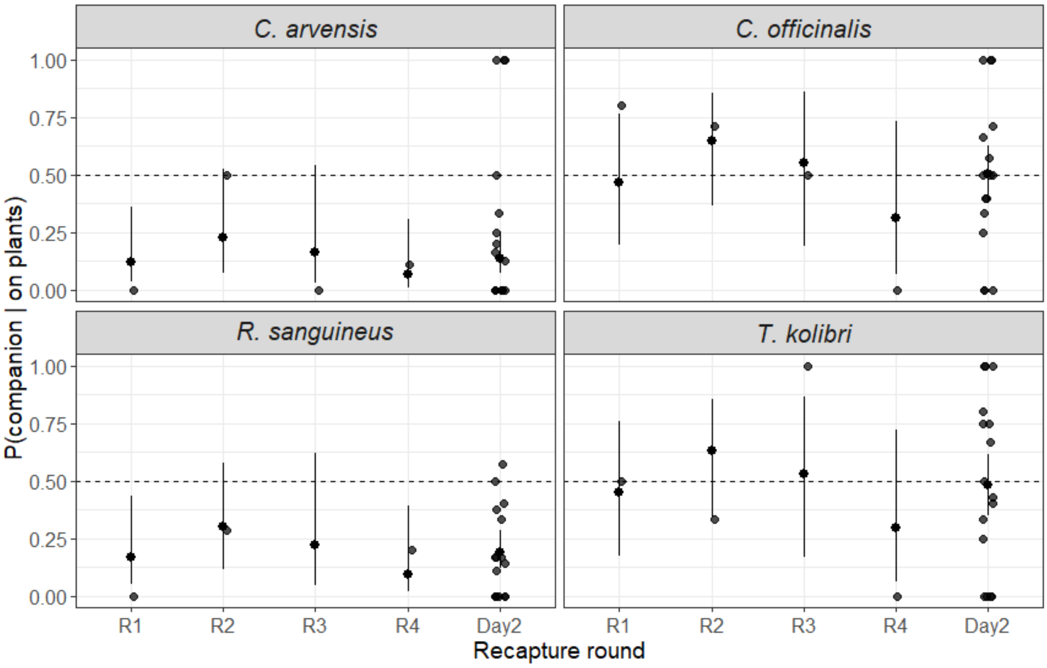

Figure 1. Conditional plant preference over time for each companion plant species. Points represent raw cage-level proportions of insects found on the companion plant relative to the crop plant sweet pepper, conditional on being located on a plant. Vertical bars show model-estimated probabilities ± 95 % confidence intervals from a quasibinomial generalized additive mixed model. The dashed horizontal line indicates no preference (0.5).

*C. officinalis* was used in the experiment for its dense structure, presenting several small leaves very close to each other, which contrast with the more open architecture of the sweet pepper plants. If compared with the other companion plants tested *C. officinalis* also present the densest architecture, followed by *T. kolibri*. Evaluations in different days could explain better if there is a pattern between leaf density and preference for *C. carnea*, but in general, in our study the adult lacewings show a preference for resting in the sweet pepper plants. In addition, we observed adult lacewings feeding on sweet pepper flowers only.

Paired comparisons of oviposition within each companion plant treatment revealed no significant differences in egg numbers between companion and crop plants (paired Wilcoxon signed-rank tests; Holm-adjusted $p > 0.05$ for all treatments). Nevertheless, insects tended to lay fewer eggs on *C. arvensis* and *R. sanguineus* than on the crop, whereas oviposition on *C. officinalis* and *T. kolibri* was similar between plants.

***Survival experiment results***

Survival differed significantly among treatments (log-rank test: $\chi^2 = 46.7$, df = 5, $p < 0.001$). Pairwise log-rank tests with multiple-testing correction revealed significant differences in survival among treatments. Compared with the negative control (water), treatments pollen + sugar-water, sugar-water, and pollen + water exhibited significantly improved survival ($p \leq 0.006$), while pollen alone did not differ from water ($p = 1.00$).

These results suggest that *C. carnea* larvae may benefit from access to sugar resources in natural environments, whereas pollen alone does not appear to support larval survival. The combination of a sugar–water solution with pollen resulted in improved survival compared with pollen-only diets. However, these benefits were limited, as none of the larvae maintained without prey underwent moulting or progressed to subsequent instars for 10 days. In contrast, larvae fed *E. kuehniella* eggs initiated moulting to the second instar (L2) within three days.

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# Are flower strips near greenhouses a risk for thrips?

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**Abstract:** The presence of flower strips near greenhouses can increase the diversity and abundance of natural enemies, which may contribute to pest management within the greenhouses. Aphid natural enemies, such as ladybird beetles, lacewings and aphidophagous hoverflies, will increase more quickly in a diverse flower strip than in short-mown grass, which is common near greenhouses. However, our surveys have shown that thrips densities also increase in these flower strips. Thrips are important pests for many greenhouse crops and vectors of tospoviruses. In this study, we present the results of biodiversity plots created at four sites near commercial greenhouse cultivation areas. Over two seasons, we monitored the abundance and species composition of thrips and their anthocorid predators in flowers of various plant species. Our results demonstrate the potential for optimising the selection of plant species to minimise thrips pressure in greenhouse horticulture, while also supporting the development of natural enemies that could contribute to pest management.

**Key words:** Thysanoptera, functional agrobiodiversity, ecosystem services

## Introduction

The greenhouse industry in the Netherlands is characterized by dense clusters of high-tech glasshouses, with in most cases limited space for vegetation near or around greenhouses. The areas surrounding glasshouses are typically uniform and simple in habitat structure, usually comprising of short grass grazed by animals or frequently mowed, fences and canals separating properties. However, due to the increasing awareness of biodiversity declines, also greenhouse growers are getting more interested in contributing to biodiversity restoration and in addition, increasing the acceptance of greenhouses in the landscape. Moreover, several studies demonstrated that flower strips near greenhouses can enhance the diversity and abundance of natural enemies, which may contribute to pest management within the greenhouses (Postic et al., 2020; Messelink et al., 2021). Aphid natural enemies, such as ladybird beetles, lacewings and aphidophagous hoverflies, will increase more quickly in a diverse flower strip than in short-mown grass, which is common near greenhouses. However, thrips densities may also increase in these flower strips, thereby posing a risk to pest management. Thrips are important pests for many greenhouse crops and vectors of tospoviruses (Whitfield et al., 2005). The majority of thrips species that cause damage to crops in greenhouses are exotic species. The most abundant species is western flower thrips, *Frankliniella occidentalis* (Pergande), a pest in many horticultural crops and also vector of tospoviruses (Mouden et al., 2017). Other important invasive pest species in Dutch greenhouses are *Echinothrips americanus* Morgan, *Thrips setosus* Moulton and more recently *Thrips parvispinus* (Karny). All these species have established in greenhouse crops and are rarely, or not at all, observed on crops outside greenhouses (Vierbergen, 2002; Mouratidis et al., 2023). Nevertheless, some of the indigenous thrips species occurring in flower strips may also function as potential pests in greenhouse crops, such as the species *Thrips tabaci* Lindeman. We therefore started a project to study the impact of increasing plant species richness in habitats surrounding greenhouses on the abundance of pests and natural enemies in these habitats. Here we show our results of sampling of thrips and anthocorid predators during the 2023 and 2024 season, and we discuss the abundance, species composition and presence of thrips in flowers of different plant species.

## Materials and methods

Four sites adjacent to greenhouses of 2 tomato growers and 2 growers of potted plants were selected in the greenhouse cluster "Oostland" near Bleiswijk in the Netherlands to create plots of 250 m$^2$ with increased biodiversity which were compared with plots with standard short-mowed grass. A mixture of 40 indigenous plant species with successive flowering period were sowed in November 2021. Thrips and *Orius* spp. abundance was monitored by collecting flower samples of the most abundant flowering species throughout the growing season, starting in the second year of the biodiversity plot development. Flowering plants were sampled once every two weeks starting in week 21 (May) and until week 38 (September) in 2023 and 2024. Each plant species was sampled 4 times per timepoint. Flowers were picked and placed in plastic containers until reaching a volume of 50 ml. Then, containers were filled with 60 % alcohol and were further processed in the laboratory. Samples were washed and sieved, and the total number of thrips and *Orius* predators was counted under a stereo microscope. Thrips adults in samples were identified to species level whenever possible, by mounting specimens on microscopic slides using Hoyer's medium, and using dichotomic keys available for the European fauna (Mound et al., 1976, zur Strassen, 2003).

## Results and discussion

Throughout the 2023 and 2024 seasons, we collected a total of 280 flower samples from 17 plant species. The thrips population peaked in July and August. This sampling resulted in 3419 thrips adults being identified at species or genus level. Our results show that flower strips create a high diversity of thrips species very soon. In total, we identified 20 species, six of which were rare, with fewer than 20 individuals per species. Figure 1 shows the relative abundance of the other 14 species. *Thrips tabaci* was by far the most common species, almost half of the total number, frequently sampled in *Daucus carota*, *Matricaria chamomilla, Dipsacus fullonum* and the common spontaneously occurring weed *Senecio vulgaris*. The second most abundant species, with a share of 10 %, was *Thrips physapus* Linneaus, which was mainly present in *Crepis biennis*. The third most abundant species was *Thrips pillichi* Priesner, which was mainly found in *S. vulgaris* and *M. chamomilla*. A fourth common species present was the European flower thrips *Frankliniella intonsa* (Pergande), which was predominantly found in *Ranunculus acris* and *Epilobium hirsutum*. The rose thrips *Thrips fuscipennis* Haliday was also found in large numbers, especially in inflorescences of *E. hirsutum*, *C. biennis*, *Centaurea cyanus* and *Cichorium intybus*. The most common greenhouse pest, *F. occidentalis* was found in low numbers, mainly in flowers of *C. cyanus* and *R. acris*. Apart from *F. occidentalis,* no other non-native species were found. The thrips fauna recorded in this preliminary study matches the results of a previous survey around glasshouses in the Netherlands (Vierbergen, 2001). Besides plant feeding thrips, we found the predatory thrips *Aeolothrips intermedius* and *Orius* spp. in various plants species sampled throughout the seasons.

***Concluding remarks***

Our study shows that increasing diversity of flowering plants near greenhouses increases overall thrips densities, including potential pest species such as *Thrips tabaci* and *Thrips fuscipennis*. However, to what extent these populations migrate into greenhouses merits further studies. The most abundant thrips in greenhouse crops, western flower thrips, was found relatively late in the season and in low numbers in the flowering vegetation, suggesting these thrips came from the nearby greenhouses and established afterwards in these flowering plants. The analysis of thrips and predator abundance per flowering plant species shows interesting differences and indicates there are possibilities to optimize biodiversity habitats near greenhouses by adjusting the mixtures that limit potential risks of increases in pest influxes and at the same time support a wide range of beneficial insects for pest management.

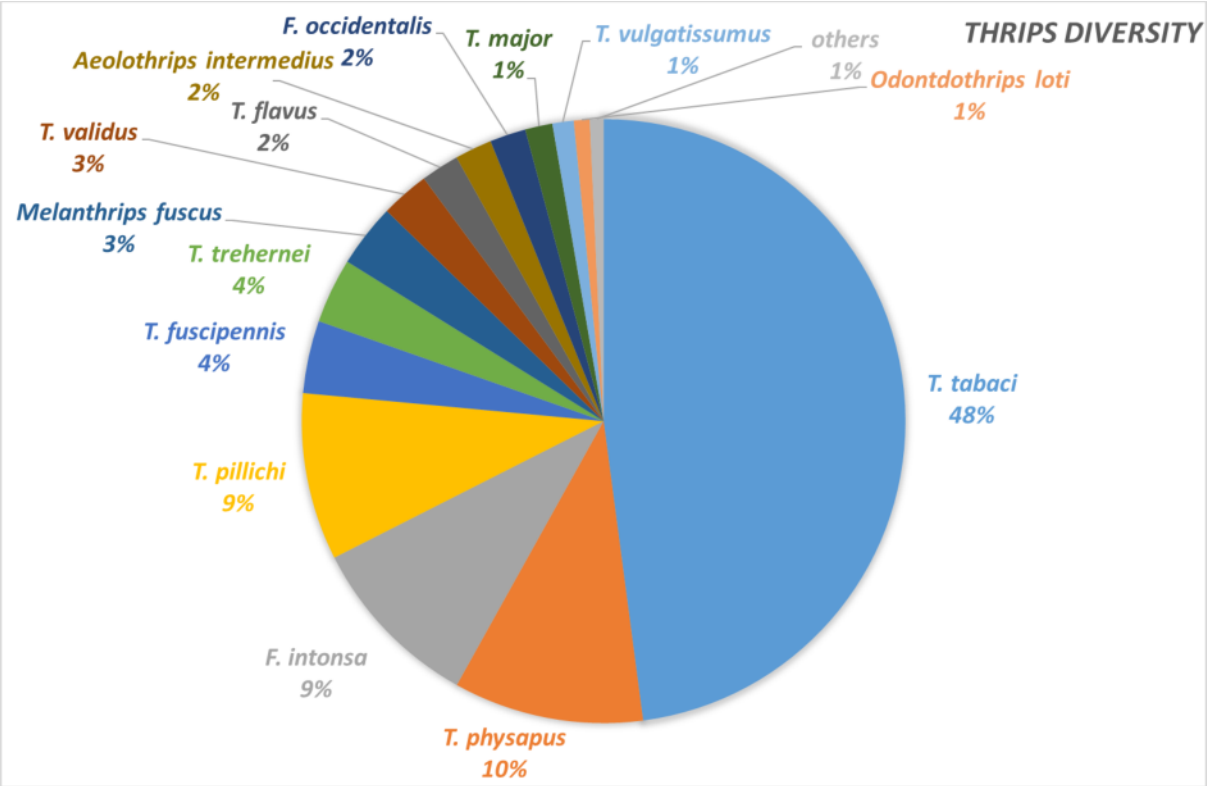

Figure 1. Thrips diversity in 17 flower species during 2 summers in 2023 and 2024. The percentages are based on 3419 identifications of thrips adults.

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# Blooming greenhouses: enhancing biocontrol with functional plant diversity?

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**Abstract:** Functional plants are increasingly recognized as a key factor in sustainable pest control, yet their application around greenhouses remains underexplored. This ongoing study examines two types of functional plant strips established outside greenhouses: one excluding thrips-attractive plants and another optimized for aphid control. These functional plant strips can provide resources for natural enemies that then may migrate into greenhouses and contribute to biological control. We will monitor natural enemy and pest populations in and around 20 greenhouses across the Netherlands in the summer of 2025 and 2026. Conventional grass strips serve as a reference treatment. We will present our preliminary monitoring data and an overview of the next steps. This research aims to provide practical guidelines for strengthening biocontrol in greenhouses and reduce the dependency on chemical insecticides.

**Key words:** biodiversity, greenhouse crops, natural enemies, pests, conservation biological control

## Introduction

In the quest for pesticide-free horticulture, achieving effective pest control while maintaining biodiversity is a major challenge (Geiger et al., 2010). A higher diversity of natural enemies, such as predators and parasitoids, can enhance biological control by promoting a more resilient and complementary pest control system (Letourneau et al., 2009). Diverse communities of natural enemies help mitigate the limitations of individual species by filling various ecological niches and responding to different pest threats (Snyder, 2019). However, despite the well-recognized potential of natural enemies in integrated pest management, their commercial availability is, compared to what nature offers, rather limited. This is primarily due to the challenges associated with mass producing of many species of natural enemies needed to target the wide variety of pest species found in agricultural systems (van Lenteren et al., 2020). As a result, many greenhouse systems continue to rely on a narrow selection of natural enemies, limiting the overall efficacy of biological control.

The vegetation around most Dutch greenhouses often consists of short-mown grassland, maintained primarily for the assumption it reduces pest influxes, but also for practical and aesthetic reasons, with little structural or floral diversity. These grass strips provide limited resources for native natural enemies. In contrast, functional plant strips, such as flower strips, have been shown to effectively attract a wide range of native natural enemies from the broader landscape in open-field systems (Balzan et al., 2014; Durak et al., 2025; Han et al., 2025; Ju et al., 2025). Since these strips provide abundant nectar, pollen, alternative prey and shelter for native natural enemies, they have been proposed as functional corridors that could facilitate the movement of native natural enemies into greenhouse environments (Messelink et al., 2021). However, empirical evidence of their effectiveness in greenhouse systems is still lacking, and this study aims to address this gap.

## Materials and methods

In total, 20 greenhouses were selected based on the grower's interest and motivation. In nine greenhouses vegetables are grown and in other 11 greenhouses ornamentals are grown (flowers and potted plants). The greenhouses were classed into six spatial clusters that are spread through the Netherlands). Two different flower mixtures (A and B, Table 1) were sown in functional plant strips surrounding these greenhouses in November 2024. Mix A included 14 plant species and was assumed to pose a lower risk for thrips than the more species-rich Mix B, which included 21 species (Table 1). The differences within these mixtures allows testing how these variables' influence the attraction and effectiveness of native natural enemies. Seven greenhouses received Mix A and 13 greenhouses received Mix B, based on the grower's preference. Biodiversity monitoring was conducted at all 20 greenhouses from mid-May till mid-September in 2025 and will be repeated in 2026. Monitoring is carried out every three weeks at each greenhouse, resulting in a total of six rounds per greenhouse and per year.

Table 1. Plant species in mixture A (low risks for thrips) and B (optimized against aphids).

| # | Mixture | Scientific name | English name |
|---|---|---|---|
| 1 | A / B | *Knautia arvensis* | Meadow crown |
| 2 | A / B | *Geranium pyrenaicum* | Hedgerow cranes-bill |
| 3 | A / B | *Fagopyrum esculentum* | Buckwheat |
| 4 | A / B | *Achillea millefolium* | Yarrow |
| 5 | A / B | *Heracleum spondylium* | Common hogweed |
| 6 | A / B | *Prunella vulgaris* | Common brown |
| 7 | A / B | *Dipsacus fullonum* | Large teasel |
| 8 | A / B | *Rhinanthus angustifolius* | Large rattle |
| 9 | A / B | *Rhinanthus minor* | Small rattle |
| 10 | A / B | *Carduus nutans* | Nodding thistle |
| 11 | A / B | *Pastinaca sativa* | Parsnip |
| 12 | A / B | *Echium vulgare* | Viper's bugloss |
| 13 | A / B | *Cichorium intybus* | Wild chicory |
| 14 | A / B | *Reseda lutea* | Dyer's rocket |
| 15 | B | *Lotus corniculatus* | Common bird's-foot trefoil |
| 16 | B | *Centaurea jacea* | Knotweed |
| 17 | B | *Matricaria recutita* | True chamomile |
| 18 | B | *Daucus carota* | Carrot |
| 19 | B | *Leucanthemum vulgare* | Common daisy |
| 20 | B | *Ranunculus acris* | Sharp buttercup |
| 21 | B | *Crepis biennis* | Large-leaved hawkweed |

In each greenhouse, the experimental design consisted of a 250 m² functional plant strip (sown with Mix A or B) adjacent to a conventional grass strip used as a control. Relative plant cover was visually estimated per species along representative transects using a Braun-Blanquet scale, including unsown species exceeding 5 % cover. Key pest and beneficial taxa were monitored using 20 sweep-net transects and two yellow sticky traps (10 × 25 cm Dry Bug-scan, Biobest®) left in the field 3-4 days in each strip at 1 m height. To count pollinators and natural enemies (bumblebees, other bees, hoverflies, ladybirds, lacewings, soldier beetles), direct visual surveys of 5-minutes were conducted by two observers simultaneously in representative 9 m² plots. To record aphid colonies (species identity, host plant, and present life stages of ladybirds or parasitic wasps), targeted observations were conducted in a 25 m² plot. Weather conditions (temperature, light intensity, pressure, and wind speed) were logged during sampling. Species richness was estimated by averaging the total amount of different identified taxa (to species level when possible) over the 20 greenhouses.

## Results and discussion

Preliminary descriptive analysis suggests that functional plant strips increase overall observed insect diversity, including pollinators, lacewings, and soldier beetles (Figure 1). On average, insect diversity was lower in the conventional grass strip compared to the functional plant strip (for Mix A and B) for both sampling rounds (May to July, and from July to September). However, there appears to be no differences between the species richness in functional plant strip with Mix A and B.

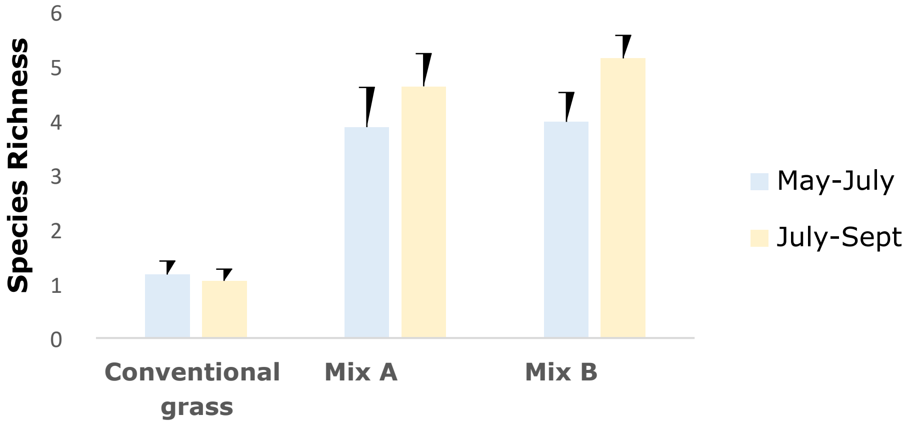

Figure 1. Species richness of insect groups in conventional grass strips and functional plant strips (with Mix A or B). Bars indicate the average species richness during the 5-minutes observations at 20 greenhouses from May till July 2025 (blue) and from July to September 2025 (yellow). Observed species groups include pollinators, lacewings, and soldier beetles.

Due to the limited observation period, these findings are not yet generalizable. These observations will be further examined using formal statistical testing in future analyses. In combination with the data from 2026 and results from a landscape analysis around the greenhouses, clearer conclusions can be made to assess functional plant strips. These results will be used to inform management practices to enhance insect diversity which could aid in better biological control in greenhouse crops.

## Acknowledgements

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# Effect of various flower strip types on *Myzus persicae* and its natural enemies in sugar beet

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**Abstract:** Flower strips (FS) support natural enemies that can potentially help regulating aphid pests in sugar beet fields. Early-season floral resources for natural enemies are particularly important for mitigating *Myzus persicae* (Sulzer) populations, the primary vector responsible for transmitting virus yellows. This study evaluated three FS types (autumn-sown annual, spring-sown annual, and young perennial FS), each established on ten insecticide-free sugar beet fields, and compared them with insecticide-free sugar beet control strips. Flowers and natural enemies were sampled within the strips, and *M. persicae* and natural enemies were counted on sugar beet plants near the FS and control strips. Autumn-sown annual and second-year perennial FS produced the earliest and highest flower volumes. These FS types also supported more natural enemies of aphids than spring-sown annual FS and control strips. *M. persicae* numbers in sugar beet increased over the season and no correlation between natural enemies and *M. persicae* was found. Nevertheless, lower numbers of *M. persicae* were observed near perennial FS compared to autumn-sown annual FS, indicating that FS composition influenced *M. persicae* abundance. Overall, the results show that overwintering FS can enhance early-season floral resources and natural enemy activity, but this alone is not enough to prevent early aphid build-up. These findings suggest that improving biological control of *M. persicae* may require additional strategies. In particular, integrating plant species with direct repellent or attractant effects on *M. persicae* could strengthen pest suppression by reducing early colonization pressure or diverting aphids away from sugar beet.

**Key words:** flower strips, sugar beet, *Myzus persicae*, beneficial insects

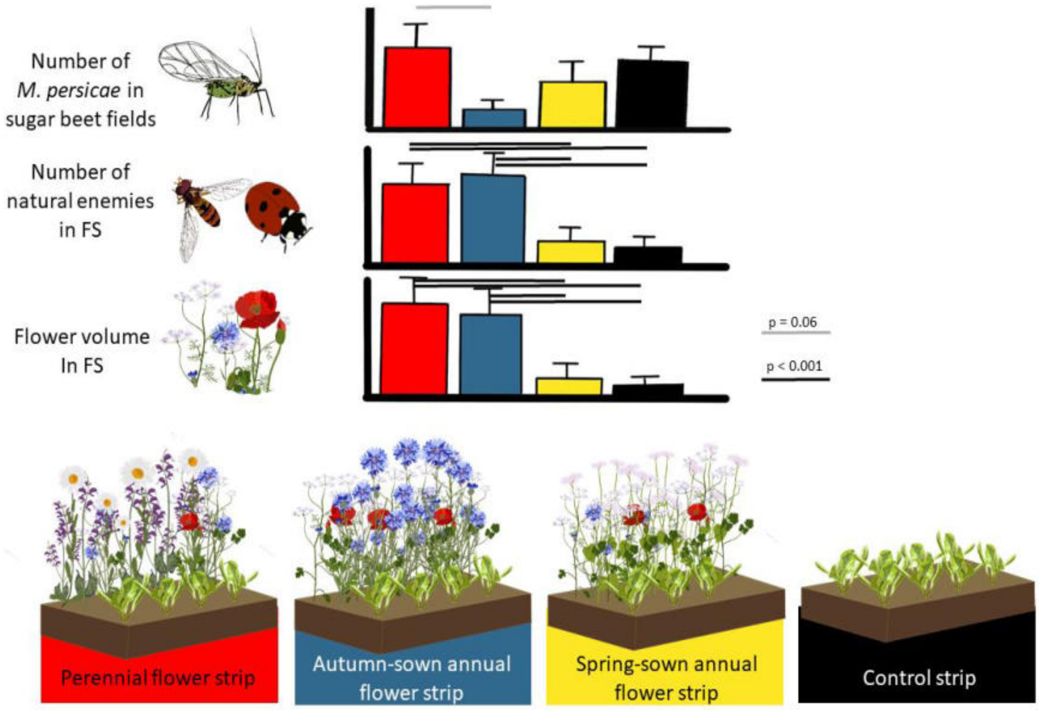

Figure 1. Graphical abstract.

## Introduction

Sugar beet production in Europe has become more vulnerable since the ban on neonicotinoid seed treatments in 2019, that were prohibited because of their negative effects on pollinators (Mahillon et al., 2022; Wagner, 2020). Without these insecticides, growers face renewed pressure from aphid-borne virus diseases that can cause major yield losses, especially when infections occur early in the season (Clover et al., 1999). Virus yellows is caused by four viruses that induce leaf yellowing. In Switzerland, Beet Yellows Virus and Beet Chlorosis Virus are the most common virus diseases (Mahillon et al., 2022). These viruses are primarily transmitted by *Myzus persicae* (Sulzer). *M. persicae* reaches sugar beet fields early, often by late April (Landis and van der Werf, 1997).

Conservation biological control provides one method for reducing pest pressure. Flower strips (FS) can supply pollen and nectar to predators and parasitoids, thereby increasing their activity near crops (Tschumi et al., 2016). Early-season floral resources are essential in sugar beet crops because *M. persicae* can be in the field from April on. FS exist in many forms, differing in plant species composition, sowing time, and age. Although many studies have compared plant mixtures (e. g., Blümel et al., 2024) or examined a single FS type in one crop (Tschumi et al., 2016; Twardowski et al., 2005), few have tested multiple FS designs with a focus on beneficial insects and pests relevant to a specific crop system. For sugar beet crops, research is particularly limited (Twardowski et al., 2005).

This study compared three FS types, autumn-sown annual, spring-sown annual, and perennial, placed next to insecticide-free sugar beet fields, and compared them to insecticide-free control strips without flowers. The aim was to address the following aspects: (1) identifying suitable sown FS types in terms of early flower resource availability for aphid antagonists, (2) quantifying the abundance of aphid antagonists in the different FS types and control strips, and (3) checking whether *M. persicae* numbers are lower near any FS type.

## Materials and methods

### *Field selection and flower strip establishment*

This experiment included five treatments: autumn-sown annual FS, perennial FS, spring-sown annual FS, and sugar beet control strips on insecticide- and fungicide-free sugar beet fields. Autumn-sown annual FS were established in late August to early September 2022, spring-sown annual FS from April to May 2023, and perennial FS from April to May 2022. Fields were located on the Central Swiss Plateau (cantons of Zurich, Aargau, Schaffhausen, Thurgau). The FS were 6 m wide and varied in sizes from 6 ares to 25 ares (autumn-sown annual FS mean: 11.5 ares, SE: 0.8 ares, spring-sown annual FS mean: 14.2 ares SE: 1.5 ares, and perennial FS mean: 13 ares, SE: 1.1 ares)

### *Flowers in the strips*

Flowers in the FS and the control strips were surveyed at three time points (mid-April, early May, and early June 2023). Flower abundance was recorded in four representative 1 m² plots, counting the number of flowers per species (for with a capitulum, the capitulum number was counted). To quantify flower volume, we measured either length, width, and height for tubular flowers or diameter and depth for flowers with radial symmetry.

### *Natural enemies of aphids in the strips*

In each treatment, insects were sampled at the same time points as the flowers using a 40 cm sweep net. On each date, sweep netting was carried out over rain-free days at temperatures above 10 °C. Within each FS and control strip, 60 sweeps were performed. Plant material was removed before processing. The following groups were identified and counted: aphidophagous hoverflies (Syrphidae), ladybirds (Coccinellidae, adults and larvae), lacewings (Chrysopidae, adults and larvae), and parasitoids (Braconidae).

### *Myzus persicae and natural enemies in sugar beet*

Visual surveys of natural enemies were conducted at three time points (early May, late May, mid-June 2023). In each field, 40 sugar beet plants were marked at distances of 5 m, 10 m, 15 m and 20 m from the FS or control strip, and each plant was inspected for natural enemies and aphid mummies. Winged *M. persicae* were counted at the same sampling dates on 100 sugar beet plants located 5 m from the strip.

### *Data analysis*

Treatment (FS types and controls) and sampling round were included as fixed factors, with field as a random factor. Flower volume of sown and spontaneous species, natural enemies of aphids and *M. persicae* was modelled using the nbinom1 or nbinom2 family in glmmTMB package (Brooks et al., 2017), and pairwise comparisons for both factors were conducted with the emmeans package (Lenth, 2024). The *M. persicae* model additionally included natural enemy abundance in the sugar beet.

## Results and discussion

Flower volume varied across sampling rounds and treatments. Autumn-sown annual and perennial FS produced significantly higher volumes of sown and spontaneous flowers than spring-sown annual FS and control strips, while spring-sown annual FS did not flower before early June (Studer et al., 2025). The low flower volume in spring-sown annual FS was likely due to delayed soil preparation and subsequent drought. These results indicate that FS established in the season before the target crop offer a more reliable source of early floral resources.

Natural enemies of aphids were significantly more abundant in perennial and autumn-sown annual FS than in spring-sown annual FS and control strips, reflecting the overall pattern of flower availability (Studer et al., submitted). The early and consistent flower production in these two strip types ensured that natural enemies had access to resources when aphids began colonizing sugar beet fields.

*M. persicae* abundance in sugar beet fields depended on bordering FS types, being lower near perennial FS than near autumn-sown annual FS and increased over the season. However, natural enemy abundance did not correlate with *M. persicae* abundance, likely because predators focus on the more common *Aphis fabae* (Scopoli) rather than on the much rarer *M. persicae* (Pervez and Yadav, 2018). Fewer *M. persicae* were found near perennial FS than near autumn-sown annual FS, possibly due to attraction or repellence effects of perennial vegetation, although the mechanisms remain unclear (Ben-Issa et al., 2017; Studer et al., submitted). Plant traits may play a role, but specific effects on *M. persicae* are not well studied. Since appropriate plant selection may help affecting early colonization, further research on targeted plant – aphid interactions is needed.

The results indicate that natural regulation of *M. persicae* might not be sufficient on its own. Including plant species with repellent or attractant effects may improve pest suppression by reducing early colonization or steering aphids toward alternative plants.

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# Multifunctional perennial flower strips promote parasitoid wasps and other beneficial insects

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**Abstract:** Subsidies for biodiversity promotion areas were implemented in Switzerland in 1994 to balance negative impacts of agriculture practice on biodiversity. This study examines and compares floral availability (volume) and beneficial insects (abundance) in two types of such areas: perennial wildflower strips and multifunctional perennial flower strips. The well-established wildflower strips were designed to foster biodiversity; the recently composed multifunctional strips intend to specifically promote natural enemies and pollinators. Seven to eight strips of each type were selected on the Swiss Central Plateau, and data on flower volume and insect abundance and diversity were collected over two years. The three-year-old multifunctional strips were compared to the equally aged wildflower strips. As predicted, similar flower volumes were observed in both strip types. The comparison between multifunctional and wildflower strips revealed a surprising similarity between the examined insect groups with no significant difference in beneficial insects. Contrary to expectations, the total flower volume in multifunctional strips did not drop from the second to the third year, and the volume of flowers with easily accessible nectar also remained stable. Despite this continuity in the flower volume, the abundance of pest controlling insects like parasitic wasps increased significantly and the numbers of pollinators dropped. The results highlight the importance of perennial strips for natural pest enemies but also the need for flower strips of various ages within the arable landscape matrix.

**Key words:** perennial flower strips, natural pest control, beneficial insects

## Introduction

In 1994, Switzerland introduced governmental subsidies for managing biodiversity promotion areas to mitigate the negative impacts of agriculture intensification on native fauna and flora and ecosystem services (Haaland et al., 2011; Stöckli et al., 2024). Perennial wildflower strips (hereafter ‘wildflower strips’) were the first such areas to be approved. They support a diverse range of fauna, for example, spiders, ground beetles, parasitoids, and birds (Stöckli et al., 2024). Other types followed, including several annual flower strips for targeted natural pest control (e. g., Tschumi et al., 2016). Around 2020, a multifunctional perennial flower strip (hereafter ‘multifunctional strip’) was designed to explicitly support insect taxa involved in biological pest control and pollination and to combine the benefits of the annual strips (targeted pest control) with perennial ones (longer-lasting habitats).

This study compares three-year-old multifunctional strips with wildflower strips of the same age to determine whether differences in the plant composition and the beneficial insect community persist in the third year despite the natural successional approximation of the plant community (Albrecht et al., 2021; Ullrich, 2001). The distinct aims of the two strip types were expected to reflect in the presence of beneficials, even in the third year. A higher abundance of beneficial insects was anticipated in the multifunctional strips.

The study also examines plant succession in multifunctional strips in the second and third flowering season. It identifies the effects of the changing vegetation on pollinating and pest-controlling insects, particularly on parasitic wasps. A drop in the available floral resources was anticipated over time (e. g., Albrecht et al., 2021). At the same time, the number of beneficial insects was expected to increase due to the more complex vegetation structure and easily accessible Apiaceae species such as *Foeniculum vulgare* and *Daucus carota* (e. g., Gillespie et al., 2016).

## Materials and methods

### *Study design*

Sixteen sites (eight multifunctional and eight wildflower strips) located in the cantons of Aargau, Schaffhausen, Thurgau, and Zurich were studied. The strips were sown in late 2021 or early 2022. Each strip was sampled in multiple survey rounds: The multifunctional strips were sampled three times in 2023; both strip types were sampled four times in 2024.

A 100-meter transect was laid along the strips' midline as a guide during data collection. Four representative one-square-meter plots were delineated within the extent of the transect. In each plot, flowers of the sown and spontaneous plant species were counted and measured to calculate the inflorescences' volume.

Insects were collected along the transect with 60 sweeps. Honeybees, wild bees, and hoverflies were categorized as "pollinators." Aphid predators (ladybugs, lacewings, hoverflies) and parasitic wasps were termed "natural enemies" (Winfree et al., 2011). All parasitic wasps were identified at the family level.

### *Data analysis*

The flower volume was calculated by multiplying the diameter by the height for flowers with radial symmetry and using the height, width, and depth for tubular flowers. Plant species were categorized as "accessible" and "non accessible" based on the accessibility of their nectar to parasitic wasps and hoverflies (e. g., Wäckers and van Rijn, 2012).

The statistical analyses for the flower strip comparison and the plant succession comparison in the multifunctional strips were done using the statistical software R (R Core Team, 2025). We analyzed flower volume and the abundance of pollinators and natural enemies using generalized linear mixed models from the glmmTMB package (Brooks et al., 2017). We examined the abundance of parasitic wasps in the same way and additionally analyzed them at the family level. The individual strips were used as a random factor in all models. 'Treatment' or 'Year' as well as 'Survey Round' were included as explanatory factors. The models were followed by post hoc pairwise comparisons using estimated marginal means from the Emmeans package (Lenth et al., 2024). A Gamma distribution was used for analyzing flower volume, while a nbinom2 distribution was used to model abundance data.

## Results and discussion

***Comparison of multifunctional and wildflowers strips in their third year***

The third-year multifunctional and wildflower strips were similar in their plant communities and floral volume (see p-values in Table 1). However, the hypothesized differences in the number of insects belonging to the examined insect groups were not confirmed. The result suggests that the differences in the seed mixtures were no longer pronounced enough in the third year to cause significant differences in the presence of beneficial insects.

***Changes in the multifunctional strips from the second to the third year***

The transition in vegetation from the second to the third year in multifunctional strips showed no change in total flower volume for sown and spontaneous species, nor in the volume of flowers with easily accessible nectar. The number of parasitic wasps significantly increased, especially within the Braconidae and Eulophidae families. Several subfamilies of the Braconidae target aphids, and the Eulophidae parasitize a wide range of hosts, including leaf-mining Lepidoptera (Goulet and Huber, 1993). Both are particularly relevant for natural pest control. Overall, aphidophagous natural enemies increased significantly. The trend was opposite for pollinators. They decreased significantly (Table 1).

Table 1. The calculated mean and standard error (SE) as well as the p-value of the models described in ***Data analysis*** for the comparison between the years and the flower strip types are shown. The means were calculated across three survey rounds when comparing multifunctional strips between years and across four survey rounds when comparing multifunctional to wildflower strips. For the parasitoid families, only those with significant differences are shown. Significant p-values are printed bold.

| | Multifunctional Strip 2023 n = 7 | Multifunctional Strip 2024 n = 7 | p-value | Multifunctional Strip 2024 n = 7 | Wildflower Strip 2024 n = 8 | p-value |
|---|---|---|---|---|---|---|
| Flower volume cm$^3$/m$^2$ | mean = 489.48<br>SE = 175.9 | mean = 240.73<br>SE = 88.66 | 0.8184 | mean = 184.87<br>SE = 68.68 | mean = 326.53<br>SE = 107.38 | 0.3283 |
| Accessible flower volume cm$^3$/m$^2$ | mean = 185.3<br>SE = 81.92 | mean = 294.09<br>SE = 157.32 | 0.5158 | mean = 294.09<br>SE = 157.32 | mean = 360.72<br>SE = 164.82 | 0.6878 |
| Pollinators | mean = 12.19<br>SE = 4.81 | mean = 4.76<br>SE = 1.86 | **0.0005** | mean = 3.60<br>SE = 1.43 | mean = 2.03<br>SE = 0.54 | 0.9314 |
| Natural Enemies | mean = 15.10<br>SE = 3.93 | mean = 25.95<br>SE = 5.50 | **0.0021** | mean = 21.6<br>SE = 4.35 | mean = 16.75<br>SE = 2.10 | 0.5783 |
| Parasitoids | mean = 9.90<br>SE = 3.52 | mean = 21.48<br>SE = 4.94 | **0.0001** | mean = 17.82<br>SE = 3.89 | mean = 15.00<br>SE = 2.04 | 0.9159 |
| Braconidae | mean = 1.90<br>SE = 0.61 | mean = 3.67<br>SE = 0.73 | **0.0085** | mean = 1.48<br>SE = 0.34 | mean = 1.38<br>SE = 0.32 | 0.8443 |
| Eulophidae | mean = 0.29<br>SE = 0.12 | mean = 5.00<br>SE = 3.33 | **0.0003** | mean = 1.77<br>SE = 1.19 | mean = 1.22<br>SE = 0.44 | 0.6006 |

The decline of pollinators after the second year has been observed previously (e. g., Albrecht et al., 2021). The significant increase in natural enemies could have reasons beyond food availability. The growing complexity in the vegetation structure and the increasing grassiness we observed were found to provide critical roosting and overwintering sites in previous studies (e. g., Gillespie et al., 2016). These successional changes could be a key factor in the parasitoids' increase. Therefore, their abundance highlights the importance of perennial strips as undisturbed habitats. Different-aged multifunctional strips within an area could optimize benefits for natural enemies by offering more flower volume and increased diversity alongside complex vegetation structures. Alternatively, we recommend including more perennial Apiaceae in the seed mixture to provide a higher availability of accessible flowers for beneficial insects.

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# Enhancing biological control through spontaneous vegetation: insights from Mediterranean *Citrus* fields

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**Abstract:** Ecological infrastructures play a central role in conservation biological control because they offer resources and refuges that sustain populations of beneficial arthropods. In Mediterranean *Citrus* orchards, allowing the development of spontaneous ground vegetation is a promising approach to enhance natural enemies, although its effectiveness depends on identifying which plant species best support these communities. To address this, we surveyed eight commercial orchards in southern Tarragona, characterizing both the herbaceous vegetation and the associated arthropod assemblages. Field sampling was carried out in spring and summer. Vegetation cover and phenology were evaluated using the Daubenmire method. Across all orchards, 77 spontaneous plant species belonging to 26 botanical families were recorded. In spring, *Hordeum murinum* L. and *Malva sylvestris* L. were the most prevalent and abundant taxa, while in summer *Convolvulus arvensis* L. and *Lobularia maritima* (L.) appeared most frequently, with *Paspalum dilatatum* Poir. and *C. arvensis* dominating in cover. Regarding natural enemies, Syrphidae represented the largest share of entomophagous arthropods (42 % of captures, 19 species), followed by Coccinellidae (15 %, largely *Coccinella septempunctata*) and Araneae (8.6 %). Among the spontaneous flora, *M. sylvestris*, *L. maritima* and *C. arvensis* showed the strongest associations with natural enemy groups. Our findings emphasize the value of identifying key plant species that sustain beneficial arthropods in *Citrus* habitats. This information can guide the design of vegetation management strategies tailored to promote conservation biological control and strengthen the sustainability and resilience of *Citrus* pest management programs.

**Key words:** conservation biological control, ground cover vegetation, Syrphidae, Mediterranean *Citrus* systems

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# More flowers in sugarcane fields in Africa: An urgent need to attract and preserve natural enemies to increase the biological control of sugarcane pests

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**Abstract:** Most sugarcane areas in Africa belonging to small and large farmers as well as sugar companies are generally poor in terms of biodiversity due to the monocropping system used with conventional agricultural and harvesting practices while they encounter many pest problems and economic yield losses. Particularly, flowering plants, flower strips and natural vegetation that provide shelter, nectar and pollen for many useful insects are missing along arable fields. Integrated Pest Management (IPM) in sugarcane remain conventional with the use of resistance varieties, pesticides and augmentative biological control. Conservation biological control is not yet used as a long-term strategy to reduce pest infestations. In Tanzania, we have discovered the importance of using flowering plants such as *Tithonia diversifolia* to not only help controlling the Yellow Sugarcane Aphid *Sipha flava* but also the white grub *Cochliotis melolonthoides*, a key pest of sugarcane in Tanzanian sugarcane fields. Regular surveys, observations and collections of different predators such as ladybirds, hoverflies, lacewings, long-legged flies, spiders and scoliid wasps in *T. diversifolia* shrubs along sugarcane fields has proven the importance of these banker plants for the abundance and activity of these natural enemies. We then concluded that more flowering plants are needed in sugarcane fields to increase pest control and could be integrated in future sugarcane crop protection in African sugar producing countries.

**Key words:** sugarcane, insect pests, biological control, flowering plant, *Tithonia diversifolia*

## Introduction

Sugarcane is an important crop in Africa but is currently threatened by three major groups of insect pests of economic importance: the sap-sucking insects with the most damaging species *Sipha flava* (Hemiptera, Aphididae), currently a problem in central, east and south Africa (Goebel, 2021); the white grubs such as *Cochliotis melolonthoides* (Coleoptera, Scarabaeidae) in Tanzania and other species (Jepson, 1956; Wilson, 1969; Katundu, 1999), and the stem borer species (Lepidoptera) *Sesamia calamistis* and especially *Eldana saccharina* responsible for significant yield losses (Goebel, 2024). Most of these pests can be controlled using pesticides but progress is currently made through different initiatives to reduce infestation by implementing agroecological crop protection and revising some agricultural practices. For example, some of these practices such as field burning before harvesting, pesticide use and over-application of fertilizers have negative effects on biodiversity and ecosystem services (Goebel et al., 2018). One of the most interesting components in agroecology is to develop conservation biological control by using companion plants and natural vegetation in cropping systems (Gardiner et al., 2009). Through studies in Tanzania, the objective of this paper is to confirm the importance and value of flowering plants such as *Tithonia diversifolia* around sugarcane fields to attract and preserve key beneficial insects and enhance conservation biological control.

## Materials and methods

Regular surveys in sugarcane fields were conducted between 2023 and 2025 in northern Tanzania, near Moshi, at TPC Limited, a company that grows sugarcane on 8000 hectares.

Different transect lines of 100 meters were used to observe and collect natural enemies of the Yellow Sugarcane Aphid (YSA) *S. flava* (Figure 1) and the white grub *C. melolonthoides* (Figure 3) on the Mexican sunflower *Tithonia diversifolia* (Asteraceae) (Figure 2), a well-known plant originated from Central America which has many interesting uses (Jama et al., 2000). All beneficial insects observed in *T. diversifolia* were captured by sweep nets and using containers and this activity took 30 minutes. The transect were surveyed in the late morning from 9 a.m. to 12 a.m. as it was observed to be the most active period for the insects. All individuals captured were then brought to the laboratory and killed by placing them in a freezer to keep them as fresh as possible for further identification.

Figure 1. Leaf damage by the Yellow Sugarcane Aphid *Sipha flava* (left) and its common predator, the ladybug *Cheilomenes sulphurea* (middle) and its larvae (right) (photos F.-R. Goebel).

Figure 2. *T. diversifolia* bordering a sugarcane field (photo F.-R. Goebel).

Figure 3. White grub in the soil (left) and a scoliid wasp on a *T. diversifolia* flower (Photos F.-R. Goebel).

## Results and discussion

The predatory species of aphids (24 in total) hosted by *T. diversifolia* belonged mostly to family Coccinellidae (ladybugs), Syrphidae (hoverflies), Chrysopidae (green lacewings), Dolichopodidae (long legged flies) (Mace and Goebel, 2024) (Table 1). During these surveys and observations in the transects, it was also observed that the control of *S. flava* colonies was significantly increased by 86 % in the sugarcane rows adjacent to *T. diversifolia* plants compared to other fields without this plant.

Table 1. Key predatory insects captured on *Tithonia diversifolia.*

| **Coleoptera, Coccinellidae (aphid)** | **Other aphid predators** | **Hymenoptera, Scoliidae (white grubs)** |
|---|---|---|
| *Cheilomenes sulphura* | *Condylostylus* sp. (Diptera, Dolichopodidae) | *Megameris soleata* |
| *Cheilomenes propinqua* | *Ischiodon aegyptius* (Diptera, Syrphidae) | *Megameris pseudofasciatipennis* |
| *Cheilomenes lunata* | *Mesembrius* sp. (Diptera, Syrphidae) | *Campsomeriella madonensis* |
| *Exochomus concavus* | *Chrysoperla rufilabris* | *Campsomeriella caelebs* |
| *Chryptolaemus montousieri* | *Eristalis* sp. (Diptera, Syrphidae) | *Cathimeris sjoestedti* |
| *Hippodamia variegata* | *Paederus littoralis* (Coleoptera, Staphylinidae) | *Cathimeris hymenea* |
| *Scymnus frontalis* | | *Micromeriella hyalina* |
| *Scymnus suturalis* | | *Scolia ruficornis* |
| *Brumoides suturalis* | | *Scolia* sp. |
| *Harmonia axyridis* | | |
| *Chilocorus* spp. | | |
| *Parexochomus nigromaticulus* | | |

This plant also attracted a high number of scoliid wasps (250 in total during our surveys) that are well-known parasites of white grubs in Africa (Betrem and Bradley, 1971). The species *Megameris soleata* that is one of the key parasites of our pest *C. melolonthoides* represented 77.6 % of the captured scoliid wasps. Not all species have been identified so far but the work is still in progress. Observations are also being conducted on transects in different areas infested by *C. melolonthoides* to evaluate whether the proximity of *T. diversifolia* that hosts these scoliid wasps has an effect on grub control. The highest scoliid wasp species richness and diversity were observed in the transect along *T. diversifolia* hedges. Considering that the combination of several parasitoid species increases the biocontrol efficiency (Wang et al., 2019), the observed species richness of scoliid wasps in these sugarcane fields in north Tanzania could be of great interest if they attack different instar larvae as suggested by Jepson (1956).

In conclusion, this was the first study evaluating the potential of *T. diversifolia* as a banker plant for pest control in sugarcane crops (Mace and Goebel, 2024) and the work is ongoing. As a local species occurring in agricultural landscapes of Tanzania, *T. diversifolia* is considered a non-invasive plant and could be even planted around sugarcane fields of different size, which was already underlined by Donatti-Ricalde et al. (2018). However, the biodiversity of natural enemies such as parasitoids and predators has been seriously compromised in uniform sugarcane landscapes where burning and intensive practices are in place since a long time. We hope to change this by introducing and planting this type of flowering plants and shrubs around sugarcane fields to restore biodiversity and increase conservation biological control. However, this will take time as some agricultural practices have to evolve towards green harvesting and/or the use of green manure and reduction of pesticides, particularly herbicides that are routinely used for weed control.

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# Edge effects of pesticide drift in flower strips: implications for functional biodiversity and landscape design

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**Abstract:** Flower-rich off-crop habitats, such as annual or perennial flower strips, are implemented in European agricultural landscapes to promote functional biodiversity and support ecosystem services, like pollination and natural pest control. As refuges for beneficial arthropods, they are central to agri-environmental schemes. Yet, their proximity to treated crops potentially results in high exposure to pesticides, which may compromise their capacity to deliver the desired ecosystem services.

We conducted a two-year field experiment (2023-2024) in annual flower strips in Switzerland to assess acute, population and community-level responses of non-target arthropods (NTAs) to realistic drift deposition of the neonicotinoid insecticide acetamiprid. A randomized block design compared untreated plots (negative control), plots treated at an assumed field rate of 40 g a.s./ha (full-rate as positive control), and plots receiving simulated drift rates of 28 %, 1.2 %, and 0.38 % of the field rate at distances of 0-1 m, 1-3 m, and 3-6 m from the edge (drift-rate). Arthropods from multiple functional guilds were collected using sticky traps, pan traps, and suction sampling.

Simulated drift rates of acetamiprid caused significant short-term knockdown effects within the first meter of the flower strip, particularly, in parasitic Hymenoptera. Effects decreased with distance, and no persistent population- or community-level changes were detected over the season when sampling the 6-m width of the flower strip. Nevertheless, the first meter proved the most vulnerable zone to drift exposure, and its negative impacts may create a management trade-off. Full-rate applications in the positive control treatment caused clear acute and sustained declines in several taxa, confirming the sensitivity of our multi-method monitoring approach.

Our results suggest that wide flower strips (≥ 6-m) can mitigate local drift impacts. Integrating drift-exposure gradients into biodiversity risk assessment and agri-environmental planning will help to ensure that off-crop habitats achieve their intended ecosystem services.

**Key words:** insects, landscape planning, non-target arthropods, off-crop habitats, pesticide exposure, spray drift

## Introduction

A diverse community of arthropods supports essential agroecosystem functions such as pollination, natural pest control, and decomposition. Agricultural intensification, through habitat loss and use of plant protection products (PPPs), is a major driver of insect decline, with consequences for ecosystem functioning and resilience (Albaseer et al., 2025).

Flower-rich off-crop habitats, such as annual or perennial flower strips, are being established in European agricultural landscapes to increase biodiversity and support ecosystem services (Albrecht et al., 2021; Cerquera et al., 2025). Their effectiveness depends on the persistence of functional groups (e. g., parasitoids, predators, decomposers) that together sustain functional biodiversity. However, the proximity of flower strips to pesticide-treated crops exposes resident arthropods to spray drift, potentially impairing their ability to deliver ecosystem services. Despite increasing implementation of flower strips, realistic drift studies in such structurally complex habitats remain scarce, and studies quantifying responses across multiple functional groups are particularly limited.

This study assessed how realistic acetamiprid drift affects arthropod communities in 6-m wide flower strips and whether different functional groups respond differently. In addition, we evaluated how the spatial distribution of impacts informs landscape design, especially flower strip width.

## Materials and methods

### *Study site and experimental design*

A two-year field experiment (2023-2024) was conducted in annual flower strips at Tänikon, Switzerland. A commercially available seed mixture, designed to promote beneficial insects (*UFA Nützlingsstreifen SK einjährig*), was sown on 6 April 2023 and 13 April 2024. A randomized block design (four blocks in 2023; five in 2024) compared three treatments: negative control (only water), positive control (full-rate acetamiprid, 40 g a.s./ha over the whole strip), and simulated drift-rates of acetamiprid (28 % of the full-rate at 0-1 m from the strip edge, 1.2 % at 1-3 m, and 0.38 % at 3-6 m) (Figure 1). Drift concentrations were based on prior deposition measurements at the same site in 2022. Insecticide applications were performed twice per season, after sunset (19 June and 6 July in 2023; 18 June and 8 July in 2024).

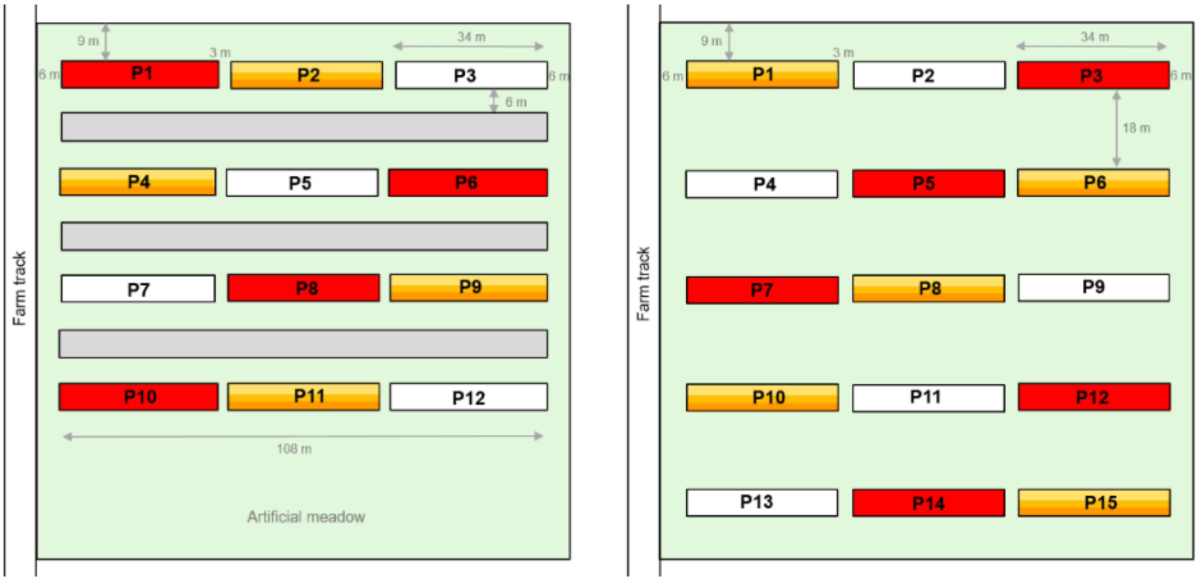


Figure 1. Experimental layout of flower strip plots in 2023 (left) and 2024 (right). Legend: Control (white), drift-rate (orange gradient), and full-rate plots (red). Grey plots represent other flower strips not included in the experiment.

### *Arthropod sampling*

Arthropods representing major functional groups were collected, covering 70 taxa including parasitoids (e. g., Braconidae, Diapriidae, Pteromalidae, Cynipoidea, Ceraphronidae), predators (e. g., Coccinellidae, Staphylinidae, Anthocoridae), herbivores (e. g., Aphididae, Cicadellidae, Chrysomelidae, Curculionidae, Thysanoptera) and detritivores (Collembola, Latridiidae, Psocoptera). Arthropods were collected using sticky traps (to quantify movement), dry pan traps (to assess knockdown – short-term mortality), and suction sampling (to monitor population responses throughout the season). Sticky and pan traps were installed before each acetamiprid application and collected the following morning. Suction sampling was conducted weekly along two transects per plot from June to August in both years. Taxa were identified at the resolution recommended by de Jong et al. (2010) and assigned to functional groups. Data were analysed in R using non-parametric tests and Generalized Linear Mixed Models (GLMMs).

## Results and discussion

### *Arthropod movement – Sticky traps*

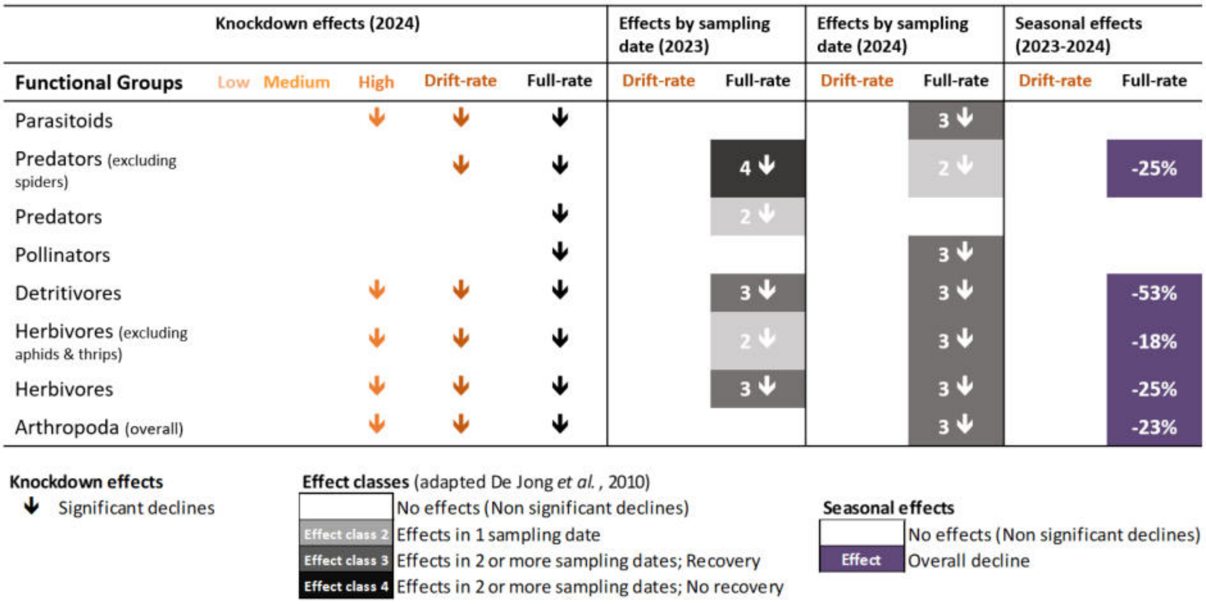
Direct overspray with acetamiprid did not lead to differences in insect movement into and out of the flower strip plots; no treatment differences were observed with sticky traps.

### *Knockdown effects (short-term) – Pan traps*

Functional groups differed in their sensitivity to drift concentrations (Figure 2). Drift exposure resulted in measurable knockdown effects in most groups, including parasitoids, detritivores, predators (excluding spiders) and herbivores, as detected by pan traps, whereas predators (including spiders) and pollinators showed no detectable short-term declines (Figure 2). Knockdown effects decreased with increasing distance, suggesting that the drift impacts were limited to the exposed edge (first meter of the flower strip). Acetamiprid at full-rate (positive control) produced strong and consistent knockdown effects across all groups.

### *Population responses (long-term) – Suction sampling*

Across the 6-m strip width, drift exposure did not reduce the overall arthropod or functional groups abundance; no persistent declines were observed by suction sampling across sampling dates or seasons. However, full-rate applications significantly reduced populations of predators, detritivores and herbivores; the predator population remained reduced at the end of the experiment in 2023 (Figure 2).



| | Knockdown effects (2024) | | | | | Effects by sampling date (2023) | | Effects by sampling date (2024) | | Seasonal effects (2023-2024) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Functional Groups** | Low | Medium | High | Drift-rate | Full-rate | Drift-rate | Full-rate | Drift-rate | Full-rate | Drift-rate | Full-rate |
| Parasitoids | | | ↓ | ↓ | ↓ | | | | 3 ↓ | | |
| Predators (excluding spiders) | | | | ↓ | ↓ | | 4 ↓ | | 2 ↓ | | -25% |
| Predators | | | | | ↓ | | 2 ↓ | | | | |
| Pollinators | | | | | ↓ | | | | 3 ↓ | | |
| Detritivores | | | ↓ | ↓ | ↓ | | 3 ↓ | | 3 ↓ | | -53% |
| Herbivores (excluding aphids & thrips) | | | ↓ | ↓ | ↓ | | 2 ↓ | | 3 ↓ | | -18% |
| Herbivores | | | ↓ | ↓ | ↓ | | 3 ↓ | | 3 ↓ | | -25% |
| Arthropoda (overall) | | | ↓ | ↓ | ↓ | | | | 3 ↓ | | -23% |

**Knockdown effects**
↓ Significant declines

**Effect classes** (adapted De Jong *et al.*, 2010)
☐ No effects (Non significant declines)
Effect class 2 Effects in 1 sampling date
Effect class 3 Effects in 2 or more sampling dates; Recovery
Effect class 4 Effects in 2 or more sampling dates; No recovery

**Seasonal effects**
☐ No effects (Non significant declines)
Effect Overall decline

Figure 2. Summary table of observed treatment effects by functional group and sampling method for drift-rate (low, medium, high) and full-rate treatments.

### *Spatial implications for functional diversity*

The first meter of flower strips acted as a vulnerable zone for sensitive groups, particularly parasitoids and detritivores, representing a management trade-off: proximity promotes biodiversity and service potential but increases drift exposure. Beyond this edge, functional diversity and community structure remained stable, indicating that the flower strip habitat acts as an effective refuge. Wide strips (6 m) in this study provided enough interior habitat to mitigate cumulative drift impacts. By contrast, narrower flower strips where most of the area lies within the exposed edge zone may fail to preserve functional services after drift events.

## Conclusions

Functional biodiversity in 6-m flower strips remained resilient under simulated acetamiprid drift but was vulnerable at the highly exposed first meter. Sensitivity differed among functional groups with parasitoids, detritivores, and herbivores being most affected, whereas predators (including spiders) and pollinators showed no measurable drift responses. Apparent stability in pollinators should be interpreted cautiously, as the sampling method underrepresents this group and may underestimate drift effects.

Wide strips (6 m) provided sufficient internal refuge to maintain functional diversity despite pronounced edge effects. Overall, insecticide drift is unlikely to undermine the general benefits of flower strips; however, it is recommended to limit drift deposition in the first meter and to incorporate drift gradients into agri-environmental planning and strip-width design to protect sensitive functional groups and maintain ecosystem service potential.

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# Proximity of complementary habitats affects natural pest control

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**Abstract:** Natural enemies of agricultural pests benefit from landscapes that provide complementary resources in diverse habitats throughout the year. Yet, the influence of landscape composition and configuration on natural pest control is poorly understood and empirical studies are often limited in scope. To address this, we developed a spatially explicit model, simulating the seasonal dynamics of predatory hoverflies and their aphid prey with various habitat types and configurations. The model incorporated woody habitats, flower strips, and an early and late crop differing in timing and type of resource availability. Woody habitat provides aphid prey and floral resources in spring and autumn, flower strips provide floral resources in summer and the two crops provide aphid prey in different periods in summer.

We demonstrate that pest suppression improves when semi-natural habitats cover a large area, with woody habitats having a larger effect than flower strips of equal size. Pest suppression further improves when crop field borders consist of flower strips as well as woody habitats, but the proximity of woody habitats is particularly critical for the early crop. Smaller crop fields strongly enhance pest control, especially when adjacent to the other crop.

Overall, the findings highlight that both habitat composition and spatial configuration can strongly influence natural pest control. Thus, designing agricultural landscapes to ensure year-round supply of essential resources for natural enemies can increase biological control and contribute to more sustainable farming systems.

**Key words:** natural pest control, complementary habitats, predatory hoverflies, aphids, floral resources, population-dynamic modelling, landscape complementation

## Introduction

Agricultural landscapes are often dominated by large fields with monocultures and few semi-natural habitats, resulting in low biodiversity and reduced ecosystem services (Schellhorn et al., 2015). One such ecosystem service is the suppression of agricultural pests by natural enemies, which depends on diverse mosaics of cropland and semi-natural areas that provide complementary resources to these enemies across seasons. Whereas empirical studies demonstrate that habitat diversity enhances natural pest suppression, the role of landscape configuration remains difficult to quantify. Modelling can offer valuable insights, especially spatially explicit models that include distances and barriers in the landscape and movement behaviour of the natural enemies.

We developed a spatially explicit model, building on our earlier, spatially implicit model of predatory hoverflies (Diptera: Syrphinae) as natural enemies of aphids, which are a major pest in arable crops (Mansier and van Rijn, 2024). Juvenile hoverflies feed and develop on aphid prey, while adults require nectar and pollen from flowers (van Rijn and Wäckers, 2016). Because these resources occur in different habitats and vary seasonally, adult hoverflies must move among them, and their survival and effectiveness can be constrained by the distances between these habitats. We therefore use our model to examine how pest control is affected by (1) habitat proportions within the landscape and (2) spatial configurations of the habitats.

## Model formulation and analysis

We assumed that adult hoverflies depend on floral resources for survival and egg production, and that they are the only dispersing and overwintering stage. Larvae rely exclusively on aphid prey, so adult females need to find aphid colonies to oviposit. To capture these resource requirements, the simulated landscape consisted of four habitat types: (1) woody habitats, providing overwintering sites, aphids specific to this habitat, and early-season flowers; (2) early crops (winter wheat), offering aphids in spring; (3) late crops (potatoes), supplying aphids (of another species) later in the season; and (4) flower strips, delivering floral resources, especially in summer. Resource availability was modelled by seasonal forcing functions based on field data, covering the cropping period from April to October. Outside this period, adult hoverflies and the aphids in woody habitat were assumed to hibernate. All functions and parameters not related to dispersal were similar to those described in Mansier and van Rijn (2024).

Adult female hoverflies were modelled as ill- and well-fed individuals searching for floral resources or aphid-rich patches for oviposition, respectively. Transitions between feeding states depended on energy expenditure and feeding rates in flower habitats. Dispersal followed simple behavioural rules on a two-dimensional grid with 5 × 5 m cells. At each time step, a fraction of hoverflies dispersed, with retention increasing with local resources: ill-fed adults were retained by flowers, well-fed ones by aphids. The dispersal probability declined exponentially with distance, with a mean dispersal distance of 50 m per day. When hoverflies were in a habitat providing the right resources for their feeding state, the dispersal was reduced to adjacent cells.

## Results

To study how the amount of semi-natural habitat influenced pest suppression, we performed simulations in a small (4 ha), simple landscape of 40 × 40 grid cells representing the four different habitats, with two crop fields and flower strips placed perpendicular or parallel to linear woody habitats. Increasing the proportion of either the flower strip or woody habitat in the landscape consistently reduced aphid densities in both the early and late crop, with stronger effects in the early crop. Parallel placement of the flower strip with the woody habitat yielded increased pest suppression in the early crop, while configuration effects were minimal in the late crop, where aphid densities were already low. The woody habitat provided overwintering sites as well as aphid prey and floral food in spring, which is particularly important for pest suppression in the early crop. The woody habitat therefore consistently resulted in better pest suppression than the flower strip. These findings show that both habitat proportion and spatial arrangement strongly shape pest control, with woody habitats playing a central role.

Subsequently, we used a larger grid (65 × 130 grid cells representing a landscape of 21 ha), consisting of two fields of 9 ha, a size typical of arable farms, as well as semi-natural habitats in various configurations. Proximity to the woody habitat was critical for pest control in the early crop, as hoverflies emerge in the woody habitat in spring and rely on its early resources. The position of the flower strip had less effect on pest control. In the late crop, pest suppression was strongest when habitats, including the crops, were arranged lengthwise (compare Figures 1 a, 1 b and 1 c), as this reduced the mean distance among them, allowing natural enemies to easily change habitats throughout the season.

We also assessed how crop field size and dispersal range influenced pest suppression. Smaller fields interspersed with flower strips and woody hedgerows consistently reduced aphid densities (Figures 1 d and 1 e). Alternating early and late crops further enhanced control (Figures 1 e and 1 f), highlighting the importance of proximity of complementary habitats. Overall, pest densities were lower with smaller fields, particularly in late crops, even when habitat proportions were similar in the landscape. This is because hoverflies failed to reach distant parts of the larger fields. Pest densities were most strongly reduced when smaller fields alternated early and late crops and were also close to woody and flower-rich habitats (Figure 1 f). Halving the hoverfly dispersal range clearly reduced pest suppression, especially in early crops, whereas doubling the range yielded only minor improvements.

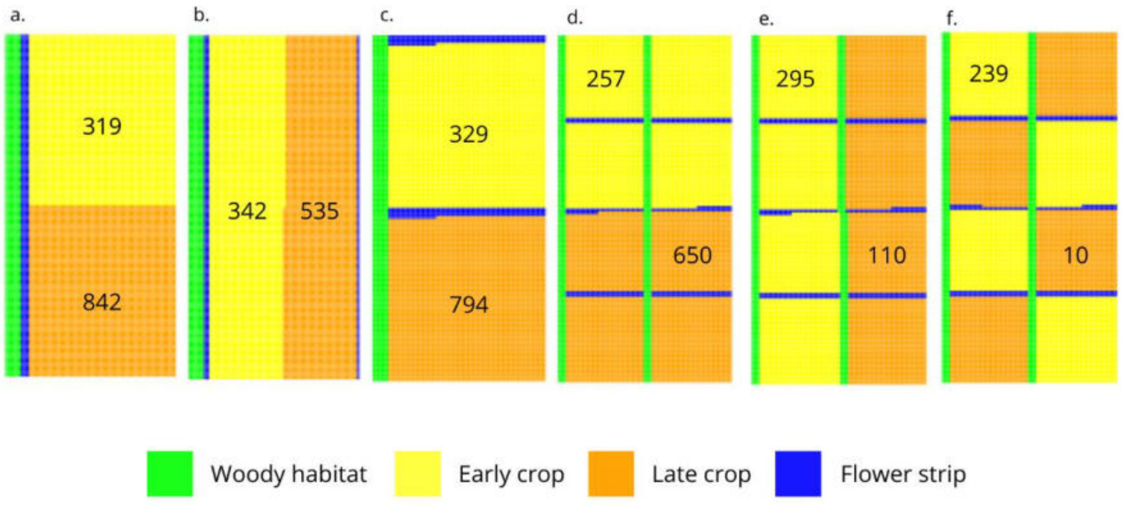

Figure 1. Examples of landscape configurations of crop fields (early and late crop) and semi-natural habitats (flower strips and woody hedgerows) on a grid of 65 × 130 cells (325 × 650 m, ca. 21 ha), all with a total cover of 43 % early crop, 43 % late crop, 5 % flower strips and 9 % woody habitat. Numbers represent the calculated yearly average aphid densities (number/m$^2$) for each crop type. Hoverflies searching for resources moved on average 10 cells/day through a landscape where opposite edges are connected, essentially simulating landscapes surrounded by similar environments.

## Discussion

We demonstrated that the spatial arrangement of habitats is important for natural pest control. The proximity of crops to woody habitat proved far more critical than to flower margins, as woody habitats provide essential resources at both the start and end of the growing season. To maximize pest suppression, landscapes should therefore be designed following three rules: (a) woody habitats positioned close to all other habitats to sustain natural enemies throughout the year; (b) early crops and flower strips adjacent to late crops; and (c) smaller fields with alternating early and late crops. These rules highlight the importance of tailored landscape designs for sustainable agriculture.

Our model focused on a specific landscape with early and late crops, flower strips, and woody habitats. This two-crop design illustrates how habitat combinations and arrangements can support natural pest control when complementary habitats are available across space and time. Results may differ in landscapes with less functional semi-natural habitats. In reality, aphid populations are attacked by several natural enemy species, but other species like lacewings and parasitoid wasps depend on floral resources in similar ways as hoverflies, so modelling them would likely yield comparable results. Whereas the importance of nearby flower strips and woody habitat is confirmed by many empirical studies (Crowther et al., 2023; Alignier et al., 2014; Dainese et al., 2017), the importance of nearby complementary crops is rarely documented (Schellhorn et al., 2015) and urges for further research.

## Acknowledgements

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# Enhancing carabid beetle populations: insights from an agroecological experiment at landscape scale

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**Abstract:** There is an important need to experiment agroecological farming at the landscape scale in order to decipher and account for key ecological processes occurring at scales larger than the field. This is especially relevant for understanding how mobile functional biodiversity delivering key services to agriculture can be enhanced. Such landscape-scale experimentation is the main aim of the INRAE CA-SYS platform created in 2018 where pesticide-free "nature-based" and highly diversified arable cropping systems are implemented and evaluated, on a spatially continuous block 125 ha of arable crops and ecological infrastructures (10 % of the area is planted with grass/flower strips and hedgerows). This innovative design was mobilized to explore the role of the spatial arrangement of contrasted cropping systems and flower strips on carabids. We found that no-till fields were the preferential overwintering habitat during carabid emergence peak. We also observed some redistribution of circulating carabids among habitats. The area of no-till fields within a 100 radius increased the abundance of circulating adults of most dominant carabid species, notably with tilled fields. The area of flower strips in the surroundings had a comparable positive effect for some species, suggesting that they can act as a temporary refuge and source.

**Key words:** Agroecology, cropping systems, conservation agriculture, tillage, flower strips, carabids, emergence trap

## Introduction

There is a global urge for designing and adopting new farming systems, that reduce pesticide use and rebuild biodiversity friendly landscapes. There is mounting evidence that agroecological cropping systems can enhance natural pest control at the field level but the effects can be strongly modulated by the landscape context (Petit et al., 2020). Providing guidelines for future redesign requires understanding the interactions between semi-natural habitats and the crop mosaic at larger spatial scales (Jeanneret et al., 2021) and upscaling the experimentation of agroecological farming and biodiversity-based options to the landscape scale (Petit et al., 2018).

## Experimenting agroecology at a landscape scale

The CA-SYS (Co-designed Agroecological SYStem experiment) platform is a collaborative research platform aiming at addressing those challenges by experimenting agroecology at the landscape scale. It aims to design and evaluate innovative agroecological systems, to develop methods to study the transition towards agroecology and understand the ecological processes underlying the functioning of agroecological systems. The experiment started in 2018 after 5 years of consultation and co-codesign with farmers, advisors, technicians, engineers, teachers and researchers, which are still involved in the life of the platform, via workshops on specific themes or visits, to benefit from their expertise. This open science approach ensures that the experiment is ambitious yet feasible, aligned with researchers' and farmers' questions.

CA-SYS experiments cropping systems inspired of two broad agroecological strategies, one relying on occasional soil tillage (TS, akin to organic farming) and the other more on no-till (SD, akin to conservation agriculture). The CA-SYS experimental design includes the spatial arrangement of cropping systems, with three distinct 'zones', one composed of TS fields another with only SD fields and a third "mixed" zone in which TS and SD fields are mixed.

We experiment pesticide-free arable cropping systems (based on wheat, barley and oil seed rape), purposely highly disruptive to compel the production of knowledge and innovation (Jacquet et al., 2022) for farming systems relying on the ecosystem services provided by planned and associated biodiversity (e. g., nutrient cycling, pest control, pollination, biodiversity conservation). Two pesticide-free cropping systems are tested: ploughed cropping systems ("TS"; occasional ploughing, with or without N fertilization) and minimum tillage cropping systems ("SD"; conservation agriculture or shallow tillage and rotational no-till). These cropping systems are implemented in a coherent landscape design strategy resulting in a mosaic of one to three hectares surrounded by a dense network of ecological infrastructures (grass and flower strips, tree lines, covering 10 % of the 125 ha of CA-SYS). This spatial design, composed of a "ploughed" zone, a "minimum tillage" zone, and a "mixed" zone in between (Figure 1), has been thought to study the spatio-temporal dynamics of pests and beneficial organisms at the field and landscape levels, and the effect of a homogeneous landscape vs. a composite landscape of farming practices on biological regulation processes.

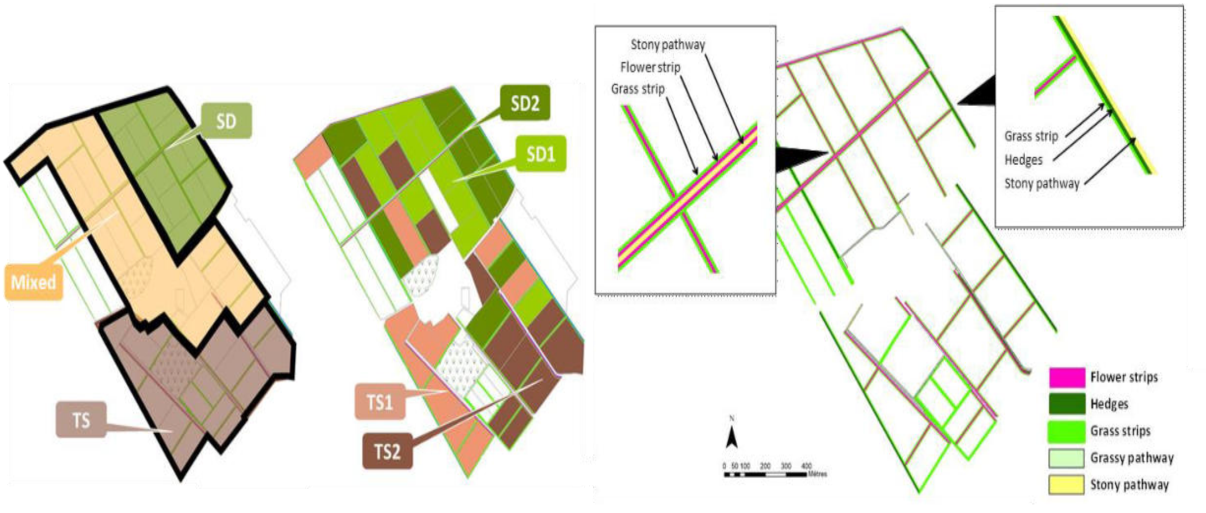

Figure 1. Experimental design of the CA-SYS platform. TS cropping systems in brown are ploughed systems, SD cropping systems in green are minimum tillage systems. There are three zones within the farm: a SD zone, a TS zone and a mixed zone where TS fields and SD fields are mixed. SD1 = direct seeding system, SD2 = shallow non-inversion tillage system, TS1 = fertilized ploughed system, TS2 = unfertilized ploughed system.

## Case study: the spatio-temporal dynamics of carabid beetles

This original CA-SYS design was mobilized to evaluate the spatio-temporal dynamics of carabid communities, which are key generalist pest predators in arable agriculture. Carabid monitoring was conducted in 17 flower strips and adjacent winter-sown crop fields in two parallel transects 20 m apart starting in flower strips toward the field interior (Figure 2). Overwintering carabids were sampled using two 0.36 $m^2$ emergence traps per field or flower strip, containing inside a pitfall trap (diameter 8.5 cm) and a bottle at the top of the tent. Besides, circulating adult carabids were sampled with a classic pitfall trap at 5 meters aside from the emergence trap. Overall, the design included 68 emergence traps and 68 pitfall traps active across 9 sessions of measurements from March 1st to July 4th, 2023. We captured a total of 5792 overwintering carabids (55 species) and 10585 circulating adults (48 species).

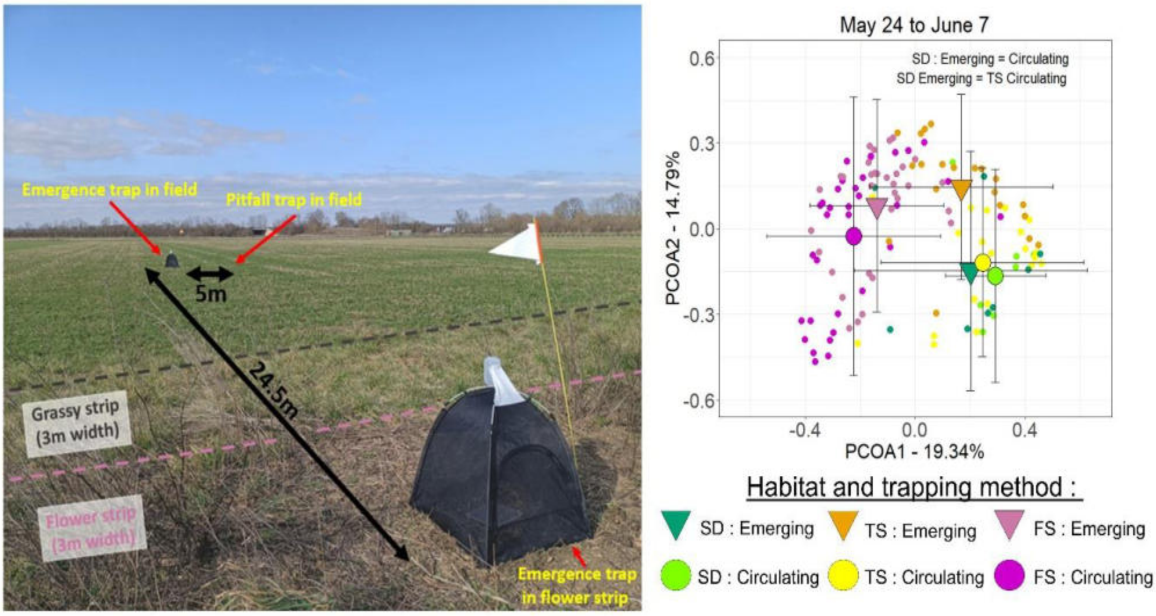

Figure 2. Left: view of one of the two transects established in each of the 17 sampled fields Right: PcoA of the taxonomic composition of emerging (cumulative) and circulating carabid communities during the 24th May to 7th June session. Absence of significant difference (PERMANOVA) are indicated on the top-right.

Densities of emerging carabids was of 478 ± 544 ind/$m^2$ in SD fields, 273 ± 157 individuals/$m^2$ in TS fields and 116 ± 58 individuals/$m^2$ in flower strips. Although no significant effect of habitat types on overall density was detected ($p = 0.06$), the interaction between habitat type and sampling session was significant ($p < 0.001$). Carabid emergence increased since early May and was higher in SD fields than in the other habitat types until mid-June ($p < 0.05$), and higher in SD and TS fields than in flower strips from mid-June to crop harvest ($p < 0.05$). Concerning community composition, we tested the hypothesis that spill-over between the three habitat types would differ according to the spatial distribution of habitats. During the 24th May to 7th June session (Figure 2), the carabid circulating communities in TS fields were similar to the overwintering communities of SD fields, suggesting a redistribution between fields. Moreover, we also found that some dominant circulating carabid species benefitted from an increased proportion of SD fields within a 100-m radius. The area of SD enhanced the activity-density of *Brachinus crepitans* and *Pterostichus melanarius*, but only within TS fields. When considering the area of flower strips, we found an increased activity of *Poecilus cupreus* (two common species of cropped habitats) in TS fields while decreasing the activity of *Pseudophonus rufipes* in SD fields.

Our results confirm the importance of within-field habitats for arthropod overwintering in agricultural landscapes and also reveal a marked beneficial effect of pesticide-free and minimum tillage-based farming, through the provision of high-quality overwintering sites for and as source habitat from which individuals redistribute to other habitat types.

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# Session Landscape management of the agricultural mosaic

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# Prioritizing options of plant diversification across scales to control multiple pests: insights from a theoretical approach

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**Abstract:** Designing agroecological farming systems and landscapes that effectively reduce pest emergence, spread and damage has become crucial for sustainable crop production. Plant diversification is a solid pathway to enhance agroecosystem resistance and resilience, and encompasses multiple management options, including within-field diversification strategies (e. g., cultivar mixture) and landscape-level strategies (e. g., crop diversity). However, managing crop health in a systemic way is challenging as multiple mechanisms to control multiple pests operate across spatial and temporal scales. The theoretical framework we propose aims to improve our understanding about the efficiency of combinations of plant diversification options to limit risks related to pests. We suggest a trait-based framework linking pest functional traits to the ecological processes that influence their dynamics, including resource use, dispersal, and host specialization. This mechanistic approach seeks to move beyond taxonomic descriptions toward a predictive understanding of pest responses to plant diversification options. Building on this framework, we developed a computational tool that allows users to produce a prioritized list of relevant plant diversification options based on simple pest traits through logical rules grounded in a mechanistic understanding of pest control. This innovative, integrated approach aims to connect ecological theory and applied pest management, fostering predictive strategies for sustainable agroecosystems.

**Key words:** insect pests, weeds, diseases, agroecology, functional traits, conceptual framework

## Introduction

Human drivers of environmental changes, including land-use changes and high levels of pesticide use, can strongly influence natural communities and trigger highly variable species responses, from extinction to invasion. These divergent outcomes highlight opportunities to manage species dynamics through targeted management strategies. However, predicting how species will respond to human-driven environmental change remains a major challenge (Gaüzère et al., 2025).

Pest outbreaks, comprising weeds, pathogens and arthropods both in soil and air, are a major issue for agricultural productivity (Savary et al., 2019). Many studies have shown the control effects of plant diversification options (that are based on using a greater variety of plant species and their spatial and temporal arrangement) on a given pest by reducing crop accessibility and/or interrupting pest life cycles (Ratnadass et al., 2012; Tamburini et al., 2020; Beillouin et al., 2021; Bellone et al., 2023). However, few have examined their joined spatiotemporal effects although their deployment is recommended on a landscape scale, that is at the nexus of local agronomic and ecological constraints (pedoclimatic, biogeographical) and agricultural socio-economic issues (local outlets, farm cooperatives, regional policies) (Vialatte et al., 2025). Managing multiple crop pests in a mosaic of crops requires tools that enable prioritization of plant diversification options.

Trait-based approaches are increasingly seen as valuable methods for understanding the assembly, structure, and thus the delivered ecological functions of communities (Green et al., 2022). They have the potential to shift our understanding from taxon-specific case studies to a more general, mechanistic, and predictive framework. Here, we present a trait-based framework designed to investigate how multiple crop pests, including arthropod pests, weeds and diseases, respond to various plant diversification management options.

## Materials and methods

### *Conceptual framework*

We developed a mechanistic, trait-based framework to investigate how plant diversification options influence pest functional responses across spatial and temporal scales. The framework explicitly links diversification-induced heterogeneity to pest functional responses through ecological mechanisms. The central assumption of the framework is that pest responses to plant diversification depend on the match or mismatch between pest functional traits and the spatial and temporal scales at which diversification modifies resource distribution, host detection, dispersal pathways, and microclimatic conditions.

### *Plant diversification options*

Plant diversification can be implemented through multiple options, which operate at different spatiotemporal scales. We considered ten types of diversification options based on the typology proposed by Vialatte et al. (2025), which differ in terms of spatial scale (intra-field, field, landscape); temporal scale (crop season or pluriannual); level of plant diversity (intraspecific or interspecific); and type of vegetation considered (cultivated or semi-natural). These options are arranged along a dual spatial and temporal gradient and include intra-field diversification such as varietal mixture and intercropping, field-level diversification like crop rotation, and landscape-level strategies such as preserving or introducing semi-natural habitats and crop diversity. Each diversification option is hypothesized to alter resource availability, resource detection, and microclimatic conditions at particular spatial and temporal scales, which thereby affect pest individuals, populations, or metapopulations depending on their characteristics.

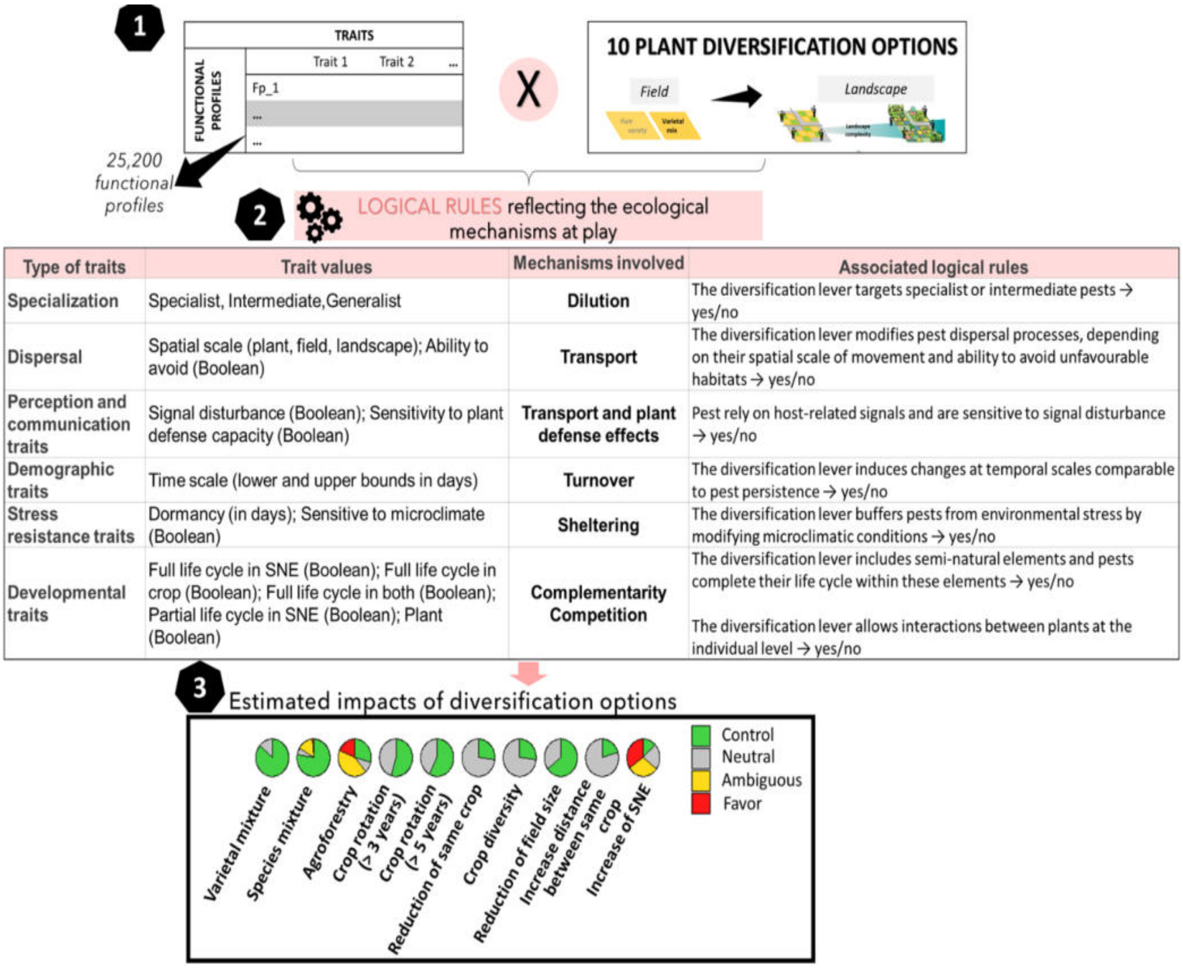
### *Pest functional traits*

Pests were described in terms of functional traits related to resource use, dispersal, and life cycle. These included host specialization, generation time, dispersal ability, spatial operating range, perception of host cues, sensitivity to microclimatic conditions, and dormancy capacity. We expressed trait values using lower and upper bounds for spatial and temporal scales, reflecting the minimum and maximum expected movement or dispersal distances (plant, field, landscape) and duration (in days) over which individuals or populations actively operate under favorable conditions, excluding dormant states. Dormancy potential was recorded to indicate the maximum expected persistence in non-active forms (e. g., spores, quiescent eggs, seeds) across seasons or unfavorable conditions. We also characterized the degree of host specificity (specialist, intermediate, generalist, e. g., Fried et al., 2010). Other traits were encoded as binary attributes representing the presence or absence of biological capacities, such as perception of host signals, ability to avoid structural barriers, sensitivity to signal disturbance, sensitivity to microclimate, or capacity to complete all or part of the life cycle within crops or semi-natural elements. Trait values were assigned based on published literature, expert knowledge, and known biological mechanisms, with consistency checks across taxonomic groups (Figure 1). We simulated the response of 25,200 functional profiles, representing all potential unique combinations of trait values (Figure 1).

### *Simulation of the effects of plant diversification options*

For each functional profile, we evaluated the potential effects of each plant diversification option by applying a set of logical rules that translate trait–environment interactions into ecological mechanisms (Figure 1). These mechanisms include spatial dilution of host resources, disruption of host detection and movement, allelopathic interference, competitive interactions, temporal turnover of habitats, habitat complementarity, and microclimatic sheltering. Each mechanism was activated only when the spatial and temporal scales of the diversification option overlapped with the operating ranges of the considered pest traits (Figure 1). For example, fine-scale spatial heterogeneity was assumed to negatively affect specialist pests with limited dispersal and strong reliance on host cues through resource dilution and disruption of host detection. Conversely, diversification options involving semi-natural elements could favor pests capable of exploiting complementary habitats or benefiting from buffered microclimatic conditions at appropriate spatial scales.

For each diversification option and functional profile, effects were evaluated and classified as having a negative (control), positive (favor), ambiguous, or neutral effect on pest, depending on the mechanisms activated and the traits involved (Figure 1).



| Type of traits | Trait values | Mechanisms involved | Associated logical rules |
|---|---|---|---|
| **Specialization** | Specialist, Intermediate,Generalist | **Dilution** | The diversification lever targets specialist or intermediate pests → yes/no |
| **Dispersal** | Spatial scale (plant, field, landscape); Ability to avoid (Boolean) | **Transport** | The diversification lever modifies pest dispersal processes, depending on their spatial scale of movement and ability to avoid unfavourable habitats → yes/no |
| **Perception and communication traits** | Signal disturbance (Boolean); Sensitivity to plant defense capacity (Boolean) | **Transport and plant defense effects** | Pest rely on host-related signals and are sensitive to signal disturbance → yes/no |
| **Demographic traits** | Time scale (lower and upper bounds in days) | **Turnover** | The diversification lever induces changes at temporal scales comparable to pest persistence → yes/no |
| **Stress resistance traits** | Dormancy (in days); Sensitive to microclimate (Boolean) | **Sheltering** | The diversification lever buffers pests from environmental stress by modifying microclimatic conditions → yes/no |
| **Developmental traits** | Full life cycle in SNE (Boolean); Full life cycle in crop (Boolean); Full life cycle in both (Boolean); Partial life cycle in SNE (Boolean); Plant (Boolean) | **Complementarity**<br>**Competition** | The diversification lever includes semi-natural elements and pests complete their life cycle within these elements → yes/no<br>The diversification lever allows interactions between plants at the individual level → yes/no |

Figure 1. Framework linking plant diversification options to pest responses. (1) Pest functional traits table and plant diversification options operating at field and landscape scales. (2) Diversification effects are evaluated based on pest functional profiles and logical rules translating trait-environment interactions in ecological mechanisms (3) These mechanisms generate pest responses, classified as control (green), neutral (grey), ambiguous (yellow), or favor (red).

## Results and discussion

The control effect emerged as the dominant response across the explored functional space, indicating that plant diversification generally has a high potential to enhance pest regulation (Figure 2). This figure should be interpreted as an illustrative example of model outputs used to explore and compare the effects of diversification levers across contrasted pest functional profiles. Other metrics, such as response archetypes derived from the similarity of multilever responses, can be investigated within the same framework, but are not detailed here.

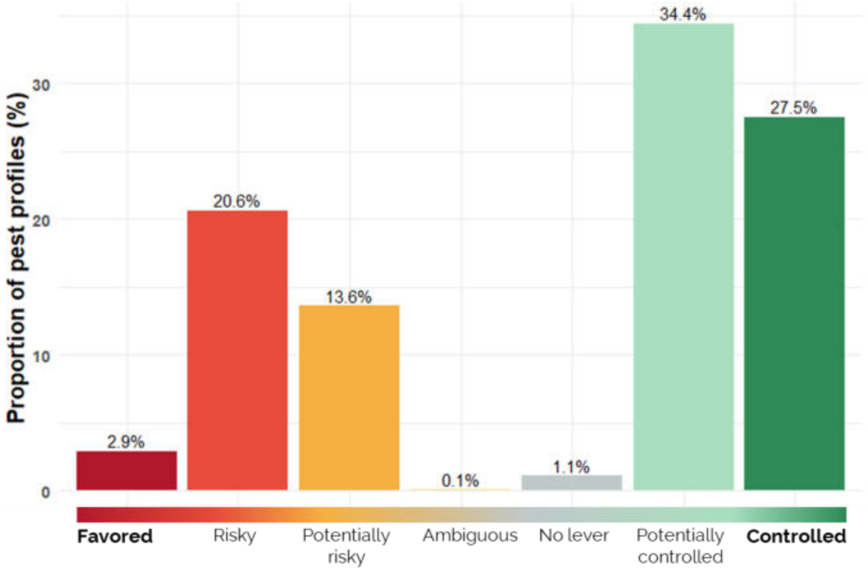


Figure 2. Example of possible output of pest responses to all plant diversification levers, aggregated as a proportion of functional profiles in risk categories, colored from red (favored) to green (controlled). Favored: at least one lever favors the functional profile, possibly with neutral effects, but no ambiguous effect; Risky: functional profiles showed both favored and ambiguous effects; Potentially risky: functional profiles were both controlled and favored by different levers; Ambiguous: only ambiguous effects, possibly with neutral effects; No effect: only neutral effects detected; Potentially controlled: at least one lever mitigated functional profiles and at least one lever produces an ambiguous effect; Controlled: at least one lever mitigated functional profiles without ambiguous or favored effects.

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# Identifying landscape targets for effective conservation biological control in arable landscapes: insights from an ecological – economic simulation and machine learning analysis

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**Abstract:** Conservation biological control (CBC) is promoted as an alternative to pesticide-based pest management, but its effectiveness depends strongly on the agroecological and economic context. We use the spatially-explicit, dynamic ecological – agronomic – economic model of Martinet and Roques (2022) to quantify CBC at a landscape for more than 400 k parameter combinations. Using clustering on profit gain and treatment frequency index reduction, we isolate "high-performing" landscapes. We then train Random Forests to identify the combinations of ecological and agronomic parameters that characterise them. The analysis highlights the key role of economic and agronomic drivers in the successful CBC, in addition to usual ecological drivers. These results will be used to identify empirical 'agricultural region–crop – pest – enemy' case studies where CBC can credibly support pesticide reduction without undermining profitability, and match them with effective policy tools.

**Key words:** conservation biological control, ecological – economic model, landscape heterogeneity, non-crop habitat, pesticide policy, machine learning (Random Forest)

## Introduction

Intensive agriculture and the simplification of farmland mosaics have led to major declines in biodiversity in agroecosystems and a weakening of natural pest regulation. In most arable systems, pest control relies mostly on pesticides, despite evidence of environmental and health externalities and social demand to reduce their use. Conservation biological control (CBC), which aims to enhance pest regulation by managing habitats that support natural enemies, is often cited as a promising strategy for reconciling crop protection with biodiversity conservation. Yet empirical results remain highly variable, and the conditions under which CBC can actually deliver substantial reductions in pesticide use without jeopardising farm income are still poorly understood.

A key difficulty is that the actual realisation of the biological control ecosystem service depends on the joint configuration of ecological processes, agronomic context and economic decisions at the landscape scale. Most existing assessments are ex post and system-specific, making it hard to derive general rules for policy design. In particular, there is little guidance on which agroecological contexts are likely to generate robust CBC benefits.

In this work, we build on the generic model of Martinet and Roques (2022), which couples a spatial and dynamic predator–prey system with profit-driven land-use and pesticide choices, to explore a large space of possible agroecological contexts. By simulating more than 3.3 M landscapes that differ in agronomic, ecological and economic parameters, we quantify the contribution of CBC to agricultural profit and pesticide use by systematically comparing scenarios with and without natural enemies. We then apply clustering to identify "high-performing" landscapes, where CBC significantly increases profit *or* reduces pesticide use, and Random Forest methods to characterise the corresponding agroecological contexts. This can inform the design of landscape management strategies aiming at reducing pesticide-use.

## Materials and methods

### *Ecological – agronomic – economic landscape model*

The model of Martinet and Roques (2022) simulates a landscape described as a regular lattice of fields. Each cell is characterised by a soil quality index that determines potential crop yield and is assumed to be spatially heterogeneous. At any date, each cell can be allocated either to non-crop habitat (NCH), pesticide-free cropland, or cropland treated at medium or high pesticide-intensity levels. NCH provides no output but hosts the natural enemy population.

Modelled farmers are profit maximisers. Given current prices, subsidies and taxes, each field-level decision is based on expected profit, defined as crop revenue minus production and pesticide costs, plus or minus policy transfers. To modify economic incentives, three types of policy instruments are combined: a unit tax on pesticide use, a per-hectare subsidy for NCH (interpreted as permanent grassland or semi-natural habitat), and a price premium for pesticide-free crops. Farmers differ only through the soil quality of their fields, and they update land-use and pesticide choices annually, according to their expectations on pest outbreaks.

Pest and natural enemy populations change continuously in space and time according to coupled reaction–diffusion equations. The pest follows a logistic growth with diffusion across the lattice, while the enemy preys on the pest following Lotka – Volterra type interactions, and diffuses too. Pesticide applications reduce pest density, but also affect natural enemy survival. NCH cells provide refuge and reproduction habitat for the enemy but no resource for the pest.

### *Simulation design*

We perform a large numerical experiment by sampling agronomic, ecological and economic parameters over 2916 agroecological contexts, in 72 economic contexts, replicated 8 times under 2 anticipation scenarios. Agronomic parameters include the mean and variance of soil quality and an index of spatial fragmentation. Ecological parameters govern pest intrinsic growth, predation rate, and pest and enemy diffusion coefficients, as well as pesticide-induced mortality of the enemy. Economic parameters include the levels of the pesticide tax, the NCH subsidy, the pesticide-free price premium, and the degree to which farmers anticipate the long-run benefits of CBC in their decisions. This leads to about 3.36 million runs.

For each parameter set, we run the model over a multi-year horizon to simulate two scenarios: a baseline without natural enemies (pest only) and a CBC scenario with natural enemies. All other parameters, including policies, are held constant across the two scenarios, so that differences in outcomes can be attributed to CBC.

### *Performance indicators*

For each simulation, we compute two landscape-scale indicators, averaged over space and time: *Agricultural profit*, defined as the sum of farmers' profits net of pesticide tax revenues and NCH subsidies. The CBC contribution is measured as the difference in profit between the CBC and baseline scenarios. *Treatment frequency index* (TFI) for pesticides, defined as the average number of full-dose applications per hectare of cropland in the landscape. The reduction in TFI between scenarios captures the pesticide-saving potential of CBC.

***Identification of high-performing landscapes and corresponding agroecological parameters***
We use K-means clustering on the two indicators (profit gain, TFI reduction) to classify all simulated landscapes into performance groups and identify cluster(s) characterizes by a significant gain in profit and a substantial reduction in TFI ("high-performing" landscapes).

To identify the agroecological conditions associated with these landscapes, we train Random Forest (RF) classifiers that predict cluster membership from ecological, agronomic and spatial parameters only (excluding policy instruments). We compute variable-importance measures and partial dependence plots to quantify the marginal effects of each parameter and their interactions on the probability of being in the high-performing cluster. We also extract decision paths from the ensemble of trees to derive simple "if – then" rules linking ranges of key parameters to a high likelihood of effective CBC at the landscape scale.

## Results and discussion

Across the full set of simulations, the effect of CBC on profit and pesticide use is generally modest, as shown in Figure 1 (density distributions on the left; 2-dimensional plot on the right).

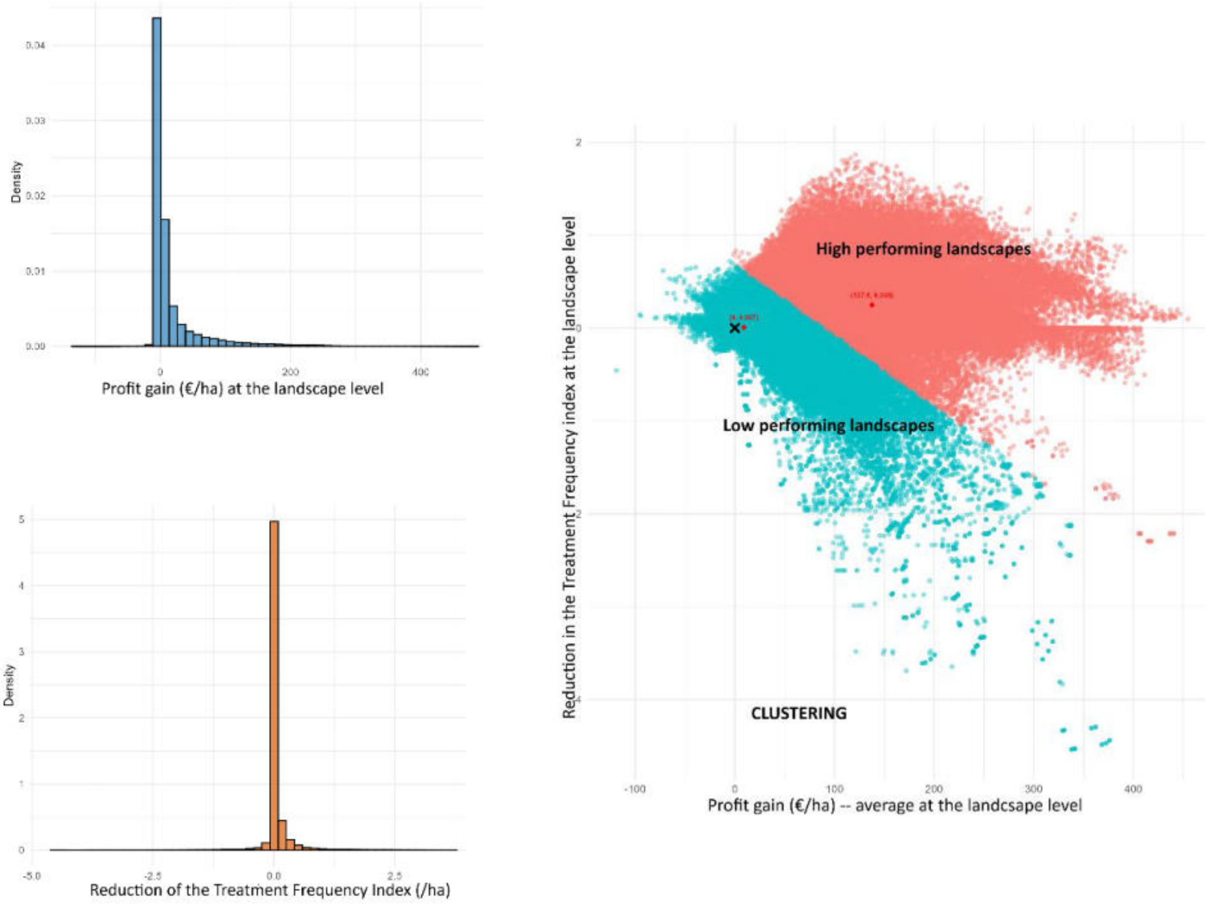

Figure 1. Left: landscape performance distribution (profit; TFI reduction); Right: clustering

Averaged over all parameter combinations, the mean profit gain from CBC is about 18 €/ha/year over the whole landscape (+ 6 %) and the mean reduction in treatment frequency index (TFI) is only 0.04 units (-2.7 %), with large variance and many cases where changes are close to zero. This confirms that, in a generic setting, CBC is far from automatically delivering large "win – win" outcomes. K-means clustering allows us isolating two typical landscape types. Most landscapes fall into a low-impact cluster with small average profit gains (≈ 9 €/ha/year) and quasi-negligible TFI reductions. By contrast, a much smaller "high-performing" cluster combines sizeable profit gains (+ 137 €/ha/year) with substantial pesticide reductions (-0.25 TFI). High-performing contexts therefore exist but represent only about 6 % of all simulated landscapes, highlighting that effective CBC is a rare outcome in the parameter space.

Comparing parameter values between clusters shows that these high-performing landscapes share a coherent set of ecological and agronomic traits. They exhibit moderate mean soil quality but higher soil heterogeneity; lower pest intrinsic growth; higher predation rates; and, crucially, much lower pesticide-induced mortality. This means that successful CBC emerges only in contexts in which the pesticide is not very efficient, in agricultural regions that are both not too productive (otherwise, the incentive to treat is too high) and heterogeneous (i. e., with some low quality land, used as non-crop habitat favoring the natural enemies). In such cases, landscapes are dominated by pesticide-free cropland (55-60 %) and keep highly treated parcels to a small fraction of the area, while maintaining important share of non-crop habitats (NCH) in a rather aggregated configuration. In other words, strong CBC emerges in moderately fertile, heterogeneous landscapes where pesticides are relatively ineffective and used sparingly, and where NCH form connected refuges for natural enemies.

The use of a RF algorithm trained on ecological and agronomic parameters alone confirms these results. Variable-importance analysis, partial-dependence plots and two-dimensional plots confirm that pesticide mortality is the dominant driver of CBC success, followed by soil heterogeneity and predation rate, while pest growth rate and mean soil quality play a secondary role, and diffusion/fragmentation parameters matter little in isolation. We also extracted interpretable "if – then" rules summarising combinations of parameter ranges associated with high success to define stylised "landscape targets" and link them to public policy mixes.

Introducing farmer anticipation of CBC sharpens these patterns. When producers account for predation in their decisions, the share of pesticide-free cropland in the high-performing cluster increases further, profit gains and TFI reductions become larger on average. The RF's precision improves, while the ranking of key drivers remains unchanged.

Overall, these results point to a fairly demanding view of CBC. In our stylised model, large, landscape-level reductions in pesticide use without profit loss are not the norm but occur in a restricted subset of contexts combining low pesticide efficiency and substantial landscape heterogeneity. In highly intensive systems with very effective pesticides, CBC rarely delivers sizeable gains. This conclusion is necessarily conditional on the simplifying assumptions of the model, and the empirical relevance of the proposed "landscape targets" needs to be tested against real crop–pest–enemy systems. But it suggests that conservation CBC is a credible alternative to reduce pesticide-intensive control without strong policies only in specific cases.

## Acknowledgements

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# Analysing and predicting the impact of agroecological practice expansion on natural pest control in agricultural landscapes

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**Abstract:** Designing agroecological landscapes promoting ecosystem services, such as natural pest control, represents a promising avenue for limiting the environmental footprint of agriculture. However, the consequences of large-scale deployment of agroecological practices (AP) on natural enemy communities and pest infestation levels remain poorly investigated, resulting in uncertain predictions. Using multiple case studies (e. g. vineyards, apple orchards, maize and wheat crops) in the Nouvelle-Aquitaine region (France), this PhD thesis will explore the consequences of the large-scale deployment of AP on the structure of multi-trophic natural enemy communities and the level of pest control service. The main objectives are (i) to quantify and rank the effects of key environmental and biotic drivers of natural enemy assembly, biological control potential and pest pressures at the field and landscape scales, and (ii) to assess and compare the predictive ability of innovative statistical models designed to forecast the consequences of different scenarios of land-use change on natural pest control at the regional scale. The originality of this work lies in several aspects, notably in: (i) developing an integrative, multi-scale approach to natural pest control; (ii) explicitly quantifying the causal relationships between environmental changes, natural enemy community structure and the level of pest control; and (iii) developing predictive approaches to help design functional landscapes minimizing pesticide dependency.

**Key words:** Community ecology, landscape ecology, agricultural landscapes, agroecological crop protection, biodiversity and agroecosystem functioning

## Introduction

Conventional pesticides have been central to crop protection but their widespread use generates substantial environmental costs. This has driven growing interest in agroecological approaches that aim to sustain crop yields while reducing environmental impacts by managing ecosystem services (e. g., Bommarco et al., 2013). Natural pest control (NPC), a key ecosystem service delivered by multiple natural enemies (i. e., predators and parasitoids), is central to conservation biological control which seeks to enhance natural enemy communities through habitat and landscape management. A core principle is the adoption of agroecological practices (AP) that reduce disturbance at field and landscape scales (Begg et al., 2017). However, the importance and interaction of the main drivers of NPC in agricultural landscapes remain unclear.

### *Relationship between natural pest regulation and biodiversity at multiple trophic levels*

Recent evidence indicates that ecosystem functioning is enhanced by biodiversity across multiple trophic levels (Buzhdygan and Petermann, 2023). There is growing empirical support for positive effects of multitrophic diversity on NPC, however the diversity-NPC relationship remains highly idiosyncratic and context dependent. In real-world ecosystems, NPC arises from complex and often poorly understood interactions among natural enemies and other trophic groups (Albert et al., 2022). To date, most studies have focused on species richness while considering other aspects of community structure (e. g., dominance, functional diversity, trait distribution) and composition (e. g., species identity) should improve our mechanistic understanding of the relationships between multitrophic diversity and NPC (van der Plas, 2019). We hypothesized that investigating the impacts of increased multitrophic diversity, considering both taxonomic and functional aspects, should provide a better mechanistic understanding of the processes shaping NPC in agricultural landscapes.

### ***Consequences of the landscape-scale expansion of agroecological practices on natural pest regulation***

Abiotic filters such as land-use intensity strongly shape local community assembly and ecosystem functioning (van der Plas, 2019). More heterogeneous landscapes generally support a greater diversity of natural enemy communities and reduce the build-up of specialist pests (Martin et al., 2019). At the field scale, management intensity also influences interaction networks between pests, predators and other trophic groups (e. g., Macfadyen et al., 2009). Although AP such as organic farming and crop diversification often enhance biodiversity and NPC locally, their effects when expanded across the landscape remain poorly understood (Petit et al., 2020). Existing knowledge is largely derived from studies in the field of biodiversity conservation and have produced inconsistent results (e. g., Kleijn et al., 2006). On the one hand, the benefits of AP for NPC may scale up as AP expand through additive or synergistic effects on top-down (e. g., lower habitat disturbance and increased resources and refuges for natural enemies) and on bottom-up mechanisms (e. g., increased plant diversity leading to dilution effects and disruption of host location). On the other hand, AP expansion may increase pest outbreaks through the widespread relaxation of chemical control or the increase in resource availability for generalist pests, or have neutral consequences due to cancelling effects of positive and negative processes. Additionally, we might observe non-linear responses with maximal NPC at intermediate levels of AP cover, as reported for semi-natural habitat effects on pest dynamics (Martin et al., 2019). To date, existing evidence remains sparse and inconsistent (Petit et al., 2020) which may be due to unaccounted changes in community structure, trophic interactions, and interactions between landscape and field-level management intensity. Moreover, most existing studies come from landscapes where AP are scarce, potentially underestimating their net effects (Petit et al., 2020). A more integrative, mechanistic framework is therefore required to assess how AP expansion could benefit NPC, and in which contexts (Brusse et al., 2024).

### ***Using predictive approaches for anticipating the effects of land-use changes on natural pest regulation***

Most NPC studies rely on explanatory statistical models which have improved our understanding of how environmental changes, community structure and pest control interact. However, we lack an integrative framework able to predict how future changes may alter agricultural landscape functioning. Spatially explicit predictive approaches are needed to forecast NPC potential, identify mismatches between pest control supply and demand, and inform landscape planning (Maes et al., 2012). Developing such models is challenging because NPC is contingent on a wide range of environmental and biotic factors, and because AP effects are predominantly studied at field scales (Alexandridis et al., 2021). Advancing predictive frameworks that integrate biotic interactions, management intensity and landscape configuration is therefore a critical step toward anticipating the consequences of land-use change on NPC at broad spatial scales.

## Summary of research objectives

This PhD project will focus on the use of observational datasets from different sites in the Nouvelle-Aquitaine region (France), including community data across multiple trophic groups with levels of pest infestation and predation rates. The general design is built on sampling pairs of organic/conventional fields selected along two orthogonal landscape gradients: % agroecological farming and % semi-natural habitats (SNH).

***Research axis 1-A: Investigating the impacts of multitrophic diversity on natural pest control***
Using multi-year landscape monitoring data in vineyards, we aim to investigate how the relationship between multitrophic diversity and natural pest control (NPC) – and potentially crop yield – is shaped by: (i) different aspects of multitrophic diversity (taxonomic, functional); (ii) potential interactions between multiple trophic groups (e. g., plants, alternative prey, arthropod natural enemies, higher-order vertebrate predators); and (iii) land-use intensity at the field (farming system) and landscape level (% SNH cover, % organic field cover), either directly or indirectly through changes in the food web or in specific trophic groups. We will use a multi-scale and multivariate approach to assess potential causal pathways of interest and gain a more mechanistic understanding of the links between community structure and pest suppression in a real-world ecosystem. Main hypotheses: We expect higher overall multitrophic diversity to promote NPC, following the niche complementarity hypothesis, despite the emergence of potential antagonistic interactions and trophic cascades. We also expect land-use intensity to negatively affect NPC by homogenising communities in the overall food-web (Barnes et al., 2014; Dainese et al., 2017).

***Research axis 1-B: Exploring the effect of land-use changes on natural enemy communities and natural pest control in agricultural landscapes***
To determine under which conditions AP expansion (i.e. amount and configuration) could generate positive or negative effects on NPC, we will explore how AP expansion interacts with semi-natural habitat heterogeneity and field-level management to shape NPC through direct and indirect processes (i. e., mediated by changes in natural enemy communities, e. g., richness, evenness, functional diversity). Main hypotheses: We expect AP amount to generate cumulative positive effects on natural enemy diversity and NPC levels. This effect is likely modulated by (i) AP spatial arrangement as well as (ii) land-use intensity at the landscape and field levels (characterized by, e. g., SNH cover, field farming system, pesticide use). We expect that benefits of AP expansion on NPC may decrease when fields implementing AP are either too dispersed or aggregated in the landscape. We also expect intensive management to reduce NPC by homogenising natural enemy communities at the landscape scale, while local farming intensity could dampen positive effects of AP expansion on NPC (Brusse et al., 2024).

***Research axis 2-A: Assessing the predictive ability of multiple statistical models on natural pest control***
We will build, evaluate and compare the predictive performance of spatially explicit models forecasting pest pressure and natural pest control (NPC) in agricultural landscapes. We will develop an innovative and integrative landscape-scale modelling framework that combines environmental (e. g., land cover and land use data, pesticide use and climatic context) and biotic

predictors (pest and natural enemy occurrence data) across spatial scales, drawing on two complementary data sources: (i) a long-term but spatially limited dataset with detailed species and farming management information, and (ii) regional or national datasets with broader spatial coverage but coarser species and management data. Models may include crop yield to allow joint predictions of NPC and agronomic performance. To capture scale-dependent drivers of NPC, we will use hierarchical and joint species distribution models (jSDMs) that account for natural enemy interactions (i. e., co-occurrence patterns).

***Research axis 2-B: Exploring the consequences of various land-use strategies on natural pest control at the regional scale***

Drawing from results obtained in previous axes, we will use the best-performing model from Axis 1-B to: (i) assess the combined effects of various climate and land-use change scenarios on NPC at the regional scale, focusing on semi-natural habitat (SNH) management and agroecological practices (AP) expansion; and (ii) identify potential areas of mismatch between NPC demand and supply to inform landscape planning decisions. First, we hypothesize that scenarios increasing landscape complexity and expanding AP will support NPC by supporting diverse natural enemies, reducing reliance on synthetic pesticides. Second, although climate warming is likely to weaken NPC, increased landscape heterogeneity and AP expansion are expected to partially buffer these negative effects, notably by promoting response diversity among natural enemy communities (Feit et al., 2021).

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# Seasonal and habitat dynamics of parasitoid Hymenoptera in forest fragments and adjacent sugarcane fields

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**Abstract:** Although hymenopteran parasitoids play a key role in biological control, their responses to seasonal and habitat variation in agricultural landscapes remain poorly understood. Here, we evaluated temporal and spatial patterns in parasitoid abundance, family richness, and community composition in forest fragments and adjacent sugarcane fields in southeastern Brazil. Relationships between forest and sugarcane parasitoid communities were analyzed. Sampling was carried out quarterly using yellow pan traps that were placed four times a year (August, November, February and May) in ten forest fragments and ten adjacent sugarcane fields. Half of the forest fragments were gallery forests, characterized by greater vegetation complexity, and the other half were plateau type forests showing higher disturbance (cutting, wildfires, liana invasion). Generalized linear mixed models revealed that both parasitoid abundance and family richness were higher in forest fragments than in sugarcane fields, and higher in gallery forests compared to plateau fragments. Parasitoid abundance varied seasonally, with significantly lower abundance in November. Parasitoid community composition also showed significant temporal changes, while neither habitat nor fragment type influenced composition. Additionally, parasitoid abundance in forest fragments showed a marginal positive relationship with abundance in adjacent sugarcane fields, but the relationship depended on season and forest type, being stronger in gallery forests. Our results demonstrated that vegetation structure and seasonality are key determinants of parasitoid dynamics in agricultural landscapes of SE Brazil. Forest fragments, particularly structurally complex gallery forests, act as reservoirs for parasitoid communities, emphasizing the role of forest quality in sustaining ecosystem services.

**Key words:** biodiversity conservation, ecosystem services, natural enemies

## Introduction

The expansion of intensive agricultural land use has led to the loss and fragmentation of natural habitats, with strong impact on arthropod biodiversity and associated ecosystem services (Liu et al., 2018). Parasitoid Hymenoptera, key natural enemies in agroecosystems, are particularly sensitive to habitat disturbance (Jonsson et al., 2012; Heraty, 2017). Natural habitats such as forest fragments in agricultural landscapes may act as refuges that sustain parasitoid communities and enhance biological control (Decocq et al., 2016; Yang et al., 2022). However, the relations between forests and crop fields are still not well understood.

Here, we studied habitat-related and seasonal changes in parasitoid communities in forest fragments and adjacent sugarcane fields. Specifically, we aimed to: (1) assess the effects of seasonality and habitat type on parasitoid community composition; (2) examine patterns of abundance and richness; and (3) evaluate whether parasitoid communities in sugarcane fields are influenced by those in nearby forest fragments.

## Materials and methods

### ***Study sites***

The study was conducted between 2023 and 2024 in ten Atlantic Forest fragments and their adjacent sugarcane fields in Jaboticabal, São Paulo, Brazil. Five fragments were classified as plateau forests, and five as gallery forests located along watercourses. Plateau fragments showed greater grass, shrub and liana cover, whereas gallery fragments were dominated by trees and legally protected as Permanent Preservation Areas (PPAs). Adjacent sugarcane fields were harvested by early July. The regional climate is classified as Aw (Köppen – Geiger), with dry winters and a rainy season from October to March.

### ***Insect sampling***

Hymenoptera were sampled quarterly after sugarcane regrowth in August and November 2023, and in February and May 2024. Two yellow pan traps (42 × 28 × 8 cm) per habitat (forest and sugarcane), were placed 15 m apart and 5 m from the habitat edge. The traps, filled with water and a detergent, were left for 48 h in the field. Specimens were identified to family level and only parasitoid taxa were retained for analysis.

### ***Data analysis***

All analyses were run in R statistical software. Parasitoid abundance and family richness were analyzed using GLMMs (glmmTMB) with negative binomial error distribution, including habitat, fragment type, and month as fixed effects and block (including forest fragment and adjacent field) as a random effect. To assess whether parasitoid abundance in forest fragments influenced abundance in sugarcane fields, we fitted additional GLMMs including forest abundance, month, and fragment type as fixed effects and block as a random effect. Model assumptions and dispersion were checked using DHARMa package. Differences in community composition were tested with PERMANOVA (999 permutations restricted by Plot) based on Bray – Curtis dissimilarity. Homogeneity of dispersion was tested with betadisper.

## Results and discussion

### ***Parasitoid abundance and family richness***

Parasitoid abundance was significantly influenced by habitat ($\chi^2 = 7.49$, p = 0.006), fragment type ($\chi^2 = 8.25$, p = 0.004), and month ($\chi^2 = 9.45$, p = 0.024). Abundance was consistently lower in sugarcane fields than in forest fragments, and lower in plateau compared with gallery fragments. The lowest values occurred in November (Figure 1).

Patterns for richness mirrored those observed for abundance, with significant effects of habitat ($\chi^2 = 10.07$, p = 0.002), fragment type ($\chi^2 = 7.97$, p = 0.005), and month ($\chi^2 = 8.26$, p = 0.041). Richness was reduced in sugarcane fields and in plateau fragments, with minimum values recorded in November.

### *Community composition*

Parasitoid community composition differed significantly between months (F = 2.12, p = 0.001), but not between habitats (p = 0.222) or fragment types (p = 0.273).

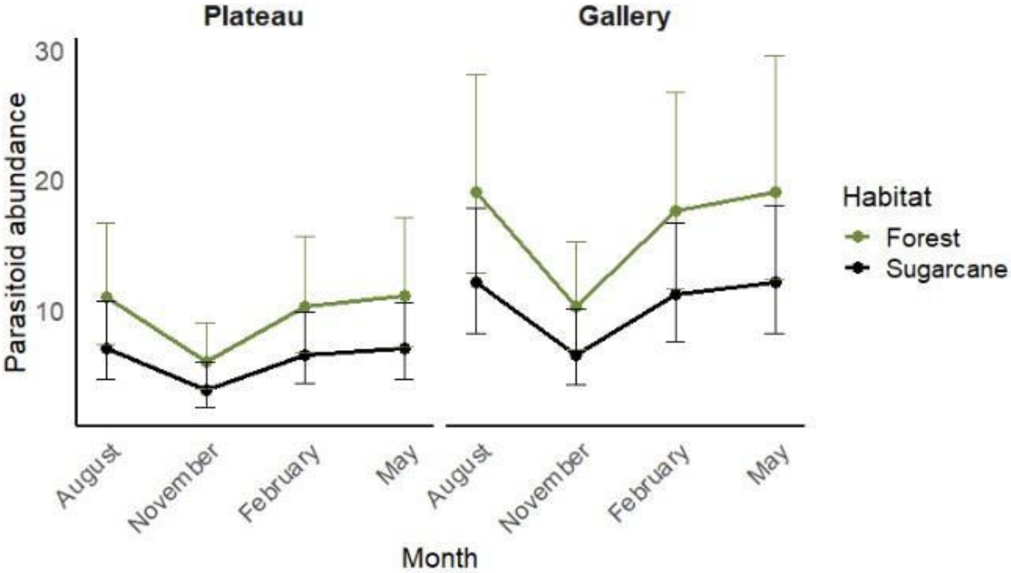

Figure 1. Temporal variation of parasitoid abundance (± 95 % CI) and effects of habitat type (forest fragments vs. sugarcane fields).

The higher abundance and richness of parasitoids in forest fragments compared to sugarcane fields, combined with the overall similarity in community composition between habitats, reinforce the importance of natural habitats for sustaining parasitoid populations in agricultural landscapes. Seasonal variation in parasitoid abundance was high, with the lowest values in November. This decline was most likely the result of reduced host availability. The dry season lasts until October, and sugarcane shows therefore limited regrowth after harvest, resulting in fewer resources for herbivores. Although increasing temperature and rainfall-induced plant regrowth usually increase insect activity in November, the drop from August to November may indicate delayed recolonization or limited movements of the small-bodied taxa (Yan et al., 2024). Host phenology may also contribute to increased parasitoid abundance, as pests such as *Diatraea saccharalis* (Lepidoptera: Crambidae), and *Saccharicoccus sacchari* (Hemiptera: Pseudococcidae), reach peak abundance at the end of the rainy or early in the dry season (Borges Filho et al., 2019). Parasitoids often synchronize their emergence with host availability (Aranda and Graciolli, 2015).

### *Forest – sugarcane relationship (spillover)*

Parasitoid abundance in forest fragments showed a marginally significant relationship with abundance in adjacent sugarcane fields ($\chi^2 = 3.078$, $p = 0.079$), indicating a limited but detectable spillover effect. Fragment type significantly influenced parasitoid abundance in sugarcane ($\chi^2 = 7.235$, $p = 0.007$), with gallery forests showing higher spillover than plateau fragments (estimate = -0.623 ± 0.232) (Figure 2). Spillover also varied across months ($\chi^2 = 14.169$, $p = 0.003$), reflecting seasonal changes in movement or habitat use.

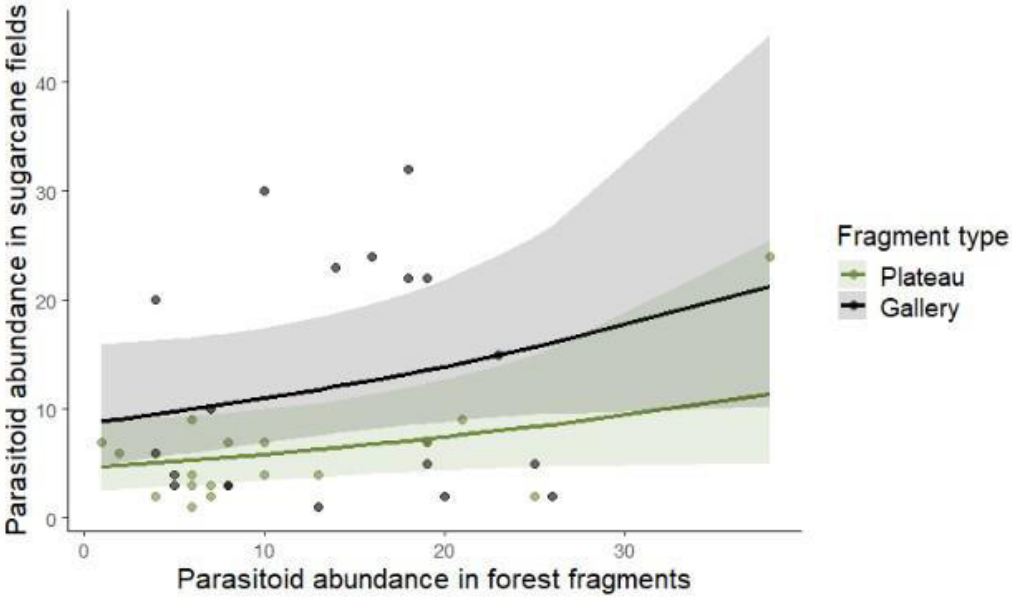

Figure 2. Relationship between parasitoid abundance in forest fragments and adjacent sugarcane fields with 95 % confidence intervals.

Our results suggest that parasitoid communities in forest fragments and sugarcane fields are similar, but movements between habitats depend on fragment quality and seasonal dynamics. The consistent advantage of gallery fragments highlights that both presence and quality of forest remnants drive the potential contributions of parasitoids to biological control in adjacent crop fields (Oliveira et al., 2025).

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# Habitat mediates pest control provided by birds using nest boxes in winegrape vineyards

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**Abstract:** Agricultural expansion threatens biodiversity, but integrating insectivorous birds into vineyard ecosystems may support both conservation and ecosystem services. We tested how nest boxes and habitat composition influence avian abundance and pest abundance in Napa Valley vineyards. Using a before-after-control-impact (BACI) experiment across 20 sites, we examined whether nest boxes increased the abundance of Tree Swallows (*Tachycineta bicolor*) and Western Bluebirds (*Sialia mexicana*), two functionally important insectivores. During the 2023 and 2024 breeding seasons we conducted avian point counts, sampled key pest and beneficial arthropods, and collected fecal samples from adults and nestlings at sites to detect vineyard pest DNA in diets. Nest boxes significantly increased swallow and bluebird abundance within one year. Swallow responses were strongest near the installed nest boxes, whereas bluebirds increased vineyard wide. Arthropod models indicated that pest counts declined farther from riparian zones after boxes were added, emphasizing the role of landscape management on ecosystem function. We found no clear evidence that nest boxes altered natural enemy dynamics. Importantly, vineyard pest DNA was detected in a subset of samples, confirming consumption of target pests by both swallows and bluebirds. Collectively, these results show that nest boxes can rapidly attract avian predators that have potential to reduce pests away from riparian edges.

**Key words:** nest boxes, insectivorous birds, viticulture, biological control, DNA metabarcoding, landscape management

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# Predatory mite communities in productive and abandoned terraced vineyards of the Cinque Terre National Park

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**Abstract:** Terraced vineyards in the Cinque Terre National Park (Italy) are embedded in a steep Mediterranean landscape where the role of viticultural management in sustaining biodiversity and biological control is still poorly quantified. This study assessed how vineyard status (productive, PRO vs abandoned, ABA) and cultivar traits influence predatory mite (Phytoseiidae) communities and their potential prey (Tetranychidae, Eriophyidae, Tydeidae, thrips, scale insects). Seven terraced sites were sampled in spring and autumn from 2020 to 2023, with one to three local cultivars (Albarola, Bosco, Vermentino) per site. At each sampling point, 25 leaves were collected for each combination of site × vineyard status × cultivar × season × year, and predator densities were analysed using Generalized Linear Models.

Across 2,325 leaves, 7,652 predatory mites belonging to 17 species were recorded. Productive vineyards hosted markedly higher phytoseiid densities than abandoned ones (3.8 vs 1.5 individuals per leaf; $p < 0.001$), and predator–pest ratios were much higher in PRO (≈ 22:1) than in ABA (≈ 7:1), indicating enhanced top-down control potential under active management. Among sites, the PRO vineyard Groppo showed highest phytoseiid densities than the reference site ($p < 0.001$), whereas Corniolo and Manarola, characterised by inter-row herbicide use and bare soil, hosted significantly lower predator densities, suggesting a negative effect of ground-cover simplification on canopy predator communities. However cultivar did not significantly influence total Phytoseiidae density in the same GLM ($p = 0.10$), suggesting that cultivar effects mainly emerge at the level of species composition.

Species-level patterns revealed clear microhabitat filtering. High-trichome Albarola promoted niche partitioning and the co-occurrence of *Phytoseius finitimus* and *Kampimodromus aberrans*, whereas glabrous cultivars (Bosco, Vermentino) were dominated by *Typhlodromus pyri*. In productive vineyards, Pearson correlations suggested partial segregation between *T. pyri* and *K. aberrans* ($r \approx -0.3$), consistent with microhabitat segregation on glabrous leaves. The less frequent phytoseiid species occurred almost exclusively in abandoned vineyards, which thus act as reservoirs of biodiversity. Overall, the coexistence of productive and abandoned terraces, combined with cultivar-specific leaf morphotypes, appears to support both the persistence of biological control services and landscape-level ecological resilience in this terraced Mediterranean viticultural system.

Terraced vineyards in the Cinque Terre host rich phytoseiid assemblages and high predator – prey ratios, indicating strong intrinsic biological control potential. Under these conditions, intensive conventional management appears partly redundant and may erode key natural enemy communities. Moving towards lighter, more sustainable practices (i. e., grass cover) would preserve these antagonists and is consistent with the EU Biodiversity Strategy 2030.

**Key words:** leaf microhabitat, ecosystem services, biological control, local grape cultivars

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# Influence of landscape-scale farming practices on diversity and community weighted mean (CWM) body size of predatory arthropod communities in permanent grasslands

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**Abstract:** Agricultural intensification and landscape simplification are major drivers of biodiversity loss in permanent grasslands, with profound consequences for predatory arthropod communities and associated ecosystem services. This research investigates how local management practices, landscape heterogeneity, and landscape-scale farming intensity jointly shape both taxonomic and functional dimensions of arthropod diversity. Ground-dwelling predators (spiders, carabid beetles, rove beetles, and chilopods) were sampled in 18 permanent grasslands in northeastern France during spring and autumn. Taxonomic α and β diversity were analyzed alongside functional structure using community-weighted mean body size metrics. Multivariate analyses identified independent gradients of local intensity, land-cover composition, and landscape-wide farming practices. α diversity was primarily driven by grassland cover in spring and by local nitrogen inputs in autumn. In contrast, β diversity and species turnover were strongly influenced by landscape-scale farming intensity, indicating environmental filtering processes. Functional analyses revealed that intensive managed landscapes, particularly those with high herbicide and fungicide use, favored communities dominated by larger-bodied predators, leading to functional imbalances. Overall, these findings highlight that agricultural intensification affects not only species composition but also functional traits critical for biological control, underscoring the need to integrate land-use composition and farming intensity into biodiversity-friendly management strategies.

**Key words:** agricultural intensification, predatory arthropods, landscape-scale management, taxonomic and functional diversity, biological pest control

## Introduction

Agricultural intensification has profoundly altered grassland ecosystems, contributing to widespread declines in farmland biodiversity and ecosystem functioning. Permanent grasslands play a key role in sustaining predatory arthropod communities that support essential services such as biological pest control (Stenberg et al., 2021; Zhang et al., 2007). While the effects of local management practices on arthropod diversity are relatively well documented, the influence of farming intensity at the landscape scale remains insufficiently understood (Brusse et al., 2024; Marrec et al., 2022). Moreover, most studies have focused on taxonomic metrics, often overlooking functional dimensions that directly mediate ecosystem services. Functional traits such as body size can provide mechanistic insights into community responses to environmental pressures and their consequences for trophic interactions (Maurey et al., 2025). Understanding how local and landscape-scale agricultural practices jointly shape both taxonomic and functional diversity is therefore critical. In this context, this study investigates the relative contributions of local management, landscape composition, and landscape-wide farming intensity to the structure of predatory arthropod communities in permanent grasslands.

## Materials and methods

Ground-dwelling arthropods were sampled in 18 permanent grasslands in spring (May) and autumn (September) 2021 using pitfall traps. Local environmental conditions were characterized by vegetation vigor and farming practices at the field scale. Vegetation vigor was quantified using the Normalized Difference Vegetation Index (NDVI), calculated from Sentinel-2 satellite imagery for each sampling period. Farming practices were documented through farmer surveys and included mowing frequency and height, livestock load, and nitrogen inputs. Landscape heterogeneity was assessed within a 500-m radius buffer around each grassland, using five metrics: grassland and crop proportions, crop diversity, mean field size, and wood grain. Landscape-scale farming intensity was quantified using standardized surveys conducted with 39 farmers across 180 fields (Maudet et al., 2025). Six farming management components were calculated: herbicide, insecticide, fungicide, fertilization, tillage, and mowing/grazing intensity. Arthropod abundance-activity and species richness were analyzed using generalized linear models with quasi-Poisson distributions. Community β diversity was assessed using Bray – Curtis and Sørensen dissimilarity indices. For functional analyses, adult arthropod body size was classified into 20 classes using fuzzy coding to account for intraspecific variability. Community-weighted mean (CWM) values were computed for each size class and cumulatively fitted to sigmoid curves, from which median body size ($x_0$) and size distribution steepness ($k$) were extracted as descriptors of functional community structure.

## Results and discussion

***Effects of local and landscape variables on taxonomic diversity***

Taxonomic α diversity of predatory arthropods varied markedly across seasons and spatial scales (Figure 1). In spring, species richness and abundance-activity were primarily driven by landscape composition, with a strong positive effect of grassland proportion in the surrounding landscape. This pattern highlights the importance of habitat availability and continuity for early-season colonization processes. In contrast, autumn α diversity was mainly influenced by local management intensity, particularly nitrogen inputs, suggesting cumulative effects of fertilization on vegetation structure and resource availability. These seasonal shifts emphasize that local and landscape drivers act in a complementary and temporally dynamic manner.

β diversity analyses revealed that landscape-scale farming intensity was a determinant of community turnover (Figure 1). High-intensity landscapes promoted compositional homogenization, consistent with environmental filtering mechanisms that favor a restricted set of tolerant species. However, a substantial proportion of unexplained β diversity suggests that stochastic processes, dispersal limitation, or unmeasured habitat features may also contribute to community assembly.

***Functional responses of arthropod communities to farming intensity***

Beyond taxonomic patterns, functional analyses revealed pronounced shifts in community body size structure along gradients of landscape-scale farming intensity (Figure 1). Cumulative community-weighted mean body size distributions showed that intensive landscapes were characterized by lower median body size ($x_0$) and steeper distribution slopes (k). These patterns indicate a dominance of smaller-bodied predators and a reduced contribution of large-sized taxa. Such functional simplification may result from differential sensitivity of larger arthropods to pesticide exposure or habitat disturbance.

The predominance of smaller predators in intensive landscapes may alter trophic interactions and reduce functional complementarity within communities. As body size is closely linked to prey range (Maurey et al., 2025) and predation dynamics, these functional imbalances could compromise the stability and effectiveness of biological pest control.

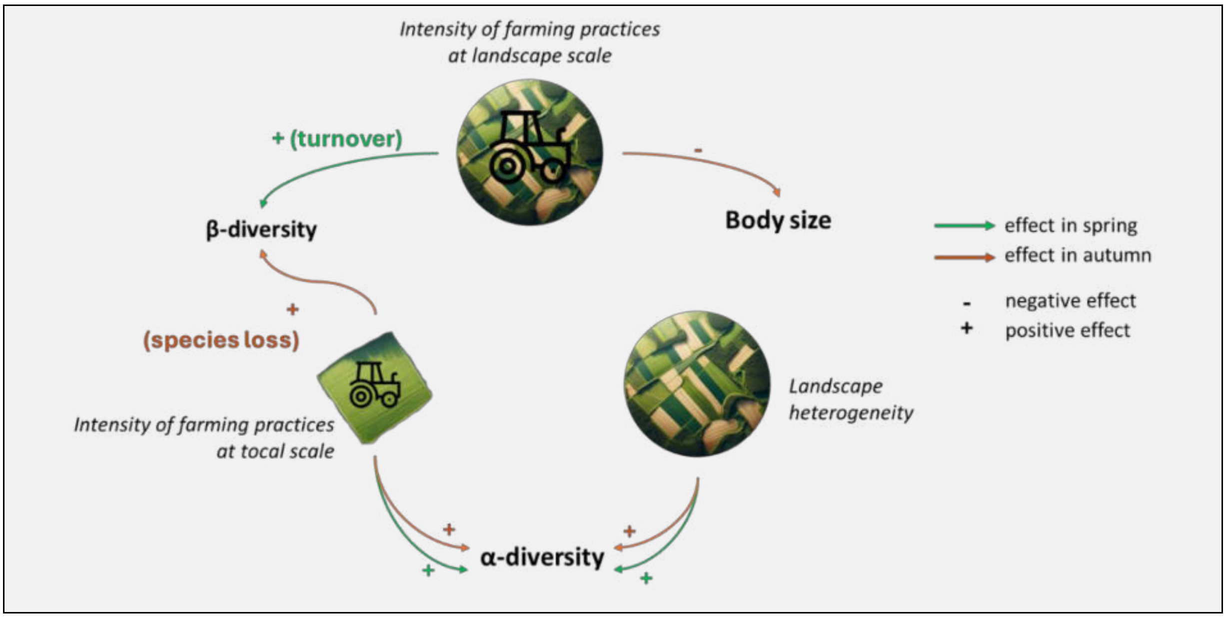

Figure 1. Summary of the influence of landscape-scale farming practice intensity, land-cover heterogeneity, and local intensity on arthropod communities in permanent grasslands.

### *Implications for biodiversity conservation and ecosystem functioning*

Together, these results demonstrate that agricultural intensification affects predatory arthropod communities not only by reducing species diversity but also by reshaping functional trait distributions. Importantly, landscape-scale farming practices exerted stronger and more consistent effects on β diversity and functional structure than local management alone. This highlights the need to move beyond field-scale conservation measures and to incorporate landscape-level regulation of farming intensity. Integrating land-cover heterogeneity with reduced chemical inputs at the landscape scale may therefore be critical to maintaining both taxonomic and functional diversity, and the ecosystem services they underpin, in permanent grasslands.

## Acknowledgements

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# Non-target effects of exclusion nets on pests in apple orchards

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**Abstract:** Alternative pest management strategies can produce non-target effects on pests, yet these effects remain poorly understood. Apple orchards face strong pest pressure, with the codling moth, the rosy and woolly apple aphids, and the Mediterranean pine vole among the most damaging species. In recent years, Alt'Carpo nets, which are highly effective against the codling moth, have become widely used in French apple orchards. Understanding how this practice influences target and non-target pest species is crucial for preventing damage and ensuring sustainable orchard management. From 2021 to 2023, we monitored key pests in 46 commercial organic apple orchards, with and without nets, within the Lower Durance Valley in southeastern France. Our surveys showed that nets exert not only local effects, but also broader landscape effects by redistributing populations of some pests. A higher proportion of netted orchards in the landscape increased codling moth and rosy apple aphid pressure in unnetted orchards, while reducing the presence of voles in those same orchards. Conversely, the presence of a net locally tended to buffer the orchard from landscape effects.

**Key words:** exclusion nets, apple orchards, integrated pest management, pests, landscape effect, non-target effect

## Introduction

In recent years, increasing pest resistance to insecticides, combined with growing concerns about their negative impact on human health and environment has driven the development of several alternative control methods. While the non-target effects of synthetic plant protection products are well documented (Serrão et al., 2022), those of alternative biocontrol methods remain comparatively unexplored (Howarth et al., 2000). In addition, their potential impacts at the landscape scale also remain largely unknown (Petit et al., 2020).

Among these alternatives, Alt'Carpo exclusion nets provide effective control of the codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae), a major pest of apple orchards (Romet and Séverac, 2008). The nets are typically closed after apple flowering (mid-late April) to avoid interfering with pollination and are opened for harvest (September-November depending on the variety). Full-block nets enclose the entire orchard, whereas single-row nets cover individual tree rows. Early trials reported a drastic reduction in fruit damage (with infestation rates limited to 0.2 %), alongside a substantial decrease in insecticide use (approximately 7-8 fewer applications per season) (Chouinard et al., 2016).

These promising results promoted their gradual adoption: from 150 hectares of netted apple orchards in 2008 to 2000 hectares in 2014 (Alaphilippe et al., 2016). As these nets have become widespread, new questions arise regarding their ecological impacts and potential non-target effects on other pests, particularly at the landscape scale.

## Materials and methods

### *Study area*

Between 2021 and 2023, we monitored 23 pairs of organic apple orchards in the Lower Durance Valley, a 490 km² region in southeastern France, one of the major apple-producing areas[1] (Poinas et al., 2025). Each monitored pair consisted of one orchard without net and a nearby orchard equipped with nets.

To assess landscape effects of nets, we used 2020-2021 aerial photographs from the IGN[2] to map the presence of nets within a 1-km radius around each monitored orchard. Across these landscapes, the proportion of orchard area covered by nets (hail nets and Alt'Carpo) ranged from 3 % to 73 %. Hail nets, which have larger mesh and open sides, were also taken into account in the analysis.

### *Pest monitoring*

Each year, surveys were carried out along two transects per orchard: one located on an edge row, and the other in the center. Rosy apple aphid (*Dysaphis plataginea*) and woolly aphid (*Eriosoma lanigerum*) presence on shoots were recorded at their peak infestation (respectively, end of May and end of June). Codling moth (*Cydia pomonella*) fruit damage was assessed at the end of the first generation (late June-early July). During the same period, the presence of scab (*Venturia inaequalis*) on fruits and of scab and powdery mildew (*Podosphaera leucotricha*) on leaves was also recorded. In October, diapausing codling moth larvae were counted in band traps wrapped around tree trunks. For Mediterranean pine voles (*Microtus duodecimcostatus),* 114 orchards (including 80 organic orchards) were monitored from 2020 to 2025, and the number of vole tumuli was recorded along each transect in spring, summer and autumn.

## Results and discussion

### *Local effects of nets*

Our analyses showed that Alt'Carpo nets were not only effective against codling moth, but also reduced the likelihood of rosy apple aphid infestation (Table 1), with a strong effect observed in 2022 and 2023 but not in 2021, a year of exceptionally high aphid pressure. Although the mesh is large enough for aphids to pass through, the nets could obscure visual cues, limiting recognition and recolonization of apple trees in autumn when they are still in place. Alternatively, the reduction in aphids could result from increased activity of some natural enemies under the net.

In contrast, voles were more abundant in netted orchards, but only under hail nets or Alt'Carpo full-block nets that enclosed the entire orchard (as opposed to single-row nets). This increase might result from reduced predation on voles when the orchard is fully covered.

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[1] https://site-atelier-basse-vallee-durance.fr/

[2] https://www.geoportail.gouv.fr/

No effect was detected on woolly aphids, which are present year-round on apple trees and whose infestation levels remained very low during the study period. Similarly, the nets had no significant impact on scab and powdery mildew.

Table 1. Results from the models evaluating the local impact of an Alt'Carpo net on pests. Significance is given as the following: NS $p \geq 0.05$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Odds ratios provide a measure of effect size. When the odds ratio is below 1, 1/odds ratio provides the risk reduction in the occurrence of an event, while an odds ratio exceeding 1 represents the risk increase. For example, the Alt'Carpo net reduces the risk of encountering codling moth fruit damage by a factor of 10 (1/0.10) and divided by 5 (1/0.20) the number of codling moth larvae.

| | **Estimate** | **Standard error** | **Odds ratio** | **P-value** | **Significance** |
|---|---|---|---|---|---|
| **Codling moth damage** | -2.29 | 0.41 | 0.10 | $4.22 \times 10^{-6}$ | *** |
| **Codling moth larvae** | -1.63 | 0.50 | 0.20 | $1.26 \times 10^{-3}$ | ** |
| **Rosy apple aphid** | -1.19 | 0.53 | 0.31 | 0.025 | * |
| **Woolly aphid** | -0.10 | 0.82 | 0.92 | 0.907 | NS |
| **Scab** | -0.39 | 0.89 | 0.68 | 0.666 | NS |
| **Powdery mildew** | -0.49 | 0.31 | 0.61 | 0.116 | NS |

### ***Effects of net coverage in the landscape***

When there was an effect of net coverage in the landscape, only orchards without net were affected (Figure 1), suggesting that nets insulate orchards from landscape influences. In unnetted orchards, the population dynamics in response to net coverage deviated from the patterns observed for local effects of net. For example, while nets reduced codling moth damage, an increasing proportion of netted orchards in the landscape (within 1 km) resulted in higher damage in unnetted orchards (Figure 1). In our study area, the risk of damage doubled when the landscape proportion of netted orchards increased by 10 %. This pattern suggests mechanisms of spatial redistribution, with a concentration of adult codling moths in the few unnetted orchards, where apples remain accessible. This effect was only observed for damage at the end of the first generation and not for larval counts in autumn, likely due to summer treatments targeting codling moth.

A similar landscape effect was observed for rosy apple aphids, but only in 2021 and within a 500 m radius. In that year, the risk of rosy apple aphid infestation in unnetted orchards was six times higher when the proportion of netted orchards in the landscape increased by 10 %. Aphids might preferentially recolonize unnetted orchards in autumn, leading to locally increased populations.

Similarly, vole populations were lower in unnetted orchards when the proportion of orchards covered with full-block or hail nets increased in the landscape (only in center transects). The probability of vole presence decreased by 60 % when the proportion of full-block and hail nets in the landscape increased by 10 %. This suggests that voles may seek refuge in covered orchards where predation is reduced, or that vole predators such as birds of prey concentrate their predation in unnetted orchards.

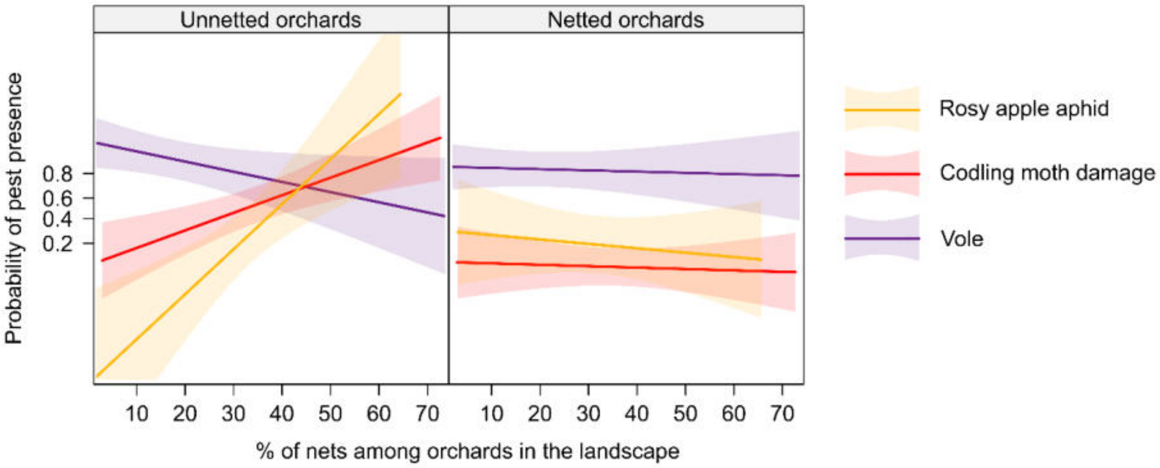

Figure 1. Relationships between the presence-absence of each pest and the percentage of nets among orchards in the landscape, for unnetted and netted orchards. The solid line represents the model effect, and the shaded area is the standard error. For rosy apple aphid, results refer to 2021 only. For vole, the effect is shown with respect to the percentage of full-block and hail nets in the landscape.

To conclude, this work opens new perspectives for farming management. The detection of landscape effects of net coverage on multiple pest groups highlights the need for a coordinated, territorial approach to net deployment.

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# From land cover to farming management: addressing a critical gap in landscape ecology research on biodiversity

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**Abstract:** Changes in agricultural management and Land Use and Land Cover (LULC) play a crucial role for biodiversity, ecosystem functioning, and the provision of ecosystem services. These environmental factors are linked to numerous anthropogenic driving forces, so-called megatrends (e. g., public policy, climate change, demographic changes, productivism shifts), the consequences of which are often intertwined. Despite extensive research on the relationship between land cover and biodiversity at the landscape scale, there is a surprising scarcity of studies examining the impacts of farming management practices on biodiversity at the same scale. There is indeed, (1) a difficulty to decipher the impact of megatrends on LULC and management intensity and (2) a lack of consideration of the impact of landscape-scale management intensity on biodiversity. This limits the identification of levers that can be mobilized to improve the management of agricultural landscapes for biodiversity and the ecosystem services it provides. Based on this observation, the aim of this presentation is to (1) discuss the approaches and tools that would enable the intensity of agricultural practices to be considered more widely in agricultural landscape ecology studies, and (2) illustrate the links between management intensities and anthropogenic driving forces in order to facilitate understanding of the issues and underlying causes, and land use planning and changes in practices in the medium term.

**Key words:** climate change, sociological changes, policy stringency, remote sensing, landscape ecology

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# Farmers' practices and landscape heterogeneity are key drivers of biodiversity underlying agroecosystem multifunctionality

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**Abstract:** Given the detrimental effects of intensive agriculture on human and environmental health, it is crucial to make a transition towards more sustainable cropping systems, conciliating multiple ecosystem functions/services, agricultural production, farmers' income or life quality. Reducing pesticide use on crops and diversifying (semi-natural) habitats at the landscape scale are considered effective strategies for shifting towards such systems. However, their impacts on agroecosystem multifunctionality remain poorly studied. We investigated the effects of organic and conventional cropping systems and of landscape heterogeneity on agroecosystem multifunctionality in North-western France, with consideration of their ecological, socio-economic, and agronomic performance. We found a strong trade-off between ecological and crop production (yield) functions. The number of field interventions and amount of nitrogen were the main drivers of agroecosystem multifunctionality and functions. At the landscape scale, habitat diversity had contrasting effects on pest control capacity, pest infestation and yield, whereas increasing amounts of semi-natural habitats enhanced biodiversity conservation and pollination capacity. Our study suggests that reducing within-field intervention and nitrogen fertilization, as well as restoring complex landscape mosaics could be key strategies for enhancing the ecological functions underlying multifunctionality.

**Key words:** biodiversity conservation, pest regulation, pollination, crop yield, organic cropping system, nitrogen fertilization, semi-natural habitat

## Introduction

Faced with global changes and the biodiversity crisis, transition towards sustainability requires the development of cropping systems with high environmental, economic and social performance. These systems should enhance agroecosystem multifunctionality by reconciling agricultural production, biodiversity conservation, and ecosystem functioning, which represents a significant challenge (Hölting et al., 2019). Gaining an understanding of the multiple drivers of agroecosystem multifunctionality requires different spatial scales to be considered. At the field scale, organic cropping is considered a promising system for promoting multifunctionality. Ecological functions supported by biodiversity are expected to be enhanced under organic system since it prohibits the use of synthetic inputs (Tuck et al., 2014; Couthouis et al., 2023). Nevertheless, organic systems are often criticized due to lower yields compared with conventional ones, even if they may not compromise farmers' income due to higher product valuation and subsidies. Whatever the type of cropping system, it might also be relevant to account for the diversity of crop management practices adopted by farmers, as this could also impact the levels of ecological functions in crop fields (Puech et al., 2014). At the landscape scale, spatial heterogeneity is a key driver of biodiversity and ecological processes. In particular, the heterogeneity related to semi-natural habitats or crops could be beneficial for multitaxa diversity and functions like pollination and pest regulation (Priyadarshana et al., 2024; Alarcon-Segura et al., 2025). However, there remains relatively little information available regarding the influence of landscape heterogeneity on agroecosystem multifunctionality.

This study investigated how cropping systems (organic vs. conventional) and landscape heterogeneity affect agroecosystem multifunctionality, as well as trade-offs and synergies among ecological, socio-economic, and agronomic performance. It aimed to highlight management practices, whether combined or on their own, and landscape structures that can be mobilized to foster agricultural production and other functions.

## Materials and methods

The study took place in the Zone Atelier Armorique, north-western France. This long-term research site is characterised by a dense hedgerow network (‘bocage’), small agricultural fields and mixed dairy farming. In this site, we selected 40 winter cereal fields (20 organic fields and 20 conventional fields) distributed along two landscape gradients (in 500 m radius circles centred on fields): the area of organic fields (from 0 % to 82 %) and the length of hedgerows (from 1368 m to 5953 m). These two gradients were not significantly correlated (Spearman correlation, rho = 0.19)

### *Multifunctionality calculation*

Agroecosystem multifunctionality was assessed in these fields based on seven functions: (i) four functions (biodiversity conservation, pollination capacity, pest control and pest infestation) as indicators of ecological performance, (ii) one function (crop production) as an indicator of agronomic performance and (iii) two socio-economic functions (labour time and income contribution) as indicators of socio-economic performance. Ecological function indicators were produced based on taxonomic data from field surveys. Biodiversity conservation was assessed by three proxies: the richness of carabid and weed species, and of pollinator morphogroups. Pollination capacity was evaluated through one proxy, i. e., the abundance of insects visiting weed flowers. Pest control was quantified by five proxies, i. e., the abundance of carabids, staphylinids, spiders, aphidophagous hoverflies, and ladybird larvae. Pest infestation consisted in the abundance of aphids and troublesome weeds (two proxies). Interviews with farmers were realised to describe crop production and socio-economic function values. Crop production was assessed through one proxy, i. e., yield (t/ha). Labour time was assessed by one proxy based on the number of working hours (cumulative duration of interventions) in the field. Income contribution was assessed through semi-net margin (€/ha) (one proxy). Each of the 14 proxies were standardized (0-1 scale) using the maximum values observed across all fields and then averaged to obtain measures of the seven functions. Functions values were averaged to obtain a single multifunctionality index.

### *Agricultural and landscape variables*

Interviews of farmers allowed to obtain detailed information on crop management practices applied to each field (amount of pesticide used, nitrogen fertilization (kg N/ha), mechanical weeding frequency, total number of interventions on crops).

Land-cover maps were digitized within 1000 m radius buffers centred on each sampled field using aerial ortho-photographs and field surveys. Compositional (amount or diversity) and configurational (edge length) heterogeneity metrics were produced based on four landscape typologies: (i) 'habitat-matrix', focusing on SNH; (ii) 'habitat mosaic', distinguishing woody, permanent or temporary grassy, and cultivated habitats; (iii) 'crop mosaic', focusing on cultivated habitats; (iv) 'mosaic of farming practices', distinguishing organic and conventional systems. Metrics were calculated for circles with radii of 250 m, 500 m, 750 m and 1000 m to account for the varying scales of responses among studied taxa.

### *Statistical analyses*

Beta or linear models were built to assess the effects of management practices and landscape heterogeneity on multifunctionality index and functions. Owing to the large number of variables compared with the number of fields, we performed variable selection procedures among variables using conditional random forest models. The residuals of models were visually checked for normality and homoscedasticity. Collinearity and spatial autocorrelation were controlled and corrected when necessary.

## Results and discussion

### *Organic cropping system impacts functions but not multifunctionality index*

The multifunctionality index showed no difference between organic and conventional cropping systems, as a consequence of trade-offs between functions. Fields under organic systems had higher biodiversity conservation (+ 36 %), pest control (+ 13 %), pest infestation (+ 24 %), and pollination capacity (+ 26 %) values, but lower (- 42 %) crop production values than fields under a conventional system. No difference between organic and conventional systems was found for income contribution and labour time. These results provide supplementary evidence that the organic system is particularly beneficial to biodiversity-based functions (Tuck et al., 2014). Interestingly, the trade-off between biodiversity conservation or pollination capacity and crop production was slightly reduced in organic system compared with conventional one.

### *Field interventions and nitrogen fertilization are main drivers of multifunctionality index and underlying functions*

The multifunctionality index was negatively correlated with the number of field interventions but positively correlated with nitrogen fertilization. The number of field interventions was negatively correlated with biodiversity conservation, but positively correlated with labour time. The quantity of mineral nitrogen fertilization had a negative effect on biodiversity conservation, pest control, pest infestation, pollination capacity, and labour time but a positive effect on crop production. We also found a positive effect of organic nitrogen fertilization on crop production. These results indicate that reducing nitrogen fertilization amount and field interventions could be integrated even in conventional cropping systems to improve their multifunctionality.

### *Landscape heterogeneity impacts ecological functions and crop production*

Landscape heterogeneity did not influence the multifunctionality index, but it had significant effects on its underlying functions, independently of the type of cropping system. Biodiversity conservation and pollination capacity were enhanced in landscapes with high amount or spatial complexity of SNH, confirming the key ecological role of these habitats (Holland et al., 2017). Habitat diversity was positively correlated with pest control and pest infestation values, negatively correlated with crop production values, but without effect on labour time and income contribution. This result suggests that landscapes with high habitat diversity may not only be beneficial for natural enemies but also for crop pests, to the detriment of yields. However, lower yields in such landscapes might not result in lower socio-economic performances for farmers.

***Multifunctionality should be assessed using multivariate approaches***

Overall, the lack of effects of local or landscape variables on the multifunctionality index highlights the limitations of univariate approaches focusing on a single index. Although more complex indices have been proposed (e. g., based on the consideration of function thresholds), our study suggests that multivariate approaches are needed for a better understanding of the drivers of multifunctionality in farming landscapes.

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# Managing populations of bruchid pests in grain legumes: role of resource provisioning at field and landscape levels

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**Abstract:** Bruchids (Coleoptera: Bruchidae) seriously affect the production of grain legumes in the world. By developing in the seeds, bruchids reduce seed weight, alter their germination potential, and compromise their value for both human and animal consumption. To date, limited effective management strategies are available, and little is known about their ecology. In order to improve the management of bruchids, we investigated how local and landscape factors support their populations and those of their main natural enemies, such as a micro-hymenoptera parasitoid. Over two years, we conducted field observations in 80 fields, grown with lentil or faba bean, across four production basins in France. At the landscape scale, we found that the bruchid population density was positively related to proportional area of host crops (faba bean or lentil) cultivated in the preceding year, whereas larger host crop areas in the current year tended to mitigate infestation pressure, consistent with a dilution effect. Wooded areas also increased the bruchid populations in lentils (overwintering habitat), while hedges reduced them in faba beans. The provision of nectar resources within the field and on field edges increased slightly bruchids populations in faba bean fields. However, these resources also had a positive effect on the parasitism of bruchids. Agronomic practices at field level had no effect highlighting the need for concerted strategies at the landscape level to improve the management of bruchids populations and of their natural enemies.

**Key words:** faba bean, lentil, landscape, biological control

## Introduction

Grain legumes like faba bean and lentil provide essential benefits to agricultural systems, including biological nitrogen fixation, improved soil health, biodiversity support, and valuable plant proteins for human and animal nutrition. Despite their potential, legume cultivation in Europe remains limited due to high yield variability caused by their sensitivity to abiotic stresses and diverse biotic threats including fungal diseases, viruses, weeds, and in particular insect pests such as bruchids. Bruchid beetles significantly impact legume seed quality by feeding inside seeds, reducing weight and nutritional value and increasing fungal infection risks. Market standards restrict seed infestation levels severely, causing notable economic losses in Europe.

Field bruchids have a univoltine life cycle, closely tied to host crop phenology and environmental conditions, overwintering in wooded habitats and emerging in spring to feed on floral resources essential for reproductive maturation. Females oviposit on young pods, where larvae feed and develop inside seeds until adult emergence (Segers et al., 2021). Natural enemies, particularly parasitoids like *Triaspis* and *Dinarmus* spp., offer biological control potential but are insufficient alone (Bellifa and Chapelin-Viscardi, 2021). Current management relies heavily on pyrethroid insecticides applied at early pod set. However, challenges such as the development of resistance and regulatory restrictions are reducing the possibility of chemical applications. Alternative strategies including biological control and habitat management to encourage natural enemies show promise, but are still inconsistent (Raderschall et al., 2025).

The impact of landscape on beetle populations and their parasitoids is not well understood. In the UK, the size of host-crop areas is a key factor in determining the extent of beetle damage, in line with the resource concentration hypothesis. However, diverse crop landscapes may suppress beetle abundance. Beetle numbers tend to be higher near wooded overwintering sites such as hedgerows and forests (Ward, 2018). There is limited understanding of how bruchid parasitoids respond to landscape features. At a local level, nectar provision through flower strips can enhance parasitoid efficacy and pest control (Gardarin et al., 2021). Critical research gaps remain concerning the drivers of bruchid beetle abundance and parasitism, particularly regarding crop management, floral resources, and landscape context. This study addresses these gaps by evaluating bruchid pest dynamics and parasitoid control in faba bean and lentil fields across varying management and landscape conditions over three growing seasons in France.

## Materials and methods

### *Experimental design*

The study was carried out across four French production regions (near Paris, Nogent-sur-Seine, Dijon, and Toulouse) during two consecutive years (2021 and 2022) in 33 faba bean (*Vicia faba*) and 47 lentil (*Lens culinaris*) fields. These fields were managed either organically (n = 70) or under conventional practices without insecticide treatments (n = 10). Observations were carried out at three different phenological crop stages: vegetative, flowering, and young pods at five distances from field edge.

### *Response variables*

Bruchid adults within the vegetation were monitored along fixed observation areas in the field and at each crop stage (80 fields × 4 distances × 3 crop stages). Insect collection was conducted using a sweep net with 20 consecutive net sweeps per transect. To assess larval parasitism, pods were sampled at pod maturity at each distance in the field. All seeds were counted and placed into individual plastic containers sealed by fine tulle mesh and kept at 18-22 °C until insect emergence. Emerged bruchids and parasitoids were recorded and identified to the species level, while parasitoids were classified to the lowest feasible taxonomic level.

### *Local and landscape explanatory variables*

The cover of flowering herbaceous dicotyledonous plants was recorded in each crop stage, in both the field and the perennial herbaceous field margin, considering five randomly selected quadrats of 1 m$^2$ each along each observation area. The percentage of flowering plant cover in each quadrat was estimated visually and averaged to obtain the total percentage of flowering plant cover by distance. Extrafloral nectar secretion by faba bean plants was assessed in the same transects on ten randomly selected plants per observation area in each crop stage. To assess the influence of landscape composition, several composition variables were calculated from spatial data in a 2000-m buffer zone around the centroid of each field studied: (i) the percentage of land grown with the same crop as the focal field (lentil or faba bean), during both the current and the previous sampling year; (ii) the percentage of area declared as organic agriculture; (iii) the percentage of grassland and (iv) woody habitats, and (v) the total linear meters of hedgerows.

***Statistical analyses***

The relationships between dependent and scaled independent variables were examined using Generalized Linear Mixed-Effects Models under R. Bruchids' abundance and parasitism rate were defined as response variables, meanwhile flower cover, field management, landscape composition were tested as fixed effects in separate models. Field identity nested within production regions was included as a random effect to account for the hierarchical structure of the data. Common covariates such as Year, Phenological Stage and Distance to field edge were included in all models.

## Results and discussion

At the field scale, bruchid abundance slightly decreased with increasing distance from the field edge in both faba bean and lentil crops (faba bean: estimate = -0.265, p = 0.002; lentil: estimate = -0.100, p-value = 0.016). This pattern reinforces the idea that field edges act as initial colonization zones for bruchids, but the very small slope indicates a high dispersal ability of bruchids within fields. Nutritional resources played a pivotal role in bruchid dynamics. In faba bean, *Bruchus rufimanus* abundance increased with the mean number of stipules bearing extrafloral nectar during flowering stage (estimate = 0.869, p < 0.001). Bruchid abundance also increased with flowering plant cover during the young pod stage (estimate = 1.896, p < 0.001), aligning with evidence that nectar provides essential carbohydrates and amino acids sustaining metabolism and reproduction. Extrafloral nectar is particularly influential for females by accelerating sexual maturation and increasing oviposition duration and rates (Pölitz and Reike, 2019). Longer availability of floral resources may also help females locate suitable pods (Medjdoub-Bensaad et al., 2007). In lentil, an inverse relationship between flowering plant cover and *B. signaticornis* abundance during flowering was observed (estimate = -0.521, p = 0.002), potentially reflecting male bruchid dispersal post-mating and sex-specific behavioural differences (Segers et al., 2021). At field scale bruchid abundance was also positively associated with field size (estimate = 0.451, p = 0.011) and sowing density (estimate = 0.358, p-value = 0.040) in faba bean, suggesting a concentration effect.

At the landscape scale, both bruchid species were less abundant in areas where their host crops occupied a larger proportion in the same year (faba bean: estimate = -0.299, p = 0.032; lentil: estimate = -0.367, p = 0.028), consistent with dilution of pest pressure when host crop availability is large. Moreover, *B. rufimanus* abundance increased with the previous year's faba bean area (estimate = 0.440, p = 0.008), reflecting a resource concentration effect whereby repeated cropping enhances host detection and recolonisation by specialist herbivores such as univoltine bruchids dependent on temporal and spatial synchrony with hosts (Segers et al., 2021). Landscape composition influenced pest dynamics differentially. *B. rufimanus* abundance was negatively associated with the total length of hedgerows (estimate = -0.755, p = 0.010), potentially due to improved biological control from natural enemies that use hedgerows as habitat. These natural enemies may spill over into fields, increasing parasitism and reducing pest populations via predation or parasitism. In contrast, *B. signaticornis* abundance was positively associated with the amount of woody habitat (estimate = 0.286, p = 0.032), reflecting overwintering preferences (Segers et al., 2021).

Parasitism rates in faba bean were variable across years and regions, averaging around 39 % to 51 %, while lentil showed much lower and more homogeneous parasitism (about 4-6 %). The parasitoid *Triaspis* cf. *thoracica* (Braconidae) dominated faba bean seed parasitism (around 99 % emergence) while it was less abundant in lentil samples (28 %), where unidentified Chalcidoidea (Hymenoptera) was the predominant parasitoid emerged (70 %). In both crops, parasitism declined with distance from the field edge (faba bean: estimate = -0.176, p = 0.011; lentil estimate = -0.339, p = 0.002) and with increasing field size (faba bean: estimate = -0.248, p = 0.049), suggesting that their dispersal ability is slightly more limited than that of Bruchids. Parasitism in lentil was positively associated with hedgerow presence (estimate = 0.636, p = 0.041), corroborating the beneficial role of semi-natural habitats in fostering natural enemy populations. Surprisingly, parasitism in faba bean was negatively correlated with extrafloral nectar presence (estimate = -0.307, p = 0.040), underscoring complex multitrophic interactions where resource availability may differentially benefit pests and their natural enemies. The abundance of Bruchid and parasitism in both crops were not significantly affected by other landscape variables such as the area of organic agriculture and grassland.

This study shows that bruchid population dynamics and parasitism in faba bean and lentil are jointly governed by local field conditions and the surrounding landscape context. Although the two focal species belong to the same genus, they exhibited both common ecological patterns and distinct, species-specific responses to crop characteristics and semi-natural habitats. Moreover, parasitism rates contrasted between crops, indicating that host – parasitoid interactions are modulated by crop identity and spatiotemporal variation in host availability.

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# Pest control in agricultural landscapes: from knowledge to action

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**Abstract:** Reinforcing the regulation of pests by their natural enemies is a promising way of reducing pesticide use. This alternative is, however, still rarely used by farmers, mainly due to a lack of references and prospective analyses about the gains to be expected from the implementation of management options at farm and landscape levels. Here, we present examples illustrating how current research can attempt to fill knowledge gaps and could increase its operational impact and foster a wider adoption of practices enhancing pest control services across landscapes.

**Key words**: natural pest control, landscape scale, collective action

## Deciphering complex interactions and cascading effects across spatial scales

There is a generic expectation that extensive agricultural systems situated in complex landscapes harbor higher levels of functional biodiversity and natural pest control services than intensive systems located in simplified landscapes. Although empirical studies generally support this expectation, they also reveal the great variability and context-dependency in the response of natural pest control to local and landscape-scale factors (Vialatte et al., 2025). Inconsistencies may result from overlooking the ecological complexity of tri-trophic interactions and their cascading effects on pest control services. Besides, even if semi-natural habitats often support pest control services, it is also important to account for the diversity of farming management at field and landscape scale as this can be strong drivers of pest control services.

We recently analysed how multitrophic interactions drive weed seed control under contrasting farming systems and landscapes (Figure 1). We hypothesised that conservation agriculture, through a drastic reduction of soil tillage and the provision of crop cover throughout the year, would benefit seed-eating organisms and thus the service of weed regulation. We found that local and landscape management under conservation agriculture favours seed predators such as carabids and rodents, higher-order predators such as shrews and alternative animal prey (Figure 1). Weed seed predation was promoted by conservation agriculture through an increase in the number of seed predators. However, alternative animal prey reduces the efficacy of carabids to consume seeds, probably due to a prey-switching behaviour. Similarly, shrews negatively affect the activity-density of carabids, resulting in an indirect negative effect on seed predation. Interestingly, we detected a direct positive effect of field-scale conservation agriculture on weed seed predation, which suggests that despite the large number of taxa considered in this study, other biotic components may play a role in the natural regulation of weeds.

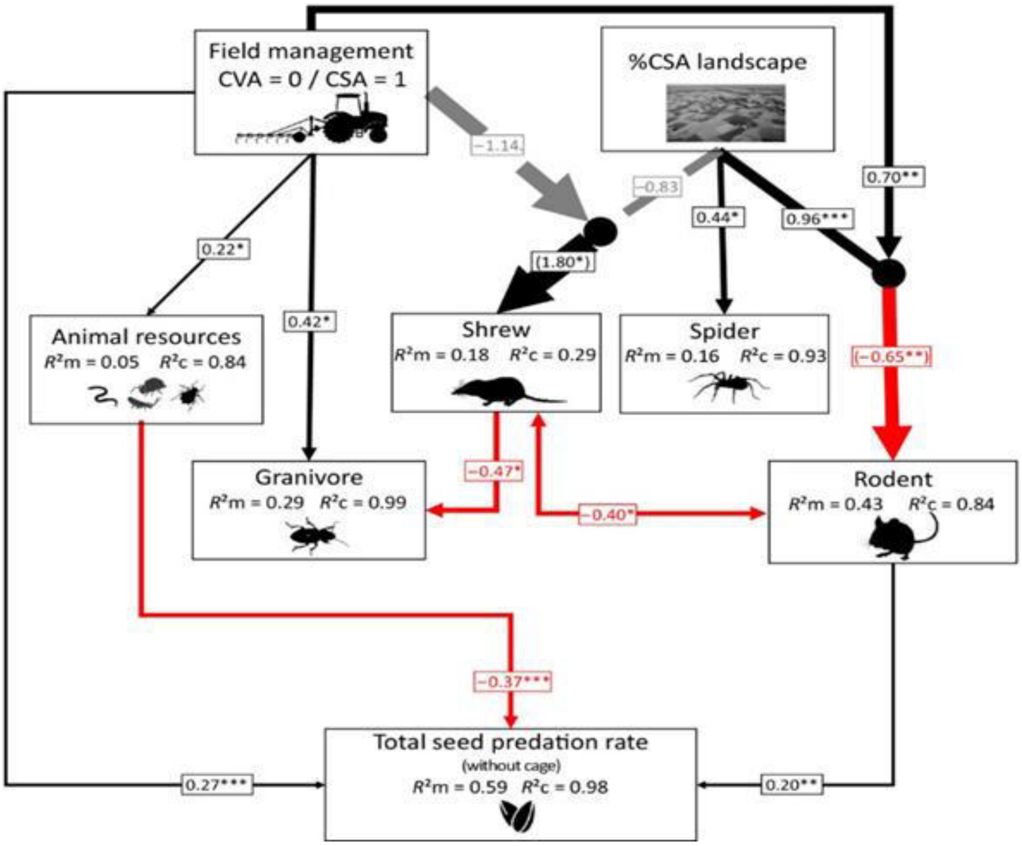

Figure 1. Structural equation model including cascading effects of field management (CVA: conventional and CSA: conservation agriculture) in interaction with the '% CSA in the landscape' on weed seed predation. Bidirectional arrows show non-causal correlations and black circles (•) show interactions. * $p < 0.05$; ** $p < 0.001$, *** $p < 0.0001$ (from Carbonne et al., 2023)

## Providing scientific evidence for effective pest regulation

Academic research often emphasizes the complexity and variability of landscape effects, reinforcing the perception among practitioners that these processes are too complex and not yet operational. Besides, there are still too few landscape-scale pest control studies that produce indicators being meaningful to farmers and likely to trigger shifts in their pest management strategies. Quantification of pest damage is sometimes conducted, but few large-scale studies go all the way to estimate how pest control services contribute to saving crop yield or reduce farmers expenses, because they can use and spend less money on pesticides.

Coming back to the case of weed regulation by seed consumers, there was scarce experimental evidence that they reduce weed emergence and weed biomass. However, due compensation mechanisms, weeds are likely to grow better and produce more seeds when they are less dense. As a result, the effect of weed seed predators on crop productivity through weed control was not established and could not be conveyed to farmers. To address this gap, we conducted a long-term exclusion experiment replicated in 30 commercial fields which compared weed biomass and crop productivity in the presence or absence of invertebrate and vertebrate seed predators (Muneret et al., 2026). We found that weeds, if neither regulated by seed predators, nor by agronomic practices, caused a yield loss of 80 %, a value that is consistent with existing literature (Oerke, 2006). We also demonstrated that seed predator activity reduced the yield loss due to weeds by an average of 20 %, which extrapolates to an economic gain of 285 €/ha. This outcome was communicated to the local farmers who hosted the experiment but also through short articles in farmer magazines that are distributed nationally. Further studies should explore how additional agronomic levers could be used to complement the action of seed predators.

## Harnessing the landscape scale to foster pest regulation

There is increasing evidence that farming practices beneficial to biodiversity and pest control services are more effective when deployed over large areas (Meier et al., 2024). Such 'pest-suppressive' landscapes are rarely designed on purpose, despite being a key to provide stronger and more stable pest regulation. For example, we showed in a recent national-scale study that doubling the length of hedgerows in the landscape would reduce aphid infestation and half the use of insecticides in French wheat-based systems (Courson et al., 2024). The context-dependency of ecological responses nevertheless limits our capacity to predict the benefits of landscape redesign for pest control services. Long-term biodiversity observatories provide robust datasets to describe the interplay between management options at multiple scales and to increase our capacity to predict pest control services in specific contexts.

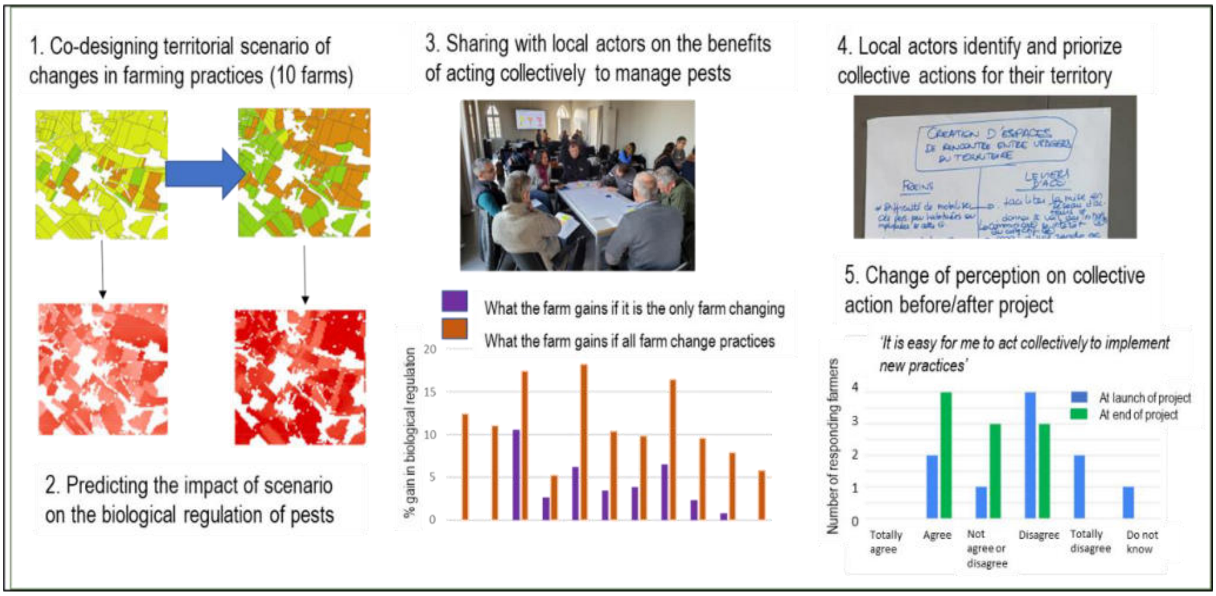

Figure 2. The different steps of the engaged participatory approach and outcomes obtained in the Dijon plain (Burgundy) in terms of the spatial interdependencies between neighboring farms in the delivery of pest control services (after Petit et al., in press)

In a recent study, we developed participatory research integrating predictive modelling on a set of long-term landscape monitoring sites scattered across France (Petit et al., in press). The general approach (Figure 2) involved an ex-ante evaluation of landscape-scale and farm-scale pest control services under alternative farming practices. First, context-specific predictive models of pest control services were developed on the basis of long-term agroecological data collected within the monitoring sites. Secondly, scenarios of landscape-scale changes in farming management were co-designed with local farmers. Finally, the evaluation of pest control services under alternative scenarios of changes was presented to local stakeholders, with a focus on the quantification of their spatial interdependencies in the delivery of pest control services. This research highlighted that there is a high degree of spatial interdependency between farmers in the delivery of on-farm pest control services. More importantly, our results demonstrated that a wide adoption of pest control friendly-farming practices in the landscape leads to a win-win situation for each farmer in the landscape. This outcome reinforced the positive attitude of farmers towards the idea of acting collectively to promote pest control services.

## Conclusion

There is increasing scientific evidence that effective pest control services can be achieved through appropriate management at field, farm and landscape scales. Worldwide, it is estimated that more than a third of existing farms, representing about 10 % of land, are adopting ecologically-friendly practices and that the redesign of farming systems is expanding fast. It is now important that this agricultural transition is thought at territorial scales as this will ensure higher pest control, as well as other ecosystem services. Management options deployed at the landscape scale are nevertheless also the most complex to implement because they cover various spatial and temporal scales and concern not only individual but also collectives of farmers, as well as other stakeholders. Long-term transdisciplinary place-based research can partly address this gap and provide a suitable playground to co-produce innovative methods and results that could help foster landscape transformation.

## Acknowledgements

I want to warmly thank past and present post-doctoral fellows as well as other close research collaborators scattered across France (Rennes, Toulouse, Avignon, Bordeaux) for their constant and fruitful partnership in pest control studies. Results presented here were developed within (i) the EIP-AGRI project RegGAE (EU Rural development 2014-2020 for Operational groups and the Region Bourgogne-Franche-Comté and (ii) the PREPARE project "Predicting and understanding the effects of landscapes of practices on biological regulation" which was funded by the French EcoPhyto programme and the French Office for Biodiversity.

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# Landscape, *Drosophila suzukii* and host plants: a three-factor evaluation of *Leptopilina japonica* establishment

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**Abstract:** *Leptopilina japonica*, an Asian parasitoid of the invasive *Drosophila suzukii*, was monitored over two years in Lombardy (Northern Italy) to assess its presence, distribution, and ecological relationships with the surrounding landscape. From June to September, ripe fruits were collected at six sites along an altitudinal gradient and incubated to document parasitoid emergence and its interactions with *D. suzukii*, other drosophilids, and host plants. *L. japonica* was consistently detected throughout the two years, with most emergences recorded from *Rubus* spp. Ongoing analyses combine host–plant data with environmental and landscape variables to identify factors influencing the establishment and distribution of the species. Overall, this monitoring effort provides an updated picture of *L. japonica* in Lombardy and helps clarify how host availability and landscape complexity may shape its ecological dynamics and potential role in the natural control of *D. suzukii*.

**Key words:** biological control, parasitoid emergence, invasive species, fruit host associations, spatial distribution

## Introduction

*Leptopilina japonica* Novković & Kimura, 2011 (Hymenoptera: Figitidae) is an Asian parasitoid wasp (Daane et al., 2016; Girod et al., 2018), known for parasitizing the Spotted Wing Drosophila (SWD), *Drosophila suzukii* (Matsumura, 1931) (Diptera: Drosophilidae), a highly polyphagous invasive species native to eastern and south-eastern Asia that causes significant economic losses to stone and small fruits (Walsh et al., 2011). *Leptopilina japonica* is now established in several countries, including Italy, and parasitizes *D. suzukii* in the field with seasonally variable rates (Puppato et al., 2020; Nair and Peterson, 2023; Stacconi et al., 2025). Although laboratory studies indicate that it is not fully host-specific, its unintended spread has renewed interest in its potential contribution to sustainable *D. suzukii* management. However, if field evidence continues to show minimal effects on non-target species, it is important to deepen the information already known (van Timmeren et al., 2025) related to the effects of landscape structure on the presence of *L. japonica.* It is necessary to evaluate whether this parasitoid may become a feasible option for augmentative biological control within integrated pest management programs.

To support this evaluation, the present two-year monitoring programme conducted in the Lombardy region (Northern Italy) aimed to: a) verify the presence of *L. japonica* in Lombardy; b) assess the emergence of *L. japonica* from different fruit infested by *D. suzukii*; c) assess the emergence of *L. japonica* from *D. suzukii* and other drosophilids; and d) evaluate the ecological relationships of *L. japonica*, with the spontaneous plants in the surrounding landscape**.**

## Materials and methods

Monitoring was conducted across six sites located in four provinces of the Lombardy region (Northern Italy) [Varese (n = 1; 280 m a.s.l.); Bergamo (n = 1; 284 m a.s.l.); Como (n = 1; 326 m a.s.l.); Sondrio (n = 3; 620 m, 640 m and 587 m a.s.l., respectively)] along an altitudinal gradient. The sites (approximately 3 ha each) were selected based on the presence of cultivated host plants of *D. suzukii* (e. g., *Vaccinium corymbosum* L. and *Rubus* spp.) present in most of the sites, as well as wild host plants in the surrounding vegetation. Sampling was carried out from June to September, covering the main seasonal window of *D. suzukii* infestation and parasitoid activity. At each site, repeated sampling events were performed throughout the season to capture temporal variation in host and parasitoid occurrence. Ripe fruits from known host plants were collected during each visit and transported to the laboratory, where they were incubated in containers (approximately 80 g of fruit per container) under controlled conditions (25 ± 1 °C, 60 % RH) and a natural photoperiod to assess the emergence of *D. suzukii*, other drosophilids, and *L. japonica.* After collection, the specimens were stored in alcohol for subsequent identification.

## Results and discussion

*Leptopilina japonica* adults were recorded in all six monitored sites in both years (Figure 1), confirming the stable presence of the parasitoid in these areas. The total number of specimens collected differed significantly ($p < 0.05$) between the two years, but this was attributed to a lower number of samples collected in 2024 due to an unusually rainy season. Moreover, across both years, the SO1 site in Sondrio province recorded the highest number of emergences, accounting for 36 % and 55 % of the total number of the parasitoids emerged across all the sites in 2023 and 2024, respectively. This was due to the high abundance of *Rubus ulmifolius* Schott along the edges. In addition, in the SO1 site *L. japonica* emergence reached the value of 0.1145 adults per gram of fruit in 2023 (4000 g sampled) and 0.0744 adults per gram of fruit in 2024 (3440 g sampled) (Figure 2). Emergences were limited in Sondrio (SO3) and Como (CO1) in 2024, with a ratio of 0.0063 and 0.0015 adults per gram of fruit, respectively. This was also confirmed by the low availability of spontaneous host fruits at these sites during the 2024 season.

The percentage of females detected was 58 % in the first year and 51 % in the second. *Leptopilina japonica* emerged from various host plants infested by *D. suzukii*, confirming its association with the pest in the monitored areas. Specifically, in 2023 most parasitoid specimens were collected from infested fruits of *V. corymbosum* and *R. ulmifolius*; in 2024, from infested fruits of *R. ulmifolius* and *Rubus fruticosus* L. (Figure 3).

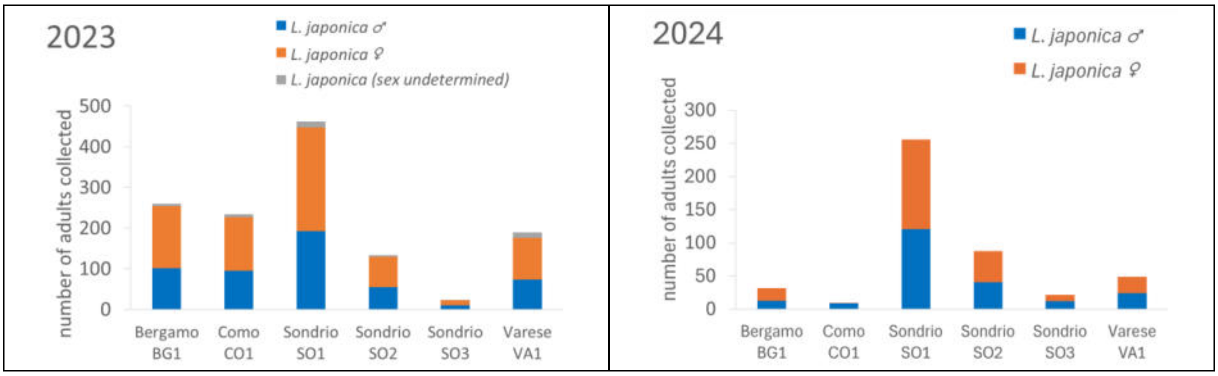

Figure 1. Numbers of adults collected in the six areas over the two monitoring years.

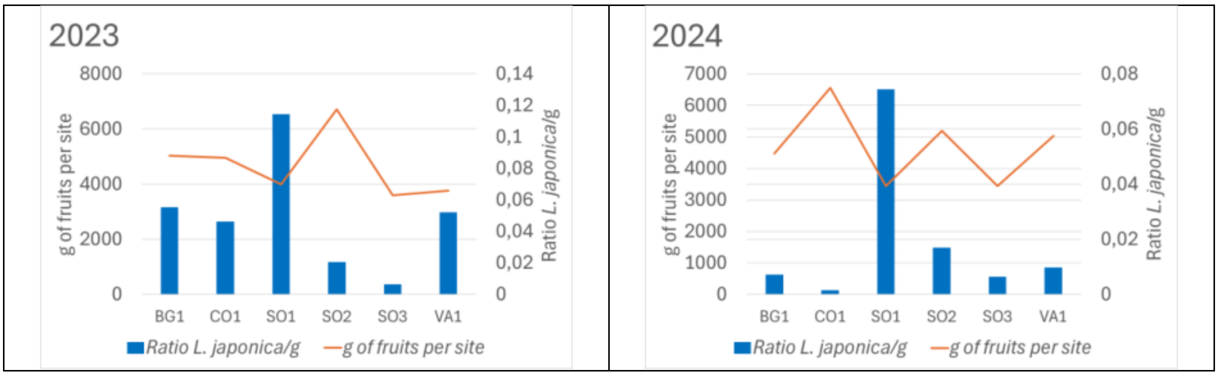

Figure 2. Ratio of *L. japonica* adults per gram of fruit and total fruit mass sampled at each site.

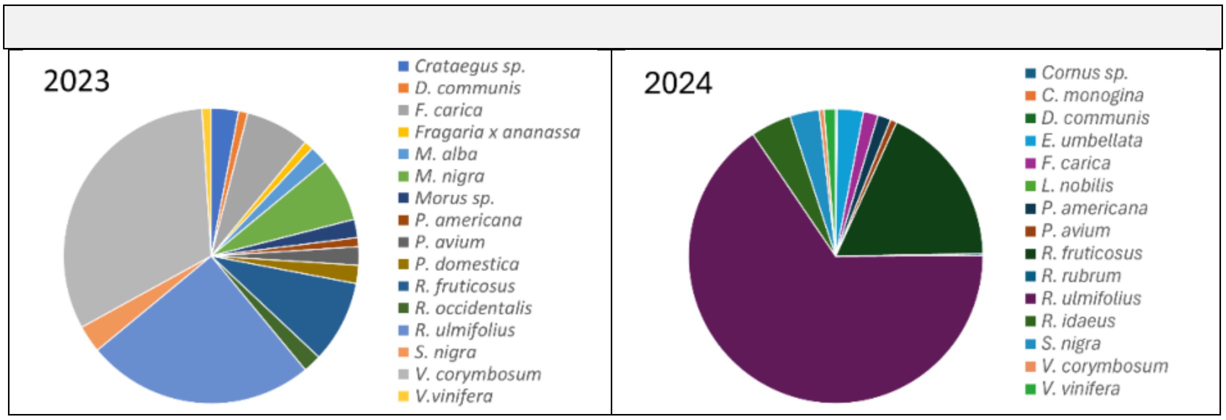

Figure 3. List of fruits from which *L. japonica* emerged in 2023 and 2024.

Host plants appear to play a fundamental role in attracting *L. japonica*, and the high number of host species represented in Figure 3 highlights a close relationship with the surrounding landscape. Many of these plants, such as *R. ulmifolius* and *Elaeagnus umbellata* Thunb., are not cultivated, but instead colonise wild areas bordering crop fields, thereby providing additional suitable habitats. In addition, the ratio in fruit of *R. ulmifolius* reached 0.1923 and 0.1694 adults per gram of fruit in 2023 and 2024, respectively, and was the highest recorded in both years. Plant species that support both *D. suzukii* and *L. japonica* ensure continuity of parasitoid presence and may enhance its efficiency against the host.

This study provides additional information on the establishment and population dynamics of *L. japonica* in Lombardy, indicating that these processes may be influenced by the presence and abundance of spontaneous host plants. The parasitoid was detected consistently across years and sites, with emergence patterns strongly linked to both cultivated and wild host plant species capable of sustaining *D. suzukii* populations. These findings suggest that heterogeneous landscapes including semi-natural elements and spontaneously colonizing plants provide vital refuges that support the continuity of parasitoid activity. As *L. japonica* continues to expand adventitiously, it is essential to understand how these three factors interact in order to evaluate its potential contribution to sustainable pest management.

## Acknowledgements

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# Hoverflies and their diet as indicators for agroecological transformation in the agricultural landscape

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**Abstract:** Since 2019, the project FInAL (Facilitating insects in agricultural landscapes) has been investigating ways to transform the agricultural landscape in Germany into more insect-friendly and insect-promoting environment in order to counteract insect decline and to preserve important ecosystem services (https://www.final-project.de/en/). In three typical German landscapes dominated by arable crops, various measures are being implemented in collaboration with farmers in a co-design process and tested in a living lab approach for their effects on indicator insect groups. Hoverflies are known for their important role in pollination and also in biological control. Therefore, we tracked the response of species assemblage and abundance of hoverfly populations in the agroecologically intensified landscape laboratory compared to the untreated reference landscape through regular monitoring with pan traps. A well-known measure to promote hoverflies is to increase flower resources through flower strips or specific flowering crops. To assess whether these introduced floral resources were utilized in the modified landscape laboratories, we examined the pollen profile in the gut of the captured hoverflies by isolating the pollen and identifying the plant species using metabarcoding. The results showed that the hoverflies indeed utilized the floral resources that had been introduced in the respective living labs.

**Key words:** agricultural landscape, agroecological transformation, conservation biological control, pollen resources

## Introduction

Unsustainable intensified agricultural production is considered as one important driver of biodiversity loss. In particular, the decline in insect populations and the associated risk of losing important ecosystem services are seen as an acute threat to land use in Germany. Therefore, agriculture is considered as important sector for innovative agroecological conservation measures. Corresponding initiatives have been in place for several years, especially since the publication of some important findings on the decline in insect populations (Hallmann et al., 2017). It has also been shown that habitat management and the provision of important resources to support ecosystem service providers will lead to a win-win situation for nature and agriculture. Improvement of agricultural landscapes by introducing resources via the crop system itself or connecting ecological infrastructures is currently tested in Germany in the joint project FInAL (coordinated by Thünen-Institute and Julius Kühn Institute).

Hoverflies are known for their dual role as pollinators and important biological control agents, notably against aphid pests on diverse field crops (Doyle et al., 2020). There exist several reports on declining populations of several hoverfly species (Gatter et al., 2020;

Hallmann et al., 2021) and also on their potential role as indicator taxa for the existing ecological status of the agricultural landscape (Ricarte et al., 2011; Sommagio and Burgio, 2014). Measures within the project FinAL aim on the ecological transformation of the agricultural landscape and are being applied in a living lab approach (laboratory site) in comparison to the unchanged field situation (reference site) in three regions of Germany: Bavaria (Rottal), Brandenburg (Havelland) and Lower Saxony (Elm).

Since 2020, hoverfly populations are monitored using pan traps. Species assemblages and abundances are derived before and after the implementation of agroecological measures. These measures include, for example, the introduction of flower strips or flowering energy crops. These resources can be used by flower-visiting hoverfly species. The aim of our research was to investigate using a metabarcoding approach whether the pollen profile in the gut of four selected species – *Episyrphus balteatus*, *Eupeodes corollae, Melanostoma* spp., *Sphaerophoria scripta* – belonged to the implemented floral resources (Lowe et al., 2022). Here we report on the initial results on the hoverflies diet in the laboratory landscape compared to the reference landscape.

## Materials and methods

### *Hoverfly sampling*

In addition to the regular monitoring with pan traps, we collected hoverflies at the reference site and at the laboratory site in the Bavaria region in 2023. We performed net sweeping (20 strokes) in a straight line along existing structures (field margin, woody edge etc.) starting from the geo-referenced station for pan traps (in total 18 stations per site, separated by at least 500 m). All individuals of the subfamily Syrphinae were extracted from the samples and transferred to 80 % ethanol on site. Flowering plants (in full bloom) in the surrounding area were recorded. Three sampling periods were performed from spring to late summer.

### *Analysis of gut content*

Collected hoverflies were identified to species level and subsequently dissected. When opening the intestine, the presence of pollen was categorized in several steps from no pollen to full pollen content. Mature eggs were counted in the females. The intestine containing the pollen was transferred to a new vial containing 500 µl of 80 % ethanol. Due to limited metabarcoding resources, several hoverflies of the same species collected at the same location had to be combined. The pooled sample was shaken and a 50 µl subsample was taken for microscopic examination. The vial containing 450 µl was labeled with a code and sent to Advanced Identification Methods (AIM) GmbH in Leipzig, Germany, for DNA metabarcoding analysis (ITS plant sequences). The metabarcoding reads obtained were further analyzed by sorting them according to hoverfly species, location, and sampling period.

## Results and discussion

### *Pollen profiles of hoverflies at different sites*

The hoverflies analyzed through metabarcoding belonged to the species *Episyrphus balteatus* (n = 30), *Eupeodes corollae* (n = 9), *Melanostoma* spp. (n = 65) and *Sphaerophoria scripta* (n = 84). In general, the pollen profiles found in the guts of the hoverflies varied depending on the sampling period and location. The pollen profile resembled many of the flowers recorded in the neighborhood (Figure 1).

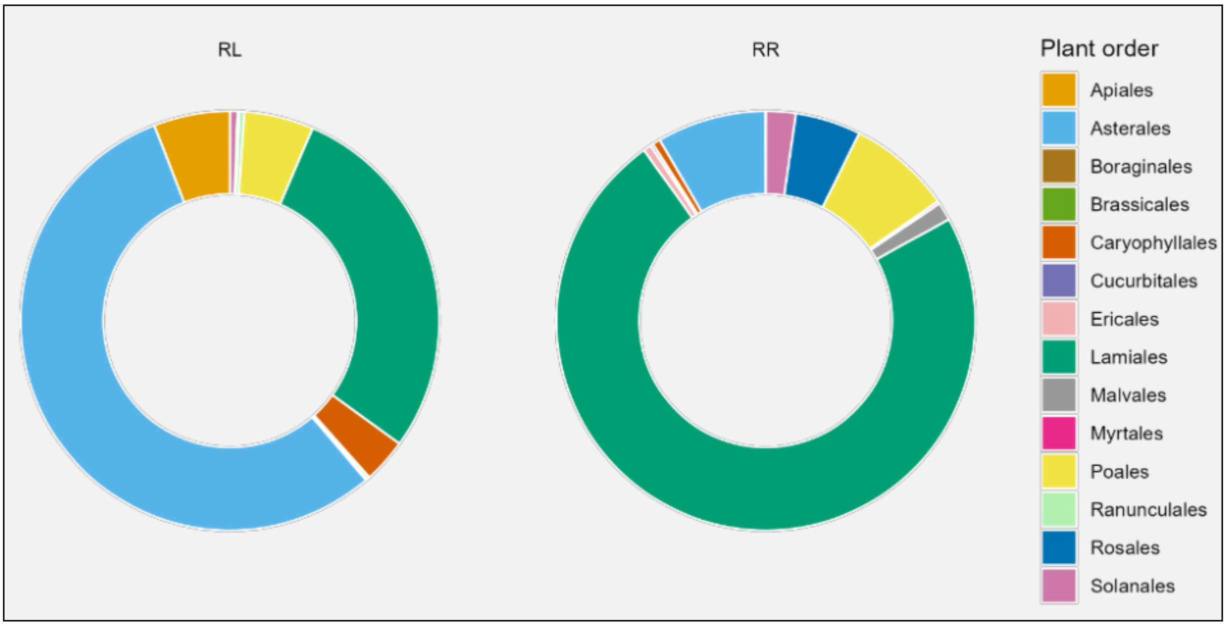

Figure 1. Pollen profile on plant order level in the gut of Syrphinae collected at the reference site (RR) and the laboratory site (RL) in the experimental region of Bavaria in the year 2023. The profile was obtained by metabarcoding of ITS2 plant sequences and shows the percentage of obtained reads for a particular plant order in the samples.

Hoverflies consumed mainly pollen of Laminales on the reference site, whereas those collected at the laboratory site fed preferably on Asterales. At the reference site, the dominant pollen and also the dominant plant recorded was *Plantago* sp. At the laboratory site, chamomille was observed frequently, and this was also the pollen with most reads in the metabarcoding of the pollen profiles. During one period, pollen of *Silphium perforatum* was found, but with less than 0.5 % of the readings. This plant was introduced in the year 2022 as crop plant in the landscape laboratory and was found flowering in 2023. Although only detected at low level, this record confirmed the assumption that hoverflies indeed visit this plant and use it for nutrition (Mueller and Dauber, 2016).

According to metabarcoding, the hoverfly species exhibited different gut pollen profiles. While *E. balteatus* preferred to consume Rosaceae, *Plantago* sp. was apparently the dominant pollen source for *M. mellinum* and *M. scalare*. The hoverfly *Sphaeorophoria scripta* was the most common species in this sampling. Its pollen profile was quite diverse, with many plant families and species. We can conclude that metabarcoding analysis of the intestinal contents of hoverflies provides a semi-qualitative assessment of their preferred food plants and also allows us to conclude whether the landscape provides the necessary resources for the respective hoverfly species.

## Acknowledgements

We would like to thank all farmers and collaborators engaged in the project FinAL to allow the sampling on their field sites and to be active in an agroecological transformation towards more insect-friendly agricultural landscapes.

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# Non-intended effects of exclusion nets on predatory and herbivorous arthropods at local and landscape scales

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**Abstract:** In recent years, alternative pest-control strategies aiming to reduce pesticide use have expanded, although their non-intended effects remain poorly documented. This is particularly true for insect-exclusion nets in perennial cropping systems, where effects may occur at both local and landscape scales. In 2021 and 2022, we monitored 17 pairs of organic apple orchards in south-eastern France, either protected by nets or not, to disentangle local and landscape-scale effects of nets on canopy-dwelling predatory and herbivorous arthropods. At the local scale, netted orchards exhibited higher predator abundance and predator–herbivore ratio compared to non-netted orchards, while herbivore abundance remained unaffected. At the landscape scale, a higher proportion of nets was marginally associated with increased herbivore abundance and a reduced predator/herbivore ratio, with no interaction with local effects of nets. Overall, these results suggest that insect-exclusion nets may represent a viable agroecological strategy with limited non-intended effects.

**Key words:** exclusion nets, apple orchards, predators, herbivores, landscape, non-intended effects, biological control

## Introduction

Many alternative approaches to agrochemicals are presently emerging to offer farmers more sustainable agricultural practices to manage pests. These methods are most often evaluated based on their direct effects on the targeted pest, at the expense of considering potential unintended effects that may affect other organisms within agroecosystems. This observation is particularly well illustrated by the use of insect exclusion nets, a practice that recently expanded in perennial-crop landscapes. With a much finer mesh than traditional anti-hail nets and generally covering a single row, these nets form a physical barrier that prevents pests from accessing the canopy, with no proven adverse effect on yield or fruit quality (Chouinard et al., 2017; Candian et al., 2021). Numerous studies have already demonstrated their effectiveness against major pests, particularly in apple orchards against the codling moth, (*Cydia pomonella*; Chouinard et al., 2017; Marshall and Beers, 2022; Poinas et al., 2025) and in nectarine orchards against the brown marmorated stink bug (*Halyomorpha halys*; Candian et al., 2021). However, few studies to date have examined the unintended effects of this practice on other arthropods present in the canopy (but see: Dib et al., 2010; Marshall and Beers, 2022), and, to our knowledge, none have assessed the consequences on these arthropods of its widespread adoption at the landscape scale. It therefore seems relevant to assess the effects of this practice at both local and landscape scales on communities of predatory and herbivorous arthropods.

Indeed, the use of exclusion nets is likely to profoundly alter community dynamics and trophic interactions, with potentially significant consequences for associated ecosystem services, particularly biological pest control.

## Materials and methods

### *Study area, experimental design and arthropods sampling*

The study was conducted at the Basse Vallée de la Durance study site (490 km², south-eastern France) in 2021 and 2022, in a landscape dominated by perennial crops. Land use in 2022 was mapped using a combination of aerial imagery, field surveys, and public databases, while aerial photographs from 2020 and 2021 were used to precisely identify orchards and the presence of nets. Each year, we monitored between 12 and 14 pairs of commercial apple orchards (totalling 17 pairs and 35 plots), with each pair consisting of one netted and one unnetted orchard. The orchards were selected along a gradient of net coverage within the landscape, and most netted orchards were equipped with single-row Alt'Carpo nets (5.5 × 2.2 mm), although a few used full-block or partial anti-hail nets. Nets were deployed over the canopy from late April to early October. Netted and unnetted orchards did not differ significantly in terms of management, cultivar, age, or plot characteristics, except for a lower use of codling moth biocontrol in netted orchards (e. g., mating disruption). Landscape composition was analysed within 250, 500, and 1,000 m buffers around orchard centroids, quantifying the proportion of orchards, netted orchards, and semi-natural habitats. In each orchard, ten trees were randomly selected in June (five in the outer row and five in the central row, ≥ 15 m from edges). On each tree, three strikes were applied to a representative branch using a stick. Dislodged arthropods were collected with a beating tray (80 × 80 cm) and a mouth aspirator. Specimens were preserved in 8 ml tubes containing 70 % ethanol and stored at 4 °C. The abundance of arthropods was quantified, and the individuals were manually classified according to their trophic role. Only strict predators and herbivores were retained for analysis.

### *Statistical analysis*

The local and landscape effects of nets on arthropod communities were analysed using generalised linear mixed models (GLMM). The abundance of predators and herbivores was modelled using a Poisson error distribution, based on the following explanatory variables: local presence of nets, sampling year, percentage of semi-natural area in the landscape, percentage of orchards and percentage of orchards equipped with nets. To assess the combined effects of nets and landscape structure, the following interactions were also tested: net × % semi-natural area, net × % orchards, and net × % orchards with nets. The field was included as a random effect in order to account for the repeated measures of the data and limit residual autocorrelation. The proportion of predators per tree was also modelled using the same explanatory variables and a binomial error distribution in order to assess the predation potential. Each model was fitted using explanatory variables calculated at three spatial scales corresponding to landscape buffers with a radius of 250 m, 500 m and 1000 m around the orchards.

## Results and discussion

Locally, the presence of netting significantly influenced predator abundance, while no significant effect was detected on herbivore abundance (Table 1; Figure 1). The positive effect observed on predators contrasts with the results of several previous studies, which report a decrease in their abundance under netting (Dib et al., 2010; Marshall and Beers, 2022). It should be noted, however, that these studies were conducted on experimental setups whose conditions may differ from those encountered in commercial orchards. The lack of increase in herbivore abundance under netting could be explained by the increase in the prey-predator ratio observed under these conditions (Table 1).

Table 1. Results of generalised mixed models assessing the impact of exclusion on predatory and herbivorous arthropods at 1000 m. The effect of years and interactions between nets and landscape variables (ns) are not presented here.

| | Netted | % SN | % Orch | % Netted Orch |
|---|---|---|---|---|
| Predators | **0.47 ± 0.19 (*)** | 0.00 ± 0.15 | -0.08 ± 0.17 | 0.05 ± 0.18 |
| Herbivores | -0.09 ± 0.24 | -0.02 ± 0.19 | -0.23 ± 0.21 | **0.65 ± 0.22 (**)** |
| % Predators | **0.55 ± 0.28 (*)** | 0.03 ± 0.22 | 0.15 ± 0.25 | **-0.61 ± 0.26 (*)** |

Estimate ± standard error; (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$; SN: Semi-natural; Orch: Orchards

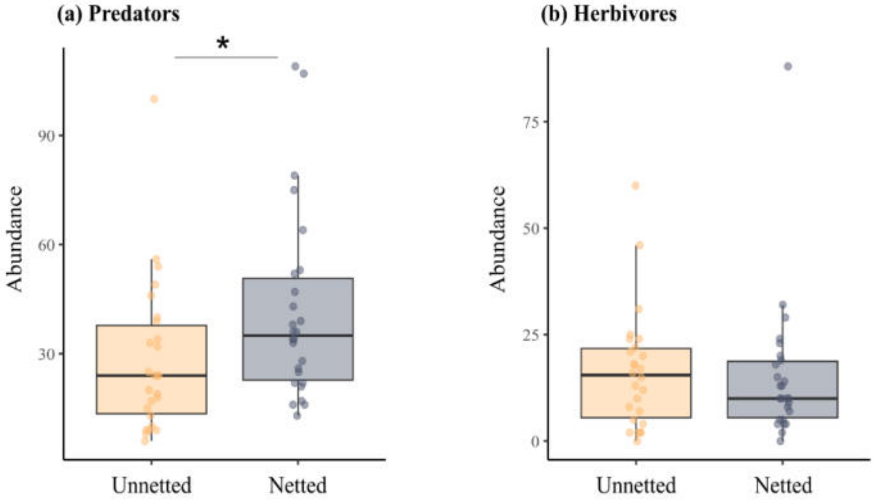

Figure 1. Abundance of (a) predators and (b) herbivores in orchards with and without nets.

At the landscape scale, no significant interaction between the presence of nets and landscape variables was found. Surprisingly, these results do not support the idea of concentration/dilution processes, which were detected by the same protocol on the main apple tree pests (Poinas et al., 2025). Overall, our results suggest limited unintended effects of nets on non-target species at the landscape scale. Nevertheless, the proportion of land covered by nets in the landscape appeared to have a positive effect on herbivore abundance and a negative effect on the predator/herbivore ratio (Table 1). However, these effects were only detected at the largest landscape scale (1,000 m buffer size), highlighting the importance of a multi-scale approach in this type of analysis. Additional analyses, particularly by taxonomic groups, would probably provide a better understanding of the underlying mechanisms, both at the local and landscape scales. Overall, these results suggest that insect-exclusion nets may represent a viable agroecological strategy with limited non-intended effects. While local-scale effects appear to favour predators, landscape-scale responses remain weak and context-dependent. This indicates that the deployment of nets is unlikely to strongly disrupt arthropod communities beyond the targeted pests.

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# Effects of landscape and mesoclimate on biodiversity in agricultural landscapes in western France

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**Abstract:** Global biodiversity is declining due to habitat loss, climate change and human activities, with agricultural landscapes particularly affected by land-use change, loss of semi-natural habitats and reduced heterogeneity. Climate change further alters environmental conditions and therefore influences species diversity differently, selecting only a fraction of biodiversity. Understanding the effects of landscape structure and mesoclimate on agricultural biodiversity is therefore crucial. This study examines the effects of landscape heterogeneity (compositional and configurational), the quantity of semi-natural habitats (hedgerows and grasslands) and mesoclimate on plants, carabids and birds across 3 major habitats (crops, grasslands and hedgerows), while accounting for dispersal capacity as a vulnerability factor. It relies on a long-term experimental design of 30 landscape windows selected along independent gradients of heterogeneity and habitat quantity. Within each landscape window we monitored landscape parameters, hourly temperatures and biodiversity surveys. Preliminary results show mixed, taxa-, habitat- and dispersal-dependent effects of heterogeneity and semi-natural habitats on diversity. Using GLMs, we assess landscape and mesoclimate effects on species assemblages. Our work will provide useful knowledge for guiding agricultural management in favor of biodiversity conservation under climate change.

**Key words:** landscape, mesoclimate, dispersal capacity, GLM

## Introduction

Biodiversity is declining rapidly due to habitat loss, climate change and human activities, especially in agriculture-dominated landscapes (Winkler et al., 2020) Agricultural intensification has reduced both the quantity of semi-natural habitats and landscape heterogeneity, leading to habitat simplification and altered community dynamics. At the same time, climate change is modifying local thermal conditions and precipitation patterns, further constraining species persistence. Understanding how landscape structure and mesoclimate jointly influence agricultural biodiversity has therefore become a major ecological challenge.

Landscape effects on biodiversity depend on both the amount of semi-natural habitats, such as grasslands and hedgerows, and on landscape heterogeneity, which shape species pool composition, species movements and ecological interactions (Holland et al., 2016). In addition, species are influenced by climatic variations that affect their activity, development and reproduction (Inouye, 2022). Dispersal ability should influence species response to landscape and climatic variations because it may condition their ability to move among isolated patches, and escape stressful conditions. Yet, few studies simultaneously consider habitat amount, heterogeneity, mesoclimate and dispersal traits.

Here, we use a long-term design of 30 landscape windows to assess how landscape structure and mesoclimate affect plants, ground beetles and birds across croplands, grasslands and hedgerow habitats. We hypothesised that dispersal capacity is a key determinant of species responses to landscape structure and climate drivers.

## Materials and methods

### *Study site characterization*

This study is based on a long-term experimental setup of 30 landscape windows of 1 km², selected along independent gradients of semi-natural habitat quantity (grassland percentage and hedgerow length) and heterogeneity (compositional and configurational), established in 2019 in the Couesnon watershed. The area is mainly agricultural (landscape mosaic of crops and grasslands), with both intensively managed fields and bocage landscapes.

### *Biological surveys*

Plants, carabids and birds were sampled in four or five sites of each of the 30 landscape windows. Plants were sampled in May and June in croplands (77 surveys, 2023), grasslands (146 surveys, 2025) and hedgerows (149 surveys, 2025). Carabids were sampled at the hedgerow-grassland interface (80 surveys, 2022) and in croplands (30m away from field edge, 77 surveys, 2023) using pitfall traps that were located in sites, from April to July (Uroy et al., 2025). Birds were sampled by dividing each window in 4 sections with 10-minutes point counts done in April and May and pulled (120 pulled surveys, 2022).

Birds were all considered long-dispersers. Using the baseflor database, plants mainly dispersed by epi/endozoochory and anemochory were considered long dispersers, while plants dispersed by autochory, myrmecochory, hydrochory and barochory were considered short-dispersers. Carabids were separated into short and long dispersers according to Hendrickx et al. (2009), through wing system and muscle capacity. Species richness and total abundance were computed per dispersal type, taxonomic group and habitat.

### *Indices characterising landscape structure and mesoclimate structure*

Landscape indices were calculated using land-use maps derived from the OSO land-use database and refined into an 8 class typology (woods, grasslands, crops, anthropised areas, tarmac roads, dirt roads, water surfaces and hydrological network). For each year preceding the related biological sampling, we computed at the window scale: compositional heterogeneity (Shannon diversity index, **SHDI**), configurational heterogeneity (proportion of non-identical pixel pairs, **pNC_hete**), the proportion of grasslands (**pNV_2**) and the total hedgerow length (**Sum_length**).

For 2021-2022, 2022-2023 and 2024-2025, "yearly" climatic indices were computed from data collected by two temperature sensors in each window, monitoring temperature hourly since 2021. To limit collinearity, only three indices were retained: mean daily temperature (**gtg**), mean daily minimum temperature (**gtn**) and mean daily maximum temperature (**gtx**).

### *Statistical analyses*

All data manipulation and statistical analyses were performed using R software. First, we scaled and centered our landscape and climatic variables. Our following statistical workflow consisted of fitting a *glmer.nb* model with the landscape window as a random effect. When no random effect was detected, we used a Poisson GLM and tested for dispersion, switching to a quasi-Poisson model in case of underdispersion and to a negative binomial GLM in case of overdispersion. Collinearity was checked at each step and problematic variables were removed. After validating the final models, we assessed the effects of landscape and climatic variables on species richness and abundance (species richness only for plants) for both dispersal subgroups of each taxon and for each habitat.

## Results and discussion

Landscape and climatic drivers influenced plant and carabid abundance and/or richness, while no significant effects were detected for birds (Table 1).

Table 1. Results of the models testing the effect of landscape structure and mesoclimate on community structure for 3 taxa.
Abbreviations: In the habitat column: GH = grassland-hedgerow interface, C = croplands, HG = hedgerows, G = grasslands. In the response variable column (var), Rich = species richness and Abun = abundance. N.C. indicates variables removed due to collinearity, and ns denotes non-significant effects. P-values: *** = 0.001; ** = 0.01 * = 0.05

| **Model information** | | | | **Landscape variables** | | | | **Climatic variables** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Group** | **Hab** | **Disp** | **Var** | **SHDI** | **pNC. hete** | **pNV_2** | **Sum_ length** | **gtg** | **gtn** | **gtx** | **R²** |
| Birds | | Long | Rich | ns | ns | ns | ns | ns | N.C | N.C | 0.068 |
| | | Long | Abun | ns | ns | ns | ns | ns | N.C | N.C | 0.068 |
| Carabids | GH | Short | Rich | ns | **0.152 ***** | ns | ns | ns | N.C | N.C | 0.168 |
| | | | Abun | ns | **0.306 **** | **0.268 **** | ns | **-0.249 **** | N.C | N.C | 0.257 |
| | | Long | Rich | **-0.164 *** | ns | **0.16 **** | **-0.153 *** | **0.18 **** | N.C | N.C | 0.106 |
| | | | Abun | **-0.466 *** | ns | **0.427 *** | ns | **0.418 *** | N.C | N.C | 0.362 |
| | C | Short | Rich | ns | ns | **0.098 **** | ns | **-0.088 *** | N.C | N.C | 0.106 |
| | | | Abun | **-0.387 **** | ns | **0.342 **** | **-0.365 *** | **-0.554 ***** | N.C | N.C | 0.38 |
| | | Long | Rich | ns | ns | ns | ns | ns | N.C | N.C | 0.109 |
| | | | Abun | ns | ns | ns | **-0.474 *** | ns | N.C | N.C | 0.397 |
| Plants | C | Short | Rich | **0.264 **** | ns | **0.233 **** | ns | **0.181 *** | N.C | N.C | 0.213 |
| | | Long | Rich | **0.267 *** | ns | **0.266 **** | ns | **0.219 *** | N.C | N.C | 0.151 |
| | H | Short | Rich | ns | ns | ns | **-0.09 *** | ns | **0.134 *** | **0.172 *** | 0.174 |
| | | Long | Rich | **0.073 *** | ns | ns | **-0.072 *** | ns | **0.12 *** | **0.113 *** | 0.188 |
| | G | Short | Rich | **0.153 ***** | ns | ns | ns | ns | ns | ns | 0.178 |
| | | Long | Rich | **0.081 *** | ns | ns | ns | **-0.045 *** | ns | ns | 0.134 |

Mesoclimate also influenced carabids in both habitat types and plants in open habitats. Mean daily temperature (gtg) showed contrasted effects: it was negatively correlated with richness and abundance of short-dispersed carabids in both habitats but positively correlated with long-dispersed hedgerow/grassland carabids. For plants, gtg positively affected cropland richness but negatively affected long-dispersed grassland richness. These contrasting responses, partly associated with dispersal classes, may reflect differences in phenology, activity, or the ability to avoid unfavorable conditions. However, as dispersal classes do not necessarily represent homogeneous response groups, further studies are needed to clarify the mechanisms underlying climatic effects.

When significant, landscape effects were consistent across taxa and habitats: configurational heterogeneity and grassland cover had positive effects, whereas hedgerow length had negative effects. Those negative effects for hedgerow communities were possibly due to biotic homogenization with increasing hedgerow density. However, the strongest negative effect occurred for cropland carabids. The positive effect of grassland cover on crop carabids likely reflects easier dispersal and the provision of overwintering habitats (Massaloux et al., 2020). Similarly, the positive effect of configurational heterogeneity (pNC.hete) on short-dispersed carabids may result from increased edge density enhancing mobility between patches (Massaloux et al., 2020). Compositional heterogeneity (SHDI) showed contrasting effects, being negative for carabids (in hedgerow/grassland and cropland habitats) but positive for plants in all habitats.

## Conclusion

Our study demonstrated that landscape and climatic variables influenced community structure of small-size taxonomic groups. The response patterns to landscape heterogeneity, habitat amount and temperature were often dependent on species dispersal ability, but also differ among groups and habitat types. Further analyses of these effects on other components of community structure such as diversity, evenness or composition should be assessed to better understand these effects. Future work will aim to explicitly integrate interactions between climatic and landscape variables in the assessment of biodiversity patterns, while maintaining a focus on species dispersal classes. Such an approach should improve our understanding of how landscape management practices differentially affect taxonomic subgroups.

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# Assessing landscape-scale impacts of agrivoltaic solar trackers on bat activity and prey availability

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**Abstract:** Agrivoltaics is an integrated approach that synergistically combines agriculture and solar energy production within the same space. However, it faces a "green-green dilemma" since positive effects on greenhouse gas emission may be compromised by biodiversity impacts. Ecological impacts of solar energy production, particularly on biodiversity, remain poorly understood. Like other energy infrastructures, photovoltaic panel deployment can fragment habitats, alter wildlife behavior, and generate disturbances that are difficult to quantify and often overlooked, yet may influence landscape structure and connectivity. Thus, we are asking how agrivoltaics can be properly planned to reconcile energy production with ecological balance. In France, its development often lacks spatial planning, as it was the case for wind energy (2002-2009), resulting in installations poorly adapted to ecological and landscape issues. Our research examines the effects of isolated bi-axial, 7-m high solar panels called "trackers" on functional biodiversity, using bats as bioindicator taxa and nocturnal flying insects to integrate prey-predator dynamics. Bats are key pest regulators in agroecosystems, and their sensitivity to landscape changes enables us to quantify the effects of trackers on ecological connectivity. Acoustic monitoring was conducted in 2025 across 28 paired pastures (with/without trackers) in western France (Ille-et-Vilaine, Mayenne, Sarthe), covering contrasted landscapes. Pairs were selected to represent diverse landscape contexts while maintaining comparable environmental conditions between paired sites. This experimental design provides a robust framework for understanding how landscape and infrastructure interact to shape local biological responses. The results provide essential insights for sustainable spatial planning that reconciles energy production with functional biodiversity while maintaining ecological connectivity in agricultural matrices.

**Key words:** agrivoltaics, landscape ecology, bats, ecological connectivity

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# Impact of pest exclusion nets on bats in apple orchards

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**Abstract:** Pest exclusion nets have recently been implemented in apple orchards to reduce the use of insecticides and are unfolded before the emergence of the codling moth, the most problematic pest. Recent studies have demonstrated that the presence of exclusion net can also impact other arthropod pests and their natural enemies. Here, we assess the effects of pest exclusion nets on insectivorous bats, which are major natural enemies of crop pests in apple orchards. We expected a lower bat activity per night in netted orchards due to a more intensive management (e. g., more frequent mowing), with a temporal effect of net deployment on bat activity per night in these orchards. We conducted a continuous acoustic survey of bats over a two-and-a-half-month period in organic apple orchards with (n = 15) and without (n = 12) pest exclusion nets in southeastern France. Global and guild-specific (functional group), bat activity per night were quantified in each orchard. Data collected during one week before and one week after net deployment in the netted orchards were extracted and used to conduct BACI (Before After Control Impact) analyses and compare bat activity per night in orchards with and without nets, before and after net deployment. Global and guild activities per night did not differ between netted and unnetted orchards in either period global and guild activities significantly declined in unnetted orchards after net deployment. More frequent insecticides applications in unnetted orchards may explain this pattern.

**Key words:** bats, pest exclusion nets, single-row nets, apple orchards, agricultural practices, organic, BACI

## Introduction

Insectivorous bats are important crop pest enemies, consuming 40 to more than 100 % of their body mass in arthropods each night (Cleveland et al., 2006; Kunz et al., 2011). They consume a high diversity of pests in different crop types, both perennial and annual such as orchards or arable crops (Ancillotto et al., 2024; Tuneu-Corral et al., 2023) and can thus significantly reduce crop damage and improve yields (Tuneu-Corral et al., 2024). Apples are the most cultivated fruit in mainland France. To reach industrial volumes and standards of quality, apple orchard management is highly intensive and relies on a heavy use of pesticides with detrimental effects to humans, non-humans organisms and the environment (One health, Zhou et al., 2025). To reduce the systematic use of insecticides, alternative methods are increasingly being implemented in apple orchards. Among them, pest exclusion nets (either full block net enclosing the entire orchard or single row nets with one net for each row of apple trees) are deployed before the emergence of codling moths (*Cydia pomonella*), small moths which are the most problematic pests in apple orchards. Previous studies have shown that nets significantly affect several arthropod taxa presence probability (either positively or negatively, Poinas et al., 2025).

Bats are sensitive to orchards tree structure (Obrist et al., 2011), landscape context (Miñarro and García, 2025) and local agricultural practices (Fialas et al., 2023). However, to our knowledge, no study has yet evaluated the impact of the presence of single-row nets and of their deployment on bats. Here, we address this gap using a Before After Control Impact (BACI, see Christie et al., 2019) design, comparing the activity per night of different bat guilds in orchards with and without nets, before and after their deployment.

## Materials and methods

### *Study site and orchard selection*

The study was conducted in the "Basse Vallée de la Durance" study area, located in southeastern France. It covers more than 400 km², stretching from the Alpilles mountains to the Durance River, and encompasses a large horticultural production area. The region is characterized by a Mediterranean climate and regular strong winds. 27 organic apple orchards were sampled across the study site, including 12 orchards without nets and 15 orchards with nets. All nets were Alt'carpo single-row nets, designed against the codling moths with a 2.2 × 5.5 mm mesh size. When deployed, each net covers one row from the top to the trunk of trees and is fastened at the bottom. Outside of the deployment period, nets stay in the orchards and are folded above the trees. Therefore, hereafter orchards are characterized by the (year-long) presence or absence of nets, and their (temporary) deployment status in the concerned orchards.

### *Bat data collection and classification*

We conducted a continuous acoustic survey of bats (i. e., recorded bat echolocation calls) from late March/early April until early June 2025. This period runs from before to after the deployment time of the nets. We deployed one passive bat detector (Wildlife Acoustics SM4BAT FS) per orchard, at 15 m from the northward hedgerow. Bats are detected according to the weather conditions (sound attenuation), their distance from the passive detector and their echolocation range, related to their guild (functional group): (i) Long Range Echolocators (LRE, between about 50 and 100 m), (ii) Middle Range Echolocators (MRE, between about 20 and 50 m), and (iii) Short Range Echolocators (SRE, between about 5 and 15 m) (Denzinger and Schnitzler, 2013). Recording was programmed from 30 minutes before sunset to 30 minutes after sunrise, following the Vigie-Chiro French National Bat Monitoring Programme guidelines ("Point-Fixe" protocol). Throughout the sampling period, each orchard was visited once a week to collect the data and note the deployment status of the nets. The microphone was moved outside the net when nets were deployed.

Bat species were automatically classified using Kaleidoscope Pro bat analyses software (version 5.7.0, Wildlife Acoustic). Files were split into sequences with a maximum duration of 5 s and analyzed using the Auto ID for Bats function with the Bats of Europe classifier (version 5.7.0), set to the balanced (neutral) sensitivity level and including an available list of 30 out of the 36 bat species occurring in mainland France. *Tadarida teniotis* were discarded due to their frequent confusions with birds. Each line of the software outputs refers to a bat bass, i. e., a sequence with at least one bat echolocation call. Species were also grouped in guilds (functional groups) based on their echolocation characteristics which also relate to their foraging behavior (Denzinger and Schnitzler, 2013). Global bat activity and activity by guild per night were then estimated as the number of bat passes per orchard per night.

***Orchard pairing***

To better account for variance in landscape context among orchards, we created 12 orchard pairs among the 27 sampled orchards, each composed of one orchard with net and one without. Pairs were determined with the *MatchIt* and *cobalt* packages on Rstudio based on values of several landscape co-variables for each orchard. These co-variables were the minimum distance from the sensor position to watercourses and to 2 × 2 lanes and highways, and proportions of built-up areas, apple orchards, wooded areas, open land (including arable crops, grasslands and fallow lands), and length of hedges in a 1 km buffer around the center of each orchard. These variables were calculated, based on a local land use layer of the study area and on BD TOPO data. We processed 100 000 iterations to maximize our chances to find the best match as possible.

***Data preparation and statistical analyses***

For each pair of orchards, we sampled the bat and weather data to retain 2 sample periods of one week before and one week after the deployment of nets in the netted orchard. We processed BACI models on bat activity per night (either global or by guild) using Generalized Linear Mixed Models (GLMMs) with a negative binomial distribution (R package *glmmTMB*). The models included the presence of exclusion nets, the period in regard to nets deployment (before, after), their interaction, rainfall per night, wind speed before sunset, and temperature before sunset as fixed effects and pair ID and apple orchard IDs as random effects. The three weather variables were scaled (mean 0, variance 1) to facilitate the comparison of their estimates.

## Results and discussion

***Bat data***

We identified 28 bat species (including *Tadarida teniosis*). The MRE guild was dominant, accounting for 96.6 % of bat passes, followed by the LRE guild (2.4 % of bat passes) and by the SRE guild (1 % of bat passes). The dominant species were *Pipistrellus kuhlii, Pipistrellus pygmaeus, Pipistrellus pipistrellus, Miniopterus schreibersii* and *Pipistrellus nathusii.* All belong to the MRE guild.

***Bat activity response to weather variables***

Global bat activity per night significantly increased with temperature before sunset (p-value < 0.001, Estimate = 0.787, Std. Error = 0.095) and significantly decreased with rainfall per night (p-value < 0.001, Estimate = -0.396, Std. Error = 0.095). Wind speed before sunset did not significantly impact global bat activity per night. For bat guild models, the same pattern was observed for temperature before sunset and rainfall per night for all guilds (MRE, SRE and LRE). However, SRE and LRE activity per night, but not MRE activity, decreased significantly with increasing wind speed.

***Bat activity response to pest exclusion net presence and deployment***

All significant responses considering global bat activity were driven by the MRE bat guild. The presence of nets did not significantly affect global and guild-level bat activity per night (Figure 1). However, the interaction between ‘presence of nets’ and ‘net deployment’ was significant (p-value of 0.012 for global activity and of 0.003, 0.001 and 0.003 for the MRE, SRE and LRE guilds), with a significant decrease of global and guild bat activity per night in unnetted orchards after net deployment (Figure 1).

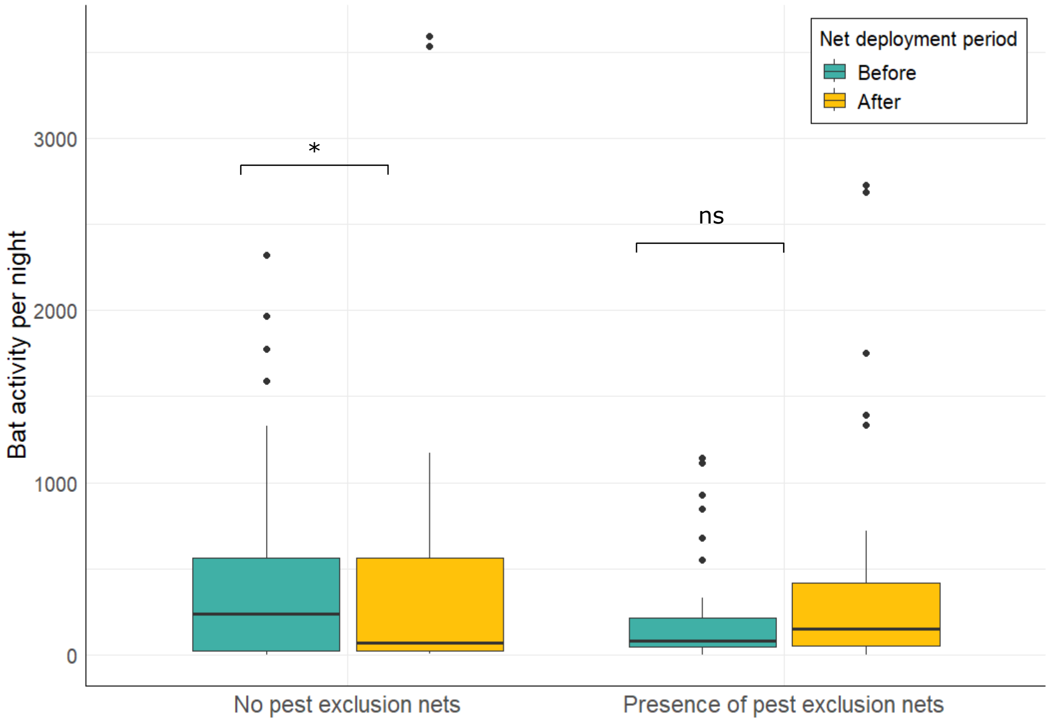

Figure 1. Global bat activity per night (number of bat passes calculated from identifications in 5 s files) according to the presence of exclusion nets in the orchard and its deployment status (before deployment = folded VS after deployment = unfolded).

### ***Discussion & prospects***

The responses of bat activity to weather conditions are consistent with the literature. The absence of response of MRE activity to wind speed can likely be attributed to the installation of all bat detectors in locations protected by windbreak hedgerows. Bat activity tendency to be higher in orchards without pest exclusion nets before net deployment could be explained by less intensive grass cover and orchard management before pest emergence, resulting in a higher abundance of prey in these orchards. The decrease in bat activity in orchards without nets after net were deployed in netted orchards was unexpected given bat phenology in the study area, but it might be explained by local agricultural practices applied in these orchards only. Insecticide applications were indeed shown to be more frequent in unnetted orchards (Poinas et al., 2025) and might affect the aerial insect community and subsequently bats which are highly mobile and opportunistic, feeding on ephemeral patchily distributed resources (Egert-Berg et al., 2018). This will be tested next by linking recorded bat activity with insect abundance data collected weekly in the same orchards and with data on pesticide applications during the bat sampling period. It is also possible that patterns in bat activity observed in this study are transient and further analyses will be conducted with data recorded over a longer period after net deployment

## Acknowledgements

We thank Xavier Said, for contacting and surveying fruit growers. We also thank all the fruit growers who allowed us to settle an acoustic sensor and visit their apple orchards. We warmly thank the LPO Auvergne-Rhône-Alpes, especially Anne Metaireau, for lending us SM4BAT FS for this study. Finally, we thank all people that contributed to field work. This study is part of the national ChiroVerger project led by the OFB and carried out in collaboration with INRAE.

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# Effects of personality on barn owl (*Tyto furcata*) hunting behavior and delivery of pest control services in an agroecosystem

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**Abstract:** American barn owls (*Tyto furcata*) provide valuable ecosystem services by removing rodent pests in agricultural systems. However, the role of individual behavioral variation in shaping these services remains poorly understood. Individual positioning along the bold-shy continuum may have consequences on habitat selection, hunting locations, and several other movement parameters that influence the intensity and distribution of rodent removal services provided by barn owls on vineyards. We investigated how personality traits influence hunting behavior and potential for rodent removal services by barn owls in a winegrape agroecosystem near Lodi, California USA. Individual boldness was assessed using novel object tests at nest boxes, while movement behavior was quantified via high-resolution GPS-accelerometer tags. Results revealed inter-individual differences in response to novel stimuli, providing evidence for personality traits among owls. Hidden-Markov models and step selection analysis of movement data quantified individual variation in foraging behavior, including search strategies, time activity budgets, and habitat selection. Accelerometer data and nest camera footage show effects of owl personality and landscape composition on when and where owls killed rodent pests, with potential implications for integrated pest management on agricultural landscapes. By linking both individual behavior and landscape composition to ecosystem function, our findings contribute to a more nuanced understanding of avian services in agroecosystems and support pest management strategies. This research underscores the importance of incorporating animal personality into evaluations of ecosystem services, and offers a first look at barn owl personality using measures of neophobia.

**Key words:** pests, integrated control, rodents, barn owls, ecosystem services, behavior, personality, neophobia, novel object, viticulture, California

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# Using Passive Acoustic Monitoring and BirdNET to identify drivers of bird populations: proposed analysis pipeline and application in an agricultural context

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**Abstract:** The combination of Passive Acoustic Monitoring and automated bird vocalization identification tools such as BirdNET offers great opportunities to document the factors structuring bird communities and populations. However, the current lack of case studies using this approach raises questions regarding the collection and processing of acoustic recordings, as well as the use of BirdNET generated data while ensuring the reliability of inferred ecological relationships. We propose a general pipeline to identify and mitigate the effects of confounding factors influencing both bird detectability and BirdNET performance. This pipeline was applied in a case study investigating the effects of agricultural practices in apple orchards on *Parus major* and *Erithacus rubecula*, the two-dominant species in this system and potential pest regulators. Our results demonstrate that although Passive Acoustic Monitoring combined with BirdNET is not yet a turnkey method and requires careful requires careful data filtering and optimization of classification confidence from BirdNET to ensure robust ecological inference, it can be a powerful tool for studying the factors driving bird populations when such precautions are implemented.

**Key words:** eco-acoustic, BirdNET, analysis pipeline, apple orchards

## Introduction

Agricultural intensification is widely recognized as one of the main drivers of bird population declines across Europe (Rigal et al., 2023). Documenting how specific agricultural practices influence bird populations therefore remains a major challenge to reconcile food production with biodiversity conservation. In this context, Passive Acoustic Monitoring (PAM), which relies on autonomous recorders to capture information across acoustic landscapes, offers powerful opportunities to monitor vocal species such as birds with high spatial and temporal resolution (Perez-Granados et al., 2023). However, the use of PAM generates large audio datasets, making the extraction of species level information a central challenge. Recent advances in deep learning-based classifiers, notably BirdNET (Khal et al., 2021), provide promising solutions for identifying bird vocalizations. While methodological studies have focused on improving BirdNET's performance, empirical applications investigating ecological drivers of bird populations remain scarce (Biffi et al., 2024). As a result, key questions persist regarding how to minimize detection biases and reduce uncertainties that may affect the reliability of ecological relationships inferred from BirdNET derived data. The present study addresses this gap by proposing a processing pipeline designed to limit factors that may influence bird detectability and BirdNET efficiency. We applied this pipeline to a case study assessing the effects of agricultural practices on *Parus major* and *Erithacus rubecula,* the two dominant species in commercial apple orchards near Avignon (France) during the breeding season. Both are insectivorous and capable of consuming pest species. In particular, the role of *Parus major* as a pest regulator in agricultural systems is well documented (Mols and Visser, 2007). This study aims to obtain high-resolution spatial and temporal data by combining passive acoustic monitoring (PAM) with BirdNET, thereby improving our understanding of the factors influencing the presence of these species and enabling a more accurate assessment of their potential role as pest regulators in orchards.

## Analysis pipeline

***Raw data acquisition and cleaning***

The first step when designing an acoustic monitoring protocol is to account for the factors that may influence sound propagation and bird activity. Some of these factors can be controlled during data acquisition, for instance by using identical recording devices and standardizing recorder placement. However, other sources of variation, such as weather conditions or ambient noise levels, cannot always be directly controlled in the field, even though they are known to affect bird detectability and vocal activity. Consequently, particular attention must be paid during data processing to ensure that recordings collected under heterogeneous conditions do not introduce bias. When recording conditions differ across sites, a data cleaning procedure is required, typically involving the exclusion of days with adverse weather and sites subject to excessive noise pollution. However, this step can be challenging, as filtering often results in substantial data loss, which may limit the capacity to detect complex ecological patterns that require large sample sizes.

***Maximization of good answer of BirdNET***

When BirdNET processes recordings, it assigns to each detected vocalization a species identity and a confidence score. This score ranges from 0 to 1, and higher values generally indicate more reliable detections. However, detection reliability varies across species, which creates a need to determine species-specific confidence score thresholds to maximize the proportion of correct identifications in the analyzed dataset (Funosas et al., 2024). Several studies have proposed methods to establish such thresholds (Barré et al., 2019; Singer et al., 2024). Although their approaches differ slightly, they all rely on validation of a subset of BirdNET detections for each species. This validation allows the construction of generalized linear models describing the probability of a correct identification as a function of the confidence score, from which a species-specific threshold corresponding to a desired accuracy level can be derived.

***Summary of the pipeline***

The different steps described above make it possible to move from heterogeneous acoustic recordings to a final dataset containing BirdNET detections with a controlled proportion of correct identifications, while reducing the influence of variable recording conditions across sites (Figure 1).

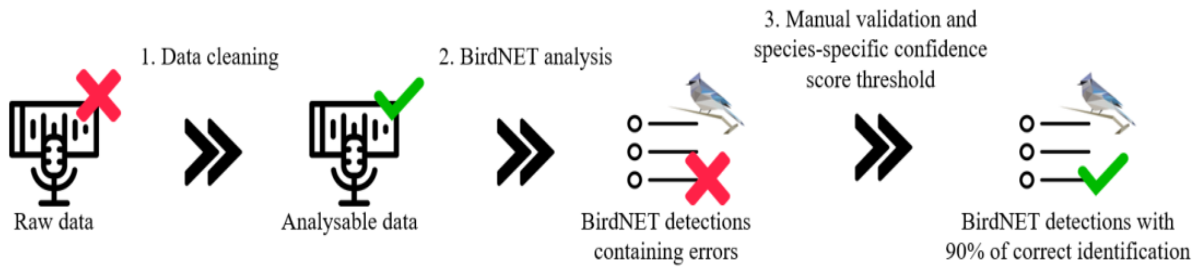

Figure 1. Overview of the analysis pipeline accounting for factors affecting bird detectability and BirdNET performance.

## Case study: Assessing the effects of agricultural practices on *Parus major* and *Erithacus rubecula* in apple orchards

### *Study area, data acquisition*

The study area is located near Avignon, southeastern France. This region is characterized by a mosaic of habitats dominated by apple orchards and intersected by a dense network of hedgerows. Surveys were conducted in 58 commercial orchards during spring 2024. Among these orchards, thirty-nine were managed under organic production methods and nineteen under conventional management. We also considered the presence of insect-proof nets (nineteen of the thirty-nine organic orchards were equipped), orchard surface area and the length of hedgerows surrounding each orchard. This value was quantified using orthophoto analysis in QGIS and normalized by orchard surface area, following the method described by Bouvier et al. (2022). Acoustic recordings were collected for 30 minutes per hour over a two-week period in each orchard, with autonomous recorders positioned at the center of the orchards. Two monitoring sessions were conducted, one early in the season between 15 March and 15 April, and another later between 29 April and 10 June. This represents a total of 168 hours of recordings per orchard.

### *Data cleaning effects*

Due to adverse weather conditions, the exclusion of days with unsuitable meteorological situations was necessary to homogenize the data across orchards. After filtering, five valid recording days remained for each orchard, which resulted in a substantial reduction in the initial dataset. To address sound pollution, the NDSI acoustic index was used to identify orchards affected by excessive anthropogenic noise. This analysis led to the exclusion of ten orchards whose proximity to roads or highways produced highly polluted recordings. The final dataset therefore consisted of five days of recordings from forty-eight orchards.

### *BirdNET identification and accuracy for the two species*

On the homogenized dataset, BirdNET detected 84 425 vocalizations of *Parus major* and 419 123 of *Erithacus rubecula*. For *Parus major*, 725 BirdNET detections were verified through expert listening, evenly distributed across the full range of confidence scores from zero to one. Among these validations, 669 detections were correct and 48 were incorrect. No errors were observed at high confidence values, and ninety percent of the misidentifications occurred at confidence scores below 0.4. For *Erithacus rubecula*, 692 detections were manually validated, of which 677 were correct and 14 incorrect. As for *Parus major*, no errors were found at high confidence levels, and ninety percent of the misidentifications occurred below a confidence score of 0.3. A binary generalized linear model was then used to estimate the confidence score corresponding to a probability of 90 % correct identification (Figure 2). This modelling step yielded species-specific thresholds of 0.34 for *Parus major* and 0.15 for *Erithacus rubecula* (Figure 2). Applying these thresholds resulted in a final dataset of 42 842 detections for *Parus major* and 365 695 detections for *Erithacus rubecula*.

***Metrics used***

The number of BirdNET detections of *Parus major* and *Erithacus rubecula* per day and per orchard was used as a proxy for the activity-density of each species across the study sites. This measure does not represent abundance, as it depends both on the number of individuals present and on their vocal activity.

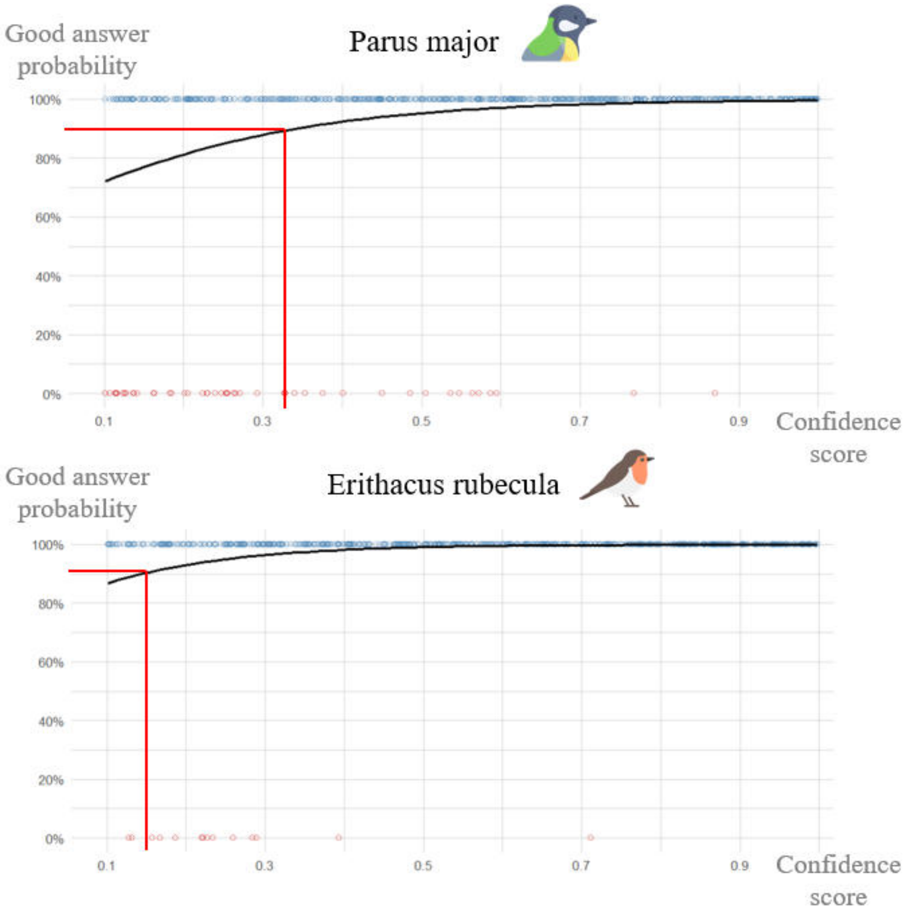

Figure 2. Binary generalized linear model of the probability of good answer from BirdNET as a function of the confidence score for the two species

***Effect of local orchard characteristics on Parus major and Erithacus rubecula***

Orchard management significantly influenced *Parus major*, with higher detection rates observed in organic orchards compared to conventional ones (Figure 3). In contrast, *Erithacus rubecula* was not affected by orchards management (Figure 4).

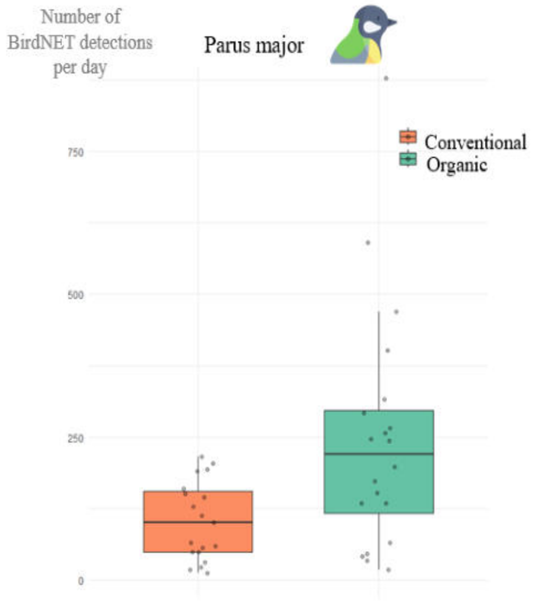

Figure 3. *Parus major* detections number per day per orchard as a function of farming system.

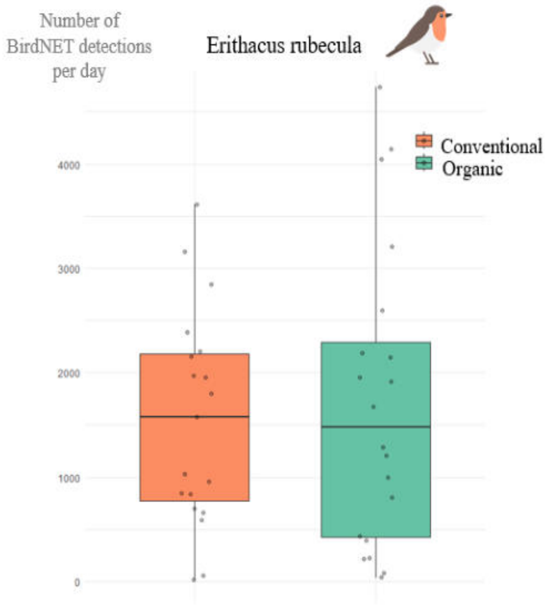

Figure 4. *Erithacus rubecula* detections number per day per orchard as a function of farming system.

The use of activity-density as an acoustic metric made it possible to identify the main ecological drivers of the two species at the orchard scale (Figures 3 and 4). These relationships are consistent with findings from previous studies based on standard point-count surveys (Bouvier et al., 2022). Together, these results demonstrate both the ability of this metric to describe species activity-density at a local scale and the importance of orchard management for different species using orchards during the breeding season.

## General discussion

The combination of Passive Acoustic Monitoring and BirdNET offers a promising approach for identifying the factors structuring bird populations in the future. However, at present, this approach is not a turnkey solution. Careful preparatory steps are required to minimize the influence of environmental recording conditions and to account for BirdNET errors to maximize the reliability of the ecological relationships inferred from the data.

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# Community-level responses of wild bees to anthropized landscapes

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**Abstract:** Post-industrial landscapes such as the one found in Northern Europe Belgium are home to an impoverished community of pollinators, probably as a by-product of ever-increasing urbanisation and intensive agriculture. Yet, cities within this kind of environments have been found to host surprisingly diverse assemblages of bees around the globe. As a result, local policies may want to take advantage of this phenomenon as a lever for conservation, rather than extending their network of nature reserves. However, the apparent richness found in urban areas may actually hide ambiguous patterns of diversity, especially when it comes to the distribution of rare or endangered species.

Our aim was to determine the effect of urbanisation on wild bee richness and evenness using increasing orders of entropic diversity. Conservation significance was also assessed by quantifying IUCN threatened species. The relative significance of protected areas in the conservation of wild bees was examined by comparing their patterns of diversity to the one found in unprotected areas. Our results suggest that while urbanisation may not have a positive effect on raw species richness, urban areas harbor a more diverse set of dominant species, albeit with a conspicuous absence of threatened ones. Conversely, nature reserves may superficially look as diverse as other types of sites, but they do concentrate rare and declining species.

This research underscores the need for a nuanced approach to biodiversity conservation, emphasizing the unique contributions of nature reserves in safeguarding vulnerable bee species.

**Key words:** urban ecology, wild bees, landscape, land cover, nature reserves, threatened species

# Wild bees in Estonian agricultural landscapes

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**Abstract:** Farmland biodiversity has declined significantly across Europe due to agricultural intensification. Habitat loss remains the primary threat to wild pollinators, making semi-natural habitats essential for sustaining pollinator communities and ecosystem functioning. Despite biodiversity-friendly policies, wild bee decline continues, with 100 additional species classified as threatened in 2025. Understanding how landscape composition and field-boundary structures influence wild bee diversity is a key to effective conservation within farming systems.

During the Horizon 2020 projects Quessa (2013-2017) and FrameWork (2020-2025), we studied wild bee diversity in Estonia's agricultural landscapes. Using a spatially guided balanced design, we assessed bee communities in relation to common field-boundary types (herbaceous and woody linear) across 18 one-kilometre radius circles. To evaluate landscape-scale effects, we applied a spatially stratified design across 18 one-square-kilometre squares dominated by agricultural land, each containing a one-kilometre transect covering the main land-use classes present (including arable fields and seminatural habitats). Bees were collected using pan traps and identified morphologically.

We recorded ~ 75 % of *Bombus* and ~ 17 % of other wild bee species know from Estonia. *Bombus lucorum*, *B. terrestris*, *B. hortorum* were the most abundant bumblebees, while *Lasioglossum albipes*, *L. calceatum*, *L. leucopus* and *Seladonia tumulorum* dominated among solitary bees. Bee abundance was influenced by habitat type and surrounding land use, with larger patch sizes linked to lower species diversity and higher edge density associated with an increased Shannon index.

Our results underscore the importance of maintaining diverse and stable microhabitats, such as field boundaries, to support wild bee species in agricultural landscapes.

**Key words:** landscape management, pollination, semi-natural habitat

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# Functional vegetative strips associated with beneficial entomofauna in a polyculture system in Québec, Canada

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**Abstract:** Diverse hedgerows promoting functional biodiversity were implemented on an ecological polyculture farm located in southwestern Québec, Canada. This study explored the potential of these hedgerows to support natural enemies of two cruciferous crop pests and pollinators of cucurbits. In 2018 and 2019, the abundance and diversity of natural enemies were measured on ten selected plant species. Larval and pupal parasitism rates of major lepidopteran pests were evaluated in crucifer plots adjacent to hedgerows, along with pollinator abundance and diversity in cucurbit plots. *Achillea millefolium* (Asteraceae), *Symphytum × plandicum* (Boraginaceae) and *Caragana arborescens* (Fabaceae) supported the highest number of hymenopteran parasitoid families targeting crucifer-defoliating caterpillars. Parasitism rates of *Pieris rapae* and *Plutella xylostella* larvae ranged from 34.4 % to 65.4 %, depending on species and years. The hedgerows were also associated with *Lasioglossum* sp. and *Peponapis pruinosa*, known to be effective pollinators of cucurbits. This project contributes to supporting evidence for ecological services provided by vegetative strips in polyculture systems.

**Key words:** pests, parasitoids, pollinators, hedgerows, crucifer, cucurbit

## Introduction

Agroecosystem components, such as shrubs and perennial plants in hedgerows near crop fields, may enhance functional biodiversity and provide essential ecosystem services (García de León et al., 2021). Recently, growers in Québec have become more aware and inclined to implement semi-natural habitats to attract beneficial arthropods, thereby improving pest regulation and pollination services. However, quantitative measurements of the impact of these habitats at a farm scale are difficult to obtain from a grower's perspective. The objective of this study was to explore the beneficial arthropods associated with a diverse hedgerow, focusing on natural enemies of cruciferous pests and pollinators of cucurbits, in Québec.

## Materials and methods

### *Hedgerow and natural enemies*

This experiment was conducted in 2018 and 2019 on an ecological polyculture farm located in southwestern Québec (Hemmingford, Québec, Canada). Eighteen hedgerows of 30 m long and 2.5 m wide were established in 2015 and featured a consistent composition of 19 shrub and perennial species, regularly spaced every 12 m along vegetable crop beds. According to field observations of flowering periods, phenology and plant health, ten species were selected for sampling during the project, as they were more likely to attract beneficial insects (data not shown). Natural enemies were sampled weekly in four hedgerows in 2018 and three in 2019. Flowering plants were randomly selected during their flowering period and were vacuum-sampled using an inversed leaf blower for 15 sec each, from May 22 to August 16 in 2018 and June 12 to September 17 in 2019.

### *Cruciferous pest and parasitism rates*

Ten randomly selected crop plants were observed weekly in each plot (two beds with two rows each) adjacent to the sampled hedgerows, and the abundance of pests and their natural enemies was recorded. Crops included several varieties of cabbage, cauliflower and broccoli, cultivated from May 22 to September 24, according to the bed and years. Larvae of the small cabbage white (SCW) *Pieris rapae* (L.) and the diamondback moth (DBM), *Plutella xylostella* (L.) that were longer than 1 cm, as well as pupae, were collected during scouting and allowed to develop under laboratory conditions (25 °C, 16 L:8 D, 65 % RH) to evaluate parasitism rates.

### *Pollinators of cucurbits*

Pollinators were sampled in two zucchini beds and in adjacent hedgerows in 2018 and 2019 using pan traps. During crop flowering, 12 to 24 traps were installed in each plot and hedgerow. Sampling occurred over 72 h every 14 days in 2018 and every 7 days in 2019, for a total of 120 and 306 trap-samples, respectively. Insects were preserved in ethanol 70 % (v/v) until identification to species level whenever possible, using a stereomicroscope.

## Results and discussion

### *Hedgerows and natural enemies*

Table 1 shows the total number of samples per species for each week of the 2018 and 2019 growing seasons, while Table 2 presents the total abundances of parasitoids and predators. *Achillea millefolium* (Asteraceae), *Symphytum* × *plandicum* (Boraginaceae), *Caragana arborescens* (Fabaceae), *Levisticum officinale* (Apiaceae) and *Monarda didyma* (Lamiaceae) were sampled more frequently due to the relative importance of their flowering periods and abundance. Along with *Sambucus canadensis* (Caprifoliaceae*)*, these species were associated with the highest catches of parasitoids and predators. All parasitoids sampled belonged to the order Hymenoptera, comprising 11 superfamilies, five of which included species parasitizing cruciferous lepidopteran larvae: Eulophidae, Encyrtidae, Pteromalidae, Braconidae and Ichneumonidae. Spiders (Araneae) were the most abundant predator group, representing 55 % and 77 % of the total catches in 2018 and 2019, respectively.

### *Cruciferous pest and parasitism rates*

The main pests scouted were SCW and DBM, with mean abundances of 1.89 SCW/plant (min. 0.10; max 5.30) in 2018 and 0.25 SCW/plant (min. 0.00; max. 1.60) in 2019. For DBM, mean abundances were 0.24 DBM/plant (min. 0.00; max. 0.65) in 2018 and 0.25 DBM/plant (min. 0.00; max. 0.95) in 2019. Among the parasitism observations, 95 % were associated with *Cotesia rubecula* (Marshall) (Braconidae) and *Diadegma insulare* (Cresson) (Ichneumonidae). *Cotesia rubecula* primarily parasitized SCW, whereas *D. insulare* was associated with DBM. The SCW parasitism rates in our study (61.3 % for larvae in 2018; 80 % and 94.7 % for pupae; Table 3) were higher than previously reported in the same region of Québec (32.4 % for larvae; 22.8 % for pupae) (Godin and Boivin, 1998), although differences may reflect variations in site conditions, sampling effort, or methodology.

Table 1. Flowering species sampled weekly in hedgerows in 2018 and 2019.

| **Year** | **Month:** | **May** | | **June** | | | | **July** | | | | | **August** | | | | **Sept.** | | | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Week number:* | *21* | *22* | *23* | *24* | *25* | *26* | *27* | *28* | *29* | *30* | *31* | *32* | *33* | *34* | *35* | *36* | *37* | *38* | |
| | **Scientific name** | Sampling effort (n samples per week) | | | | | | | | | | | | | | | | | | |
| *2018* | *Achillea millefolium* | | | | | | | 2 | 1 | 2 | 2 | 3 | 2 | 2 | | | | | | 14 |
| | *Amelanchier canadensis* | 1 | | | | | | | | | | | | | | | | | | 1 |
| | *Aronia melanocarpa* | | 1 | | | | | | | | | | | | | | | | | 1 |
| | *Caragana arborescens* | 1 | 2 | 1 | | | | | | | | | | | | | | | | 4 |
| | *Levisticum officinale* | | | | | | 2 | 2 | 1 | 2 | 2 | 2 | 1 | | | | | | | 12 |
| | *Monarda didyma* | | | | | | | 2 | 1 | 2 | 2 | 2 | 1 | 1 | | | | | | 11 |
| | *Ribes nigrum* | 1 | | | | | | | | | | | | | | | | | | 1 |
| | *Sambucus canadensis* | | | | | | 2 | 2 | 1 | 2 | | | | | | | | | | 7 |
| | *Symphytum x plandicum* | | | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 1 | | | | | | | |
| | *Viburnum lentago* | | 1 | 1 | | | | | | | | | | | | | | | | 2 |
| | **Total 2018** | 3 | 4 | 4 | 2 | 2 | 6 | 10 | 5 | 10 | 8 | 10 | 5 | 4 | | | | | | 73 |
| 2019 | *Achillea millefolium* | | | | | | | | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 17 |
| | *Levisticum officinale* | | | | | | | 1 | 2 | 1 | 1 | 1 | | | | | | | | 6 |
| | *Monarda didyma* | | | | | | | | 1 | 1 | 1 | 1 | | | | | | | | 4 |
| | *Sambucus canadensis* | | | | | | | 3 | 2 | 2 | | | | | | | | | | 7 |
| | *Symphytum× plandicum* | | | | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | | | 21 |
| | *Viburnum lentago* | | | | 2 | 1 | | | | | | | | | | | | | | 3 |
| | **Total 2019** | | | | 3 | 3 | 2 | 6 | 9 | 8 | 6 | 5 | 2 | 4 | 4 | 2 | 2 | 1 | 1 | 58 |

Species not sampled: *Aralia cordata,* Aster spp, *Coreopsis verticillata, Deschampsia cespitosa, Juniperus communis, Lonicera caerulea* var. *edulis, Prunus tomentosa, Ribes × nidigrolaria, Shepherdia canadensis.*

Table 2. Abundance of parasitoids and predators from vacuum sampling on flowers in the hedgerows in 2018 and 2019.

| **Parasitoids** | | | **Predators** | | |
|---|---|---|---|---|---|
| **Superfamily** | **2018** | **2019** | **(Super)Family** | **2018** | **2019** |
| Ceraphronoidea | 17 | 5 | Araneae | 109 | 77 |
| Chalcidoidea* | 200 | 206 | Caraboidea | 1 | 1 |
| Chrysidoidea | 0 | 1 | Chrysopidae | 1 | 0 |
| Cynipoidae | 38 | 10 | Cimicoidea | 62 | 6 |
| Diaprioidea | 1 | 0 | Coccinelloidea | 7 | 9 |
| Evanioidea | 1 | 0 | Elateroidea | 7 | 5 |
| Ichneumonoidea* | 35 | 24 | Nabidae | 3 | 3 |
| Mymarommatoidea | 0 | 1 | Pentatomoidea | 1 | 5 |
| Platygastroidea | 58 | 50 | Reduvioidea | 6 | 3 |
| Proctotrupoidea | 0 | 3 | Staphylinoidea | 3 | 0 |
| | | | Vespoidea | 0 | 1 |
| **Total** | **350** | **300** | **Total** | **200** | **110** |

(*) Superfamilies that included species parasitizing cruciferous defoliating caterpillars.

Table 3. Parasitism rates observed on larvae (> 1 cm) and pupae of *Pieris rapae* (SCW) and *Plutella xylostella* (DBM) scouted and collected, in cruciferous crops in 2018 and 2019.

| | **SCW** | | **DBM** | |
|---|---|---|---|---|
| | **2018** | **2019** | **2018** | **2019** |
| Larvae (n) | 142 | 32 | 36 | 26 |
| Pupae (n) | 75 | 5 | 16 | 33 |
| Larvae parasitism (%) | 61.3 | 34.4 | 52.8 | 65.4 |
| Pupae parasitism (%) | 94.7 | 80.0 | 81.3 | 87.9 |
| **Total parasitism (%)** | **72.8** | **44.1** | **61.5** | **76.7** |

***Pollinators of cucurbits***

Table 4 presents the species composition and abundance of pollinators sampled in zucchini plots and hedgerows. The two most abundant pollinators were *Lasioglossum* sp. and *Peponapis pruinosa* (Say). *Lasioglossum* species are common solitary, ground-nesting bees in eastern Canada that forage on a wide range of plants (Packer et al., 2007). *Peponapis pruinosa* is a solitary specialist bee that feeds exclusively on cucurbit pollen and typically nests in soil near cucurbit crops (Kevan et al., 1989).

Table 4. Composition and abundance of pollinators sampled in zucchini crop and adjacent hedgerows in 2018 and 2019.

| | | **2018** | | **2019** | |
|---|---|---|---|---|---|
| **Family** | **Genus - species** | **Zucchini** | **Hedgerow** | **Zucchini** | **Hedgerow** |
| Andrenidae | *Andrena* sp. | | | 3 | 2 |
| Apidae | *Peponapis pruinosa* | 15 | | 21 | 12 |
| | Other sp. (9, each less than 5 %) | 1 | 3 | 10 | 8 |
| Colletidae | *Hylaeus* sp. | 1 | | | 2 |
| Halictidae | *Lasioglossum* sp. | 13 | 14 | 22 | 14 |
| | Other sp. (9, each less than 5 %) | 2 | 4 | 14 | 3 |
| Megachilidae | *Coelioxys* sp. | | | 1 | |
| Pemphredonidae | | | 3 | | |
| Pompilidae | | 2 | | | |
| Syrphidae | | 1 | 1 | 19 | 17 |
| Total number of pollinators (n sample) | | 35 (60) | 25 (60) | 90 (174) | 58 (132) |

This observational study provides a descriptive overview of beneficial entomofauna associated with functional vegetative strips on a polyculture farm in Québec. Despite its limited scope, the results support the relevance of plant diversity as a component of agroecosystem complexity compatible with biological control and pollination services.

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# Monitoring farmland biodiversity in European agricultural landscapes

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**Abstract:** Agricultural intensification is cited as the main contributing factor to declines in farmland biodiversity. While many countries have implemented agri-environment schemes and adopted biodiversity-friendly measures on EU and UK farmland to counteract these declines, monitoring efforts of these schemes are often inconsistent, limited to the farm-level, and focused only on scheme-specific target taxa. Therefore, there is a requirement to monitor overall farmland biodiversity in a more consistent manner, at the landscape-scale, to determine if conservation efforts are aiding in biodiversity recovery. Through the FRAMEwork project, a novel biodiversity monitoring protocol was assembled. Relevant landscape-scale biodiversity indicators were identified, and the monitoring protocols are presented as a comprehensive guide, from selecting appropriate survey squares and transect placement for different farming systems and European landscapes, to providing guidance on how to conduct biodiversity surveys of birds, pollinators (bumblebees, butterflies, solitary bees, and hoverflies), and vegetation within these survey squares.

**Key words:** conservation, biodiversity surveys, landscape-scale, Farmer Clusters

## Introduction

Farmland biodiversity has been declining over the past decade, with agricultural intensification considered the leading factor (Potts et al., 2010). In response, numerous agri-environment schemes (AES) have been implemented across EU and UK farmland to counteract these declines. These schemes incentivise farmers to adopt biodiversity-friendly farming practices and create areas on the land for wildlife to co-exist.

Biodiversity monitoring on agricultural land is typically conducted at farm- or AES option-level. Surveys targeting specific taxa or species might be conducted by a farm advisor or researcher on a single farm or across multiple farms. However, findings from such surveys do not always reflect the state of biodiversity across the wider landscape.

To address this gap, landscape-scale monitoring approaches are increasingly recognised as essential for capturing broader biodiversity trends across farmed environments (Brusse et al., 2024). Through the FRAMEwork project (Farmer clusters for Realising Agrobiodiversity Management across Ecosystems), an EU Horizon 2020 project, eleven Farmer Clusters (aggregates of farms within a region that collaboratively instigate biodiversity-friendly farming activities on their land) were established, covering a variety of farming systems, farm numbers and sizes, and landscape dispersal levels. Although there are several multi-taxa programmes that monitor biodiversity, a protocol was required that could be adapted to the diverse range of Farmer Clusters landscapes established, and capture the biodiversity indicators selected. Therefore, a new protocol was developed and trialed. This protocol could then be used to monitor changes in biodiversity across agricultural landscapes through either Before-After-Control-Impact experiments or long-term monitoring. The aim of this paper is to describe these monitoring protocols.

## Materials and methods

### *Biodiversity indicators*

The aim was to select biodiversity indicators that accurately reflect landscape-scale biodiversity. A rigorous evaluation process with a constant feedback loop was used to narrow down an initial list of over 50 potential indicators. Selection criteria included relevance at the landscape-scale and to the farmers, availability of established monitoring protocols, and the expertise of project partners in identification and monitoring. This resulted in six biodiversity indicators being selected: flowering plants (to genus) and other vegetation features (vegetation types, percentage cover of each type, height of the different vegetation layers, colour diversity of flowers etc.); butterflies (species); bumblebees (species or morphospecies); solitary bees (family, genus, or species depending on available expertise); hoverflies (as a group); and farmland birds (species).

### *Survey design*

First, all of the farms within each of the eleven Farmer Clusters were confirmed, before they were mapped and the agricultural landscape defined, confirming the specific area for biodiversity monitoring in each landscape. They were then split into 1 $km^2$ squares (0.25 $km^2$ in landscapes with smaller or more fragmented farms), as shown in Figure 1 A. In each square, the different habitats were categorised into broad habitat classes through a combination of digital mapping and on-the-ground habitat surveys, and the transects for the biodiversity indicators placed, as shown in Figure 1 B. A bird transect was oriented either north-south or east-west across each of the squares, while the pollinator and vegetation transects were co-located in different habitats that were representative of each square, ensuring that roughly 96 transect co-locations were placed across each Farmer Cluster. At least half of the pollinator transects also had a pan-trap station. This design ensured that the landscape was monitored in a stratified manner, capturing biodiversity not only across the landscape, but also encompassed different habitat types.

### *Breeding bird surveys*

Each survey square held a single 1 km transect line (500 m if in smaller squares) split into 100 m sections. The transects were walked twice each year, once between 1st April - 15th May, and once between 16th May - 30th June, dependent on local climatic conditions, adaptable to match migratory species. Surveys were conducted 1 hour after sunrise. The transects were walked at a steady pace, identifying farmland birds (Pan-European Common Bird Monitoring Scheme, nd) by either sight or sound and recording them in their representative distance bands on the survey sheet (BTO, 2018). Specific breeding behaviours were also noted.

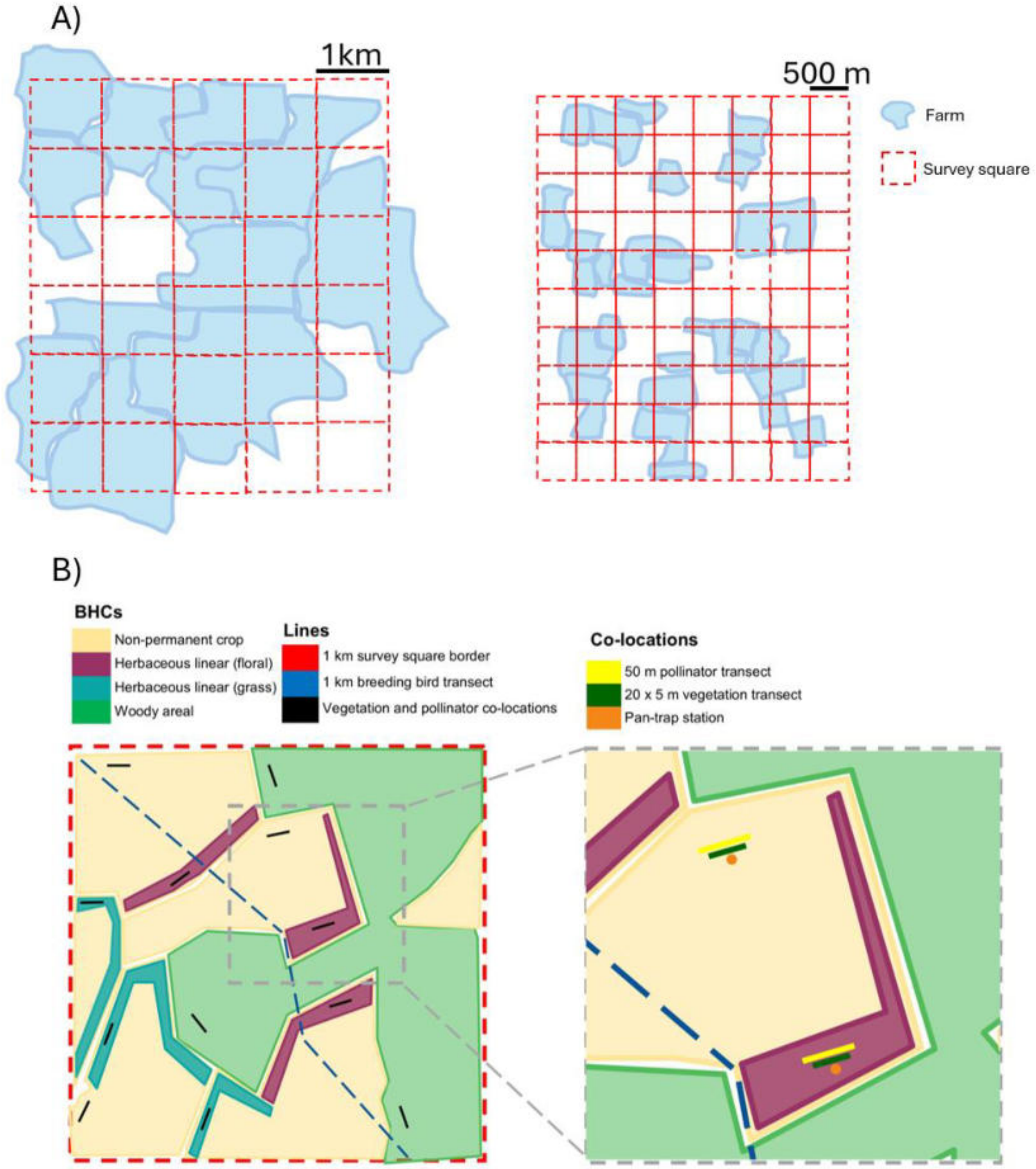

Figure 1. Survey square layout and mapping demonstration. A) a highly aggregated landscape of large farms with 1 km$^2$ grid overlayed (left) in comparison to a sparse landscape of smaller farms with 0.25 km$^2$ grid overlayed (right); B) the different Broad Habitat Classes (BHCs) mapped in a 1 km$^2$ survey square, with the transects marked on the map, and a close-up of the co-locations, each containing pollinator and vegetation transects, as well as a pan-trap station.

### ***Pollinator surveys***

All pollinator transects were surveyed four times between May and August with a minimum interval of two weeks between successive surveys. Surveys were conducted under optimal weather conditions (dry with no more than 75 % cloud cover, and temperatures above 13° C). Transects were walked lengthways at a steady pace, recording all bumblebees and butterflies within 2-4 m of the observer to species level where possible. Pan-traps were also deployed four times between April and August, at fixed locations co-located alongside the pollinator and vegetation transects. To maximise the insect pollinator diversity recorded on the farms, pan-traps were also deployed. Pan-traps were left out for 6-48 hours depending on local prior knowledge of insect attraction rates. Bumblebees, solitary bees, and butterflies were identified to species (or family/genus) level, and hoverflies were counted as a group. The data from the transects and pan-traps should be considered separately.

### ***Vegetation surveys***

Vegetation surveys were conducted twice per year, once in the late-spring to early summer (mid-April to late-June), and once in mid-to-late summer (early-July to late-August). The length of the vegetation transect was walked, and observations recorded on the survey sheet. The numbers of flowering species, flower density, flower colours, presence of indicator species are all examples of the records that were made for each transect. Surveys were similar to the EMBAL surveys (Oppermann et al., 2018).

## Conclusion

The EU's Nature Restoration Regulation sets targets to restore degraded ecosystems by 2050. In agricultural landscapes, these include reversing the decline of pollinators and improving trends for grassland butterflies and farmland birds (European Commission, n.d.). The protocols described here support landscape-scale biodiversity monitoring and may contribute to informing National Restoration Plans, particularly in farmland ecosystems. By implementing stratified sampling approaches that can be adapted to different landscapes and farming systems, these methods can help track biodiversity trends and guide restoration priorities in Member States.

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# Effects of farmland abandonment on Carabidae abundance, species richness and natural pest control

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**Abstract:** Habitat loss and intensive farming are major drivers of biodiversity decline in arable landscapes. In Europe, intensification continues in areas with fertile soils, while farmland abandonment occurs in regions affected by environmental or socioeconomic constrains. Agricultural abandonment is a land-use change in which farming operations cease and no agricultural management is carried out. Important questions remain regarding how wildlife and biodiversity respond after farming stops, as the effects can vary depending on region, soil conditions, and other abiotic or biotic factors. Rewilding these areas can potentially strengthen ecosystems and increase their resilience and sustainability. The Horizon 2020 project FrameWork (2020-2025) examined how land abandonment influences Carabidae abundance, species richness, and natural pest control rate in Estonian arable fields, using six clusters of abandoned, managed, and control fields. Abandoned fields had to have remained unmanaged for at least 5 years prior to the start of the project, while control fields were selected to ensure they were not surrounded by natural or seminatural habitats. Carabidae abundance and species richness were assessed using pitfall traps, and natural pest control was measured using sentinel prey placed at each sampling spot. Our case study revealed that natural pest control was considerably stronger in abandoned fields than in managed and control fields. Similarly, Carabidae species richness varied among field types. Overall, our findings indicate that abandoned fields through their higher pest control potential and with diverse communities, represent essential habitat patches that support key ecosystem services in agricultural landscapes.

**Key words:** ground beetles, land-use change, biodiversity, agroecosystems

# AI-based prototype sensor platform for real-time biodiversity and environmental monitoring in agroecosystems

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**Abstract:** Monitoring biodiversity is a major challenge for habitat management in agricultural landscapes. Therefore, effective tools are needed to monitor habitat quality in order to understand and preserve ecosystem functioning dynamics.

In this context, within the framework of Agritech Next EU Generation programme, specifically in the task REINFORCe ("Generate new evidence and exploit new technologies to strengthen the role of biodiversity in agriculture"), an innovative biodiversity monitoring station was developed for continuous field deployment in agroecosystems. The station has a compact footprint (30 × 30 cm; ~ 1 m height) and runs continuously under stable power and connectivity conditions. It integrates three complementary modes of data acquisition: (i) acoustic recordings, through a permanently active microphone, (ii) visual monitoring, targeting soil arthropods and pollinators, with images automatically captured every 20 seconds (from 6:00 to 20:00); and (iii) environmental sensing, recording temperature, pressure, relative humidity, VOC-based indoor air quality (IAQ), and volatile organic compound resistance every minute.

Considering a reference timeframe from July 30th to August 3rd, 2025, and from August 29th to September 30th, 2025, imagery data enabled the recognition of 10 instances of insects with an average confidence of 0.497, whereas acoustic recordings allowed the classification of 96 instances of birds with an average confidence of approximately 0.79.

Future work will focus on further improving system integration and expanding its applicability across agricultural contexts.

**Key words:** biodiversity monitoring; agroecosystems; automated sensing technologies

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# Extensive management of inter-row vegetation promotes soil fauna in Mediterranean vineyards

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**Abstract:** Soil degradation threatens ecosystem functioning, making sustainable management a global priority. In perennial crops such as vineyards, extensive inter-row vegetation may support soil biodiversity and associated functions. We assessed the effects of inter-row management on soil invertebrates by sampling vegetation, soil properties, and fauna (springtails, mites, and earthworms) in 25 organic vineyards in south-eastern France. Three practices were compared: fully vegetated inter-rows, alternating vegetated inter-rows, and shallow tillage. Shallow tillage showed direct negative effects on Gamasida mites, whereas vegetation cover and soil physic and chemistry were the main drivers of soil fauna. Anecic earthworm abundance, particularly *Lumbricus terrestris*, increased with vegetation cover and endogeic earthworm abundance with organic matter. These results underline the importance of reduced tillage and diverse inter-row vegetation to sustain soil habitats and ecological functions in vineyards.

**Key words:** soil biodiversity, ground cover, agroecology, Structural Equation Models

## Introduction

Soil degradation threatens key ecosystem services, particularly in agricultural systems where intensive practices accelerate erosion, organic matter loss, and biodiversity decline (Castellini et al., 2021). In perennial crops such as vineyards, extensive inter-row vegetation management is increasingly promoted as an alternative to intensive tillage and herbicide use, especially in Mediterranean regions prone to erosion following drought – rainfall cycles (Winter et al., 2018). Permanent or semi-permanent vegetation cover has been shown to enhance soil fertility, carbon storage, and erosion control, while supporting biodiversity and ecological functions (Brussaard et al., 2007).

While numerous studies have documented the benefits of permanent vegetation for aboveground fauna (Blaise et al., 2021), and earthworms (Vršič, 2011) fewer have examined how gradients of mechanical management influence vegetation cover, soil properties, and soil-dwelling invertebrates simultaneously (Rocher et al., 2025). Here, we investigated the effects of three inter-row vegetation management intensities – fully tilled, partially vegetated, and fully vegetated – on soil invertebrate communities, including springtails, mites and earthworms, in Mediterranean vineyards. We hypothesized that reduced management intensity, through increased plant cover and diversity, improves soil physico-chemical conditions and promotes the abundance and diversity of soil meso- and macrofauna.

## Materials and methods

### *Study sites and experimental design*

The study was conducted in 25 organic vineyards located in a rural Mediterranean region of south-eastern France (Luberon area). Vineyards were characterized by three inter-row management types: i) no vegetated inter-rows, ii) every second inter-row vegetated, and iii) all inter-rows vegetated. Although plant species were sown prior to the study, plant communites were predominantly composed by spontaneous species. The management types were coded as i) 0/2 (N = 6), ii) 1/2 (N = 9) and iii) 2/2 (N = 10), representing the number of vegetated inter-rows out of the two sampled in each plot.

### *Vegetation surveys, invertebrate sampling, and soil physical and chemical analysis*

Six samplings plots, distributed across two inter-rows, were selected in the center of each vineyard. Plant communities were surveyed in May 2019 in 2 × 2 m plots, species were identified and the total plant cover of the plot was estimated.

Springtails and mites (mesofauna) were collected in April 2019 using soil cores (5 × 7 cm) and extracted with the Berlese-Tullgren method. Specimens were subsequently counted and identified to suborder level and classified as primary consumers (Symphypleona, Entomobryomorpha, Poduromorpha and Oribatida) or secondary consumers (predatory Gamasida). Earthworms were collected during winter 2021 using soil monoliths (25 × 25 × 25 cm). Specimens were identified to the species level and classified into Bouché's (1972) ecological categories: epigeic, anecic and endogeic.

Soil properties were assessed using the upper 10 cm of soil collected from each plot. Samples were homogenized into two bulk samples per vineyard to analyze the following parameters: clay proportion, $NH_4^+$, C:N ratio, total organic matter and available copper.

### *Statistical analysis*

A Structural Equation Model (SEM) was used to assess direct and indirect relationships between inter-row management intensity, vegetation characteristics, soil properties, and soil invertebrate communities. Mean invertebrate abundances were calculated at the vineyard scale, and vegetation management intensity was coded from fully vegetated to fully tilled vineyards. Analyses were performed using piecewise SEM (piecewiseSEM package, Lefcheck, 2016) with linear models. It included covariance between plant cover and diversity. Model selection was based on AIC minimization, and model adequacy was validated using directed separation and global goodness-of-fit tests (Fisher test).

## Results and discussion

### *Limited direct effects of inter-row vegetation management*

The path analysis showed a good model fit (C = 37.8, P = 0.99). Figure 1 revealed both direct and indirect effects of inter-row vegetation management on soil communities. Increasing management intensity was directly associated with reduced plant cover and diversity, lower mesofauna secondary consumer abundance, and decreased copper availability, but with higher endogeic earthworm abundance. The weak overall tillage effect likely results from the shallow depth and low frequency of soil disturbance, that could even benefit some invertebrates (Betancur-Corredor et al., 2022; D'Hose et al., 2018). Winegrowers till during the driest months of the year, when earthworms may be less affected as they are in diapause. The low frequency of tillage decreases plant cover without reaching zero, allowing regrowth of vegetation from autumn to spring, which also maintain the periodic availability of resources and shelter for invertebrates.

### *The key role of vegetation for invertebrates and soil chemistry*

Vegetation had strong direct effects on anecic earthworms and indirectly on mesofauna secondary consumers through the increase in $NH_4^+$. Permanent inter-row vegetation likely improves microclimatic conditions by increasing soil moisture and reducing temperature fluctuations, which are known to promote mesofauna activity and survival (Pflug and Wolters, 2001). Earthworms similarly benefit from higher soil moisture (Eggleton et al., 2009). Increased plant cover also improves habitat heterogeneity and resource availability, benefiting decomposers and their predators (Hooper et al., 2000). Clay is also a major driver of vegetation, invertebrates and soil chemistry as it closely related to soil moisture (Gaur and Mohanty, 2016). Although inter-row vegetation is still often perceived by Mediterranean winegrowers as competing with vines for water and nutrients, increasing evidence points to its multiple agronomic and ecological benefits. Our results show that higher plant cover promote higher abundances of soil invertebrate communities, that could support in turn key soil functions such as nutrient cycling, soil structure, and water infiltration, representing a clear asset for sustainable viticulture.

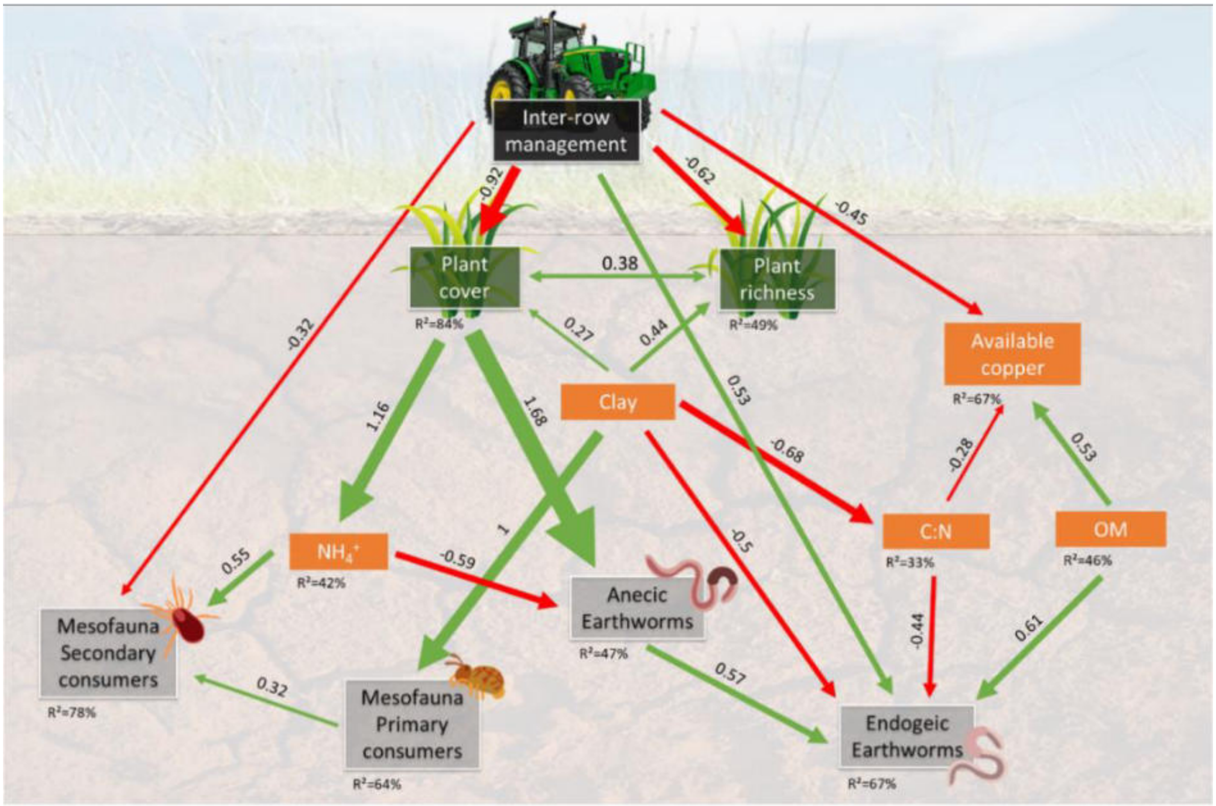

Figure 1. Path analysis model showing causal relationships between inter-row vegetation management, plants, soil physico-chemistry and invertebrates (df = 64, Fisher's C= 37.8, P-value= 0.99). Arrows are proportional to standardized and each dependant variable is associated with its percentage of explained variance.

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# Session Ecosystem services

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# A systematic map on the effects of pesticides on vineyard-associated microbiota

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**Abstract:** Chemical pesticides are widely used in viticulture to prevent diseases and arthropod pests, control weeds, and increase yield. These substances, however, can have detrimental effects on plant- and soil-associated microbiota, which is essential for nutrient cycling and other processes that support crop productivity and quality, as well as ecosystem services. In this work, we developed a systematic map to identify the literature investigating the direct effects of pesticides on vineyard-associated microbiota. A literature search conducted in 2025 across Web of Science, Scopus, and CAB Abstracts retrieved 42 relevant studies following rigorous screening and selection. The number of published papers increased from the 1980s to 2025, with more than half published between 2020 and 2025, most of them originating from Europe. Most studies assessed the impacts of chemical fungicides and herbicides, particularly on soil microbiota. Reported effects varied widely, although negative impacts on structure and growth of microbial populations were most common. In many studies, microbiota effects were not examined as the primary research objective. This systematic map shows that research has expanded only recently but remains geographically concentrated. The findings highlight significant knowledge gaps and emphasize the need for further investigation in this increasingly important field.

**Key words:** microbiota, pesticides, vineyard, literature search

## Introduction

Grapevine is a crop of global economic importance. As a perennial crop, grapevine can host a great biodiversity of microorganisms. The grapevine microbiota is composed mainly of fungi, bacteria, and protists, which are associated with the rhizosphere, roots, and aerial organs, as either endophytes or epiphytes (Bettenfeld et al., 2022). In vineyards, soil microbial communities play key roles in plant health, grape yield, wine quality, and regional wine characteristics (Silva et al., 2025). The soil microbiota also provides ecosystem services such as nutrient cycling, pathogen suppression, and soil formation (Steiner et al., 2024). Pesticides are widely used in viticulture to control pests (arthropods, pathogens and weeds) and may have a detrimental effect on non-target microorganisms and the ecosystem services they provide.

In this study, we developed a systematic map to assess the current state of research on the direct effects of pesticides on vineyard-associated microbiota through the analysis of available literature. Systematic mapping is a method for exploring broad research areas and building comprehensive literature databases with qualitative and quantitative information. By this systematic map, we aim to provide an overview of existing knowledge and highlight research gaps that require further investigation.

## Materials and methods

### *Literature searching*

The methods for developing this systematic map were adapted from existing systematic map reports (James et al., 2016; Fedele et al., 2022). On 27 October 2025 we conducted a search in three relevant online bibliographic databases: i) Web of Science Core Collection (http://webofknowledge.com/WOS), ii) Scopus (https://www.scopus.com/), and iii) CAB Abstracts (https://www.cabidigitallibrary.org). Database searches were conducted in English, and papers with the title and abstract in English, but main documents in another language were also included. Keywords for the systematic map were identified and combined into search strings. Wildcards (*) were used to detect multiple word endings. Search terms were combined using the operator AND and OR. This allows the search terms to be structured according to four thematic blocks: "Crop" (which included terms such as *Vitis vinifera*, grapevine, and vineyard), "Microbiota" (e. g., microbiome, microbiota, microflora, microbial communit*), "Pesticide" (e. g., fungicid*, pest*, insecticid*, herbicid*), and "Topic to exclude" (fertili* and biostimul*). The papers obtained from the first search in each of the selected databases were imported, then duplicates were removed.

### *Paper screening and inclusion criteria*

The titles of all papers retrieved from the database search were independently screened by each author to exclude studies that: i) did not consider grapevine as the main crop and vineyards as the primary study system; ii) did not apply pest control strategies based on plant protection products (PPPs, i. e., chemical pesticides, natural substances, or biocontrol agents); iii) did not include experiments assessing the direct effects of PPPs on the microbiota; iv) investigated the effects of management strategies on the microbiota without involving PPP applications. Standardized descriptive metadata from all studies meeting the inclusion criteria were then extracted from the abstracts and recorded in an Excel spreadsheet. The country where the trials were conducted was identified from the abstract or the corresponding author's affiliation. Additional relevant information was mainly collected from the abstract, and when necessary, verified in the full text.

## Results and discussion

### *Spatial and temporal analysis*

A total of 42 articles met the inclusion criteria for the systematic map. The earliest study was published in 1983, which was the only contribution in the 1980s; similarly, only one paper was identified from the 1990s. The number of publications increased in subsequent decades, as shown in Figure 1, indicating a marked rise in research interest in recent years. It also reflects broader methodological advances in microbial ecology, the increase in publications coinciding with the adoption of next-generation sequencing, which allowed deeper, cost-effective characterization of microbiomes (Hanson and Weinstock, 2016).

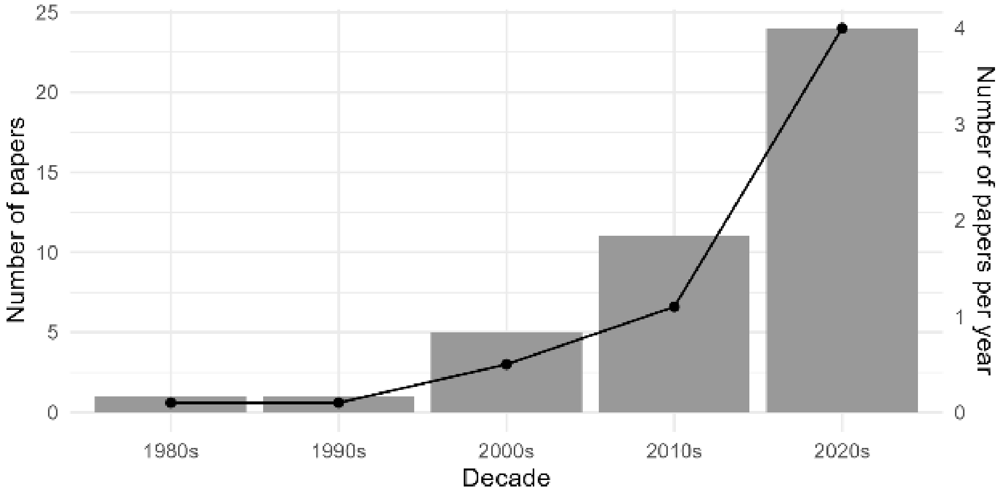

Figure 1. Average (dots) and total number (bars) of papers retrieved per each decade. Data corresponding to the 2020's consider the years from 2020 to 2025.

Field trials were conducted across 14 countries. Most studies took place in Europe, with the highest number reported in Italy and Spain (n = 9), followed by France (6), Austria (3), Portugal, Germany and Switzerland (2), and Denmark (1). One Swiss study conducted trials across Austria, Switzerland, Germany, France, and Romania, while the Danish study referred to South African vineyards. Outside Europe, most publications originated from the USA (4), Canada, Australia, China, India, and Taiwan (1). This distribution reflects the economic importance of viticulture and the strong research activity in key wine-producing countries such as Italy, France, Spain, and the USA (Cimini and Moresi, 2022). However, the exclusion of non-English literature could have resulted in the omission of relevant studies.

***Scope and results of the studies***

The primary objective across the literature was to assess the impact of PPPs on microbial communities. In several studies, this evaluation was combined with agronomic or ecological aspects, including soil functional responses, disease interactions, pesticide dissipation, and comparisons among different vineyard management practices.

Most studies focused on the microbiota associated with soil, while fewer addressed the rhizosphere, leaves, grapes or berries, and wood. In few papers, the substrate under investigation was not clearly specified. Fungicides were the most considered PPP, with emphasis for copper-based products.

Overall, the effects of pesticides on the microbiota were highly variable and dependent on the PPP used, its dosage, exposure duration, and the microbial group assessed. Documented negative impacts on microbial structure, growth, or metabolic activity were reported in roughly half of the studies, mainly involving chemical fungicides and herbicides. In several cases, however, these detrimental effects co-occurred with neutral or even positive responses in other components of the microbiome or in plant physiological traits, underscoring the inherent complexity of microbial systems (e. g., Puglisi et al., 2012; Pose-Juan et al., 2017; Chang et al., 2023). Such divergent outcomes show that a single PPP can suppress certain microbial taxa while leaving others unaffected or even promoting their activity. Some studies were considering a narrow set of microbial taxa with the aim of reducing complexity and clarifying specific mechanisms, but this approach may miss relevant microbial interactions and emergent properties at the community scale.

Some studies focused on the evaluation of how different management practices influence the soil microbiome. Under field conditions, however, numerous additional factors shape soil functioning and fertility. Abiotic properties such as pH (Fernández-Calviño et al., 2012) and soil moisture (Imfeld et al., 2024), along with spatiotemporal drivers including seasonality (Hernandez and Menéndez, 2019), and site-specific characteristics (Steiner et al., 2023; Yang et al., 2024), often exert a stronger influence on microbial communities than PPP applications themselves. Soil management practices act across multiple trophic levels, and the adoption of more nature-based approaches, such as mowing instead of herbicide use, reduced tillage, permanent cover crops, or organic farming, has been shown to enhance soil biodiversity and microbiome resilience (Del Duca et al., 2024; Blanco et al., 2024; Bopp et al., 2025). These improvements can help sustain key ecosystem services that may be diminished under conventional management. In this context, biocontrol agents and other biopesticides represent promising alternatives to synthetic pesticides, as they tend to exert fewer disruptive effects on the microbiota while simultaneously suppressing plant pathogens (He et al., 2024).

In conclusion, the scientific literature addressing PPP effects on the grapevine microbiota remains highly heterogeneous, with substantial variation in the vineyards' compartments examined, PPP types, management strategies, and observed results. This variability reflects both the intrinsic complexity of plant–microbiome interactions and the strong influence of external ecological factors, which can sometimes outweigh the effects of PPP applications. Advancing this field will require more research efforts aimed at clarifying the functions of specific microbial taxa and unravelling the interactions among the various biotic and abiotic factors that structure microbial communities. Long-term studies are particularly needed to generate more consistent evidence and support broader generalizations regarding the impacts of different PPPs on the microbiota. The growing research activity in recent years offers promising prospects for narrowing these knowledge gaps.

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# Evaluation of the augmentative effect of natural enemy releases under codling moth exclusion nets in apple orchards

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**Abstract:** In orchards, native natural enemies (NE) tend to establish too late in the season to provide effective aphid control. Augmentative biological control represents a promising strategy to enhance early-season aphid regulation. However, it remains difficult to implement in open-field due to released NE dispersal, intraguild interactions, and high dependency on weather variability. This study aims to evaluate whether codling moth exclusion nets could enhance the presence of NE after early releases of NE targeting aphids. Three netting strategies were compared: single-row, full block, and anti-hail nets as a control. Generalist predators (Chrysopidae and Forficulidae), and a specialist predator (Coccinellidae) were released. NE groups were monitored before and after releases to assess the occurrence and early arrival of NE. Analyses showed that neither the interaction between species released and netting nor netting alone affected NE group occurrence after releases. Chrysopidae releases did not show an increase in detection, whereas Coccinellidae releases enhanced both detection and precocity. Forficulidae were initially abundant, and the releases sustained high detection over time.

**Key words:** augmentative biological control, natural enemy, aphid, exclusion net, apple orchard, pest regulation

## Introduction

In apple orchards, the rosy apple aphid (RAA) *Dysaphis plantaginea* (Hemiptera: Aphididae) is a major pest. RAA natural enemies (NE) have been widely studied, but their control effect often occur too late to ensure satisfactory regulation (Dib et al., 2010). This limitation highlights the interest of early season releases of NE to control RAA populations before exponential growth. The use of augmentative biological control against aphids and other pests is mostly limited to a few agriculture systems, such as greenhouses (ex. Pineda et al., 2007). In open field, its success is constrained by released NE dispersal, intraguild predation or cannibalism, and unfavorable weather conditions (Dib et al., 2017). Since 2007, codling moth exclusion nets (Alt'Carpo nets) have been increasingly used in southern France as an effective alternative control method against *Cydia pomonella* (Lepidoptera: Tortricidae) (Poinas et al., 2025). These exclusion nets may cover either the entire orchard (full-block nets) or individual apple rows (single-row nets). A third type of nets protects fruit against hailstorm damage (anti-hail nets) and consists in covering the upper part of the orchard. We postulate that exclusion nets could enhance the success of augmentative releases of NE targeting aphids by limiting their dispersal. To test this hypothesis, we released of three NE species in a commercial apple orchard under three different types of netting and evaluated how both NE releases and netting affected NE occurence.

## Materials and methods

### *Experimental design*

The study was carried out during the 2025 spring season within a 2.15 ha organic commercial orchard (Story cultivar) located near Mallemort in Southeastern France. During the experimental period, the orchard was managed following the producer's practices but it did not receive any insecticide treatments during the winter or spring.

There were four different treatments crossed with three different netting systems in this experiment, resulting in a total of twelve different strategies (Treatment x System). The four treatments consisted of one control (no NE release) and three treatments, each involving the release of a single NE: *Adalia bipunctata* (Coleoptera: Coccinellidae), *Chrysoperla carnea* (Neuroptera: Chrysopidae) provided Koppert® FRANCE, and *Forficula* spp. (Dermaptera: Forficulidae, trapped in peach orchards). The three netting systems were single row (SR) and full block (FB) Alt'Carpo exclusion nets (mesh size: 5.2 × 2.2 mm) and anti-hail net as control (AH). For each treatment, FB and AH consisted of blocks of 63 trees each (3 rows of 21 trees) and MR consisted of 37 trees per block. FB blocks were enclosed with net partitions. The distance between blocks with different treatments was 40 m in the FB and AH, and 20 m in the SR. To avoid any edge effect, the blocks in the south and north of the orchard were at least 15m away from the edge. Anti-hail nets were closed on the 10/03 and Alt'Carpo nets were closed on the 17/04 at the end of blossom.

### *Natural enemy releases*

*Adalia bipunctata* and *C. carnea* were released using Di-boxes (5 × 5 × 6cm cardboard boxes). *Forficula* spp. were released using artificial shelters consisting of corrugated cardboard rolled to form cylinders which were inserted into PVS cylinders (5 cm diameter). One release system was attached per tree. The NE were released on two dates (Table 1). The first releases were made on 24/04 when optimal meteorological conditions were met for at least a week. The second releases were made on 15/05.

Table 1. Date, life stage and quantity of natural enemy releases per tree.

| Natural enemy | Stage released | Release 1 | Release 2 | Total per tree |
|---|---|---|---|---|
| *A. bipunctata* | 1st and 2nd instar larvae | 60 | 30 | 90 |
| *C. carnea* | 1st instar larva | 60 | 60 | 120 |
| *Forficula* spp. | 4th instar larvae and adults | 23 | 27 | 50 |

### *Arthropods sampling*

To assess whether NE releases had an effect on their presence within the experimental blocks, six trees were randomly selected at each sampling date within each block, and two solid branches were beaten three times using a stick, causing arthropods to fall on a white cloth held under. All arthropods were counted and identified (mostly at the family level). This protocol was conducted throughout the RAA infestation period; before NE release on 22/04 and after each of the two releases on 02/05 and 21/05.

***Data analysis***
All data analyses were carried out using RStudio software, version 4.5.0 (2025-04-11). Data analyses were restricted to adult and larval stages of Coccinellidae and Forficulidae and larval stages of Chrysopidae. NE group presence/absence was analyzed using binomial generalized linear models (GLM) for each date separately to specifically assess the effect of NE releases on their early-season occurrence. To analyze the effect of each treatment, release and non-release blocks were compared. Treatment and netting system effects were initially tested with an interaction term, which was removed when not significant.

## Results and discussion

Neither the interaction between treatment and netting system nor the netting system alone had a significant effect on NE group occurrence, irrespective of date or treatment.

*Chrysoperla carnea* release did not significantly increase Chrysopidae detection (Figure 1). This result is consistent with findings from a previous study (Schmidt-Jeffris et al., 2025) reporting very low capture following Chrysopidae larvae release, despite our release of 120 larvae/tree compared to 17 larvae per tree in that study. In contrast, *A. bipunctata* releases significantly increased both occurrence and early-season presence of Coccinellidae, with detections in the released treatment twice as high as in the no-release treatment following the first release. (Figure 1). Forficulidae were initially quite abundant, and releases had a significant positive effect on detection (Figure 1). As Coccinellidae are specialist predators, it is valuable to increase their occurrence early in the season, when they would likely be unable to establish naturally due to lack of prey. Unlike Chrysopidae and Coccinellidae, Forficulidae are present in the orchards year-round. *Forficula* spp. releases affected their detection rate. Releases could thus enhance their presence in orchards over the years. As generalist predators they are able to establish and feed on other resources between aphid infestation periods.

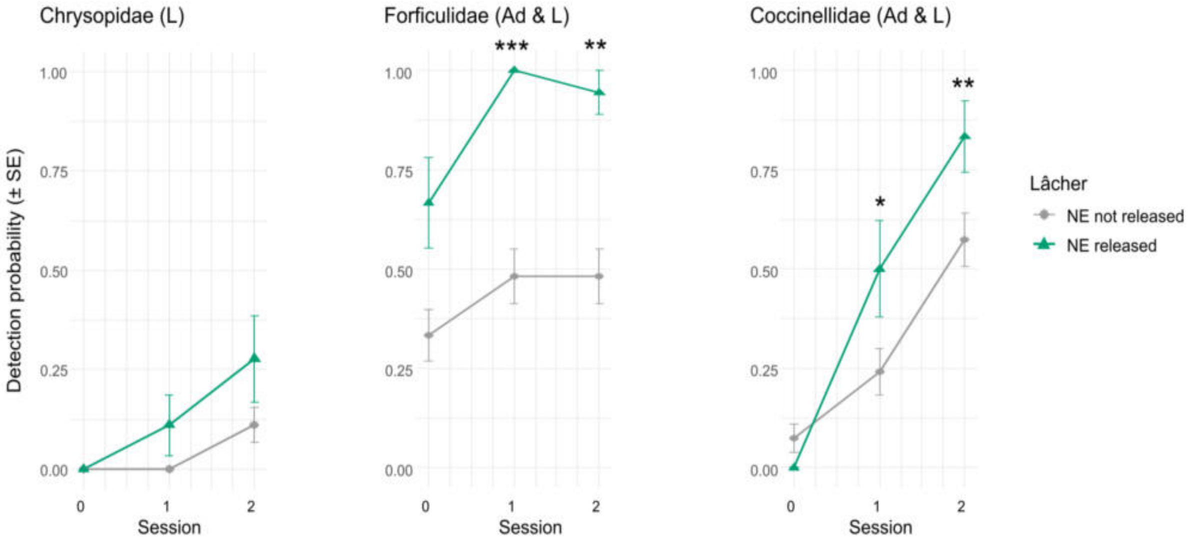

Figure 1. Temporal evolution of presence probability of NE groups (mean ± SE) observed on branch beatings in the studied treatments (released and not released). Natural enemy groups were Chrysopidae (larvae), Coccinellidae (adults and larvae) and Forficulidae (adults and larvae). Significance codes: 0.0001 '***'; 0.001 '**' ; 0.01 '*' ; > 0.05 ''.

All three systems evaluated in the study were net-covered, consequently, the observed positive effect of releases could be attributed to the presence of nets rather than to the specific type of net used. Previous findings show that releases in open orchards did not increase NE population compared to releases made under nets (Dib et al., 2017). Limitations related to our experimental design such as uncontrolled intra-orchard heterogeneity of aphids and NE presence should be kept in mind when discussing the results, particularly because NE occurrence and abundance are strongly influenced by prey availability. The present analysis provides an initial assessment of releases effects, and further analyses will allow to better understand the underlying population dynamics.

## Acknowledgements

We would like to thank Jouffruit company who allowed the experiment to be conducted on their orchard and everyone who participated in the experimental setup and data collection. This work was publicly funded by the Provence-Alpes-Côte d'Azur region with the support of Koppert FRANCE.

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# Effect of agroecological management and pesticide reduction on noxious organisms and natural enemy abundance in oilseed rape

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**Abstract:** Agroecological pest management aims to reduce pesticide reliance by redesigning cropping systems to enhance ecological processes for pest control, yet its performance under real farming conditions remains uncertain. Throughout three years (2020-2022), we compared agroecological and Swiss standard integrated management systems in paired oilseed rape fields across a Swiss network of 22 commercial farms. We quantified the extent of implementation of 17 different agroecological pest management practices and pesticide use reduction, and assessed their effects on weeds, insect pest pressure, natural enemy abundance, and yield. We also evaluated how environmental factors – landscape structure, weather conditions, and soil properties – contributed to variability in these response parameters. This study provides insights into the challenges of agroecological transitions in oilseed rape and highlights the importance of environmental context in shaping their agronomic performance.

**Key words:** crop protection, insect pest, weed management, pollen beetle, rapeseed, canola

## Introduction

Agricultural intensification over the last century has relied heavily on synthetic fertilizers and pesticides to secure high yields (Martín-Retortillo and Pinilla, 2015). While effective in the short term, this model has simplified agroecosystems and weakened resilience through ecological regulation, increasing vulnerability to weeds, pests, and diseases (Altieri and Nicholls, 2017; Tilman et al., 2002). The widespread use of pesticides has also generated major environmental and health concerns, including resistance evolution and negative effects on non-target organisms (Landrigan, 2018; Pimentel, 1995).

"Agroecological Crop Protection" (ACP) has emerged as an alternative approach aiming to reduce pesticide dependence by restoring ecological processes within cropping systems. Going beyond classical Integrated Pest Management – which frequently remains reliant on chemical control in practice (Hokkanen, 2015) – ACP emphasizes system redesign, prevention, and the combination of complementary practices that support biological regulation (Altieri, 2009; Deguine et al., 2021).

Although ACP offers a robust framework for reducing pesticide dependence, its effective implementation in real farming systems requires adaptation to the technical, economic, and social constraints faced by farmers, as well as to the strong influence of environmental context. Climate, soil properties, and landscape composition jointly shape pest dynamics and biological control, leading to heterogeneous outcomes across different situations (Rusch et al., 2016; Tscharntke et al., 2016). On-farm studies that explicitly embrace this complexity are therefore essential to evaluate how ACP principles can be translated into effective strategies in the field.

Oilseed rape (*Brassica napus*) is a key arable crop, providing valuable vegetable oil, protein-rich by-products, and agronomic benefits by diversifying cereal-based crop rotations. It is however highly sensitive to early weed competition, and the window for effective insect pest control is narrow, while the effectiveness of chemical control has declined due to resistance and the ban of several active compounds (Skellern and Cook, 2018), narrowing farmers' options. These characteristics make oilseed rape a stringent test case for assessing and implementing agroecological approaches.

This study evaluates whether ACP strategies, co-designed with farmers and implemented under real farming conditions, can effectively control weeds and insect pests in oilseed rape while maintaining yields. Beyond management practices, particular attention is given to the role of the environmental context – including soil properties, weather and landscape composition – in shaping outcomes.

## Materials and methods

The study was conducted within a network of commercial farms distributed across three regions of the Swiss Plateau (cantons Geneva, Solothurn and Vaud), over three consecutive growing seasons (2020-2022), with a diversified region-specific crop rotation of 6 years. On each farm, an oilseed rape field managed under agroecological principles was paired with a control field, at least at 500 m distance, managed according to integrated production standards. In total, there were 6 fields in 2020, 10 in 2021, and 20 in 2022. This paired design aimed at controlling local environmental conditions while reflecting realistic farming constraints.

We characterized management types based on field calendars sent from the farmers by quantifying pesticide application and agroecological measures implemented on both fields. Total pesticide load for a given field was calculated as a "Treatment Frequency Index" (TFI) = sum [(applied product amount / authorized product amount) * (treated field area / total field area)]. Agroecological management was defined by a strong reduction, or complete avoidance, of herbicides and insecticides, combined with a significantly higher use of preventive (undersowing, flower strips, push-pull with strips of turnip or early variety of oilseed rape) or non-chemical curative practices selected by farmers (interrow hoeing, harrowing). In contrast, control fields relied more on chemical weed and insect control.

We assessed weed biomass before harvest in eight 25cm$^2$ squares, insect pest pressure (adult pollen beetles' abundance and number of egg-laying stings from rape stem weevils, mean of two measures during critical crop stages BBCH50 and BBCH75), natural enemy abundance (parasitic wasps, hoverflies and ladybirds, mean of seven weekly measures during spring), and crop yield at harvest. Environmental covariables such as soil clay content, pH, nitrogen inputs, weather conditions (cumulative degree-days and precipitations; www.agrometeo.ch) were determined, and landscape composition (proportion of oilseed rape fields in a 3 km radius or semi-natural habitats – including hedgerows, forests and extensive meadows in a 1 km radius) were derived. Mixed linear models (generalized or not) and structural equation modelling were used to disentangle direct and indirect effects of management and environmental factors on pest pressure, natural enemy abundance and yield with the packages glmmTMB (McGillycuddy et al., 2025) and piecewiseSEM (Lefcheck, 2016).

## Results and discussion

### *Yield responses and cumulative biotic stress*

Agroecological management exerted a significant indirect negative effect on yield (on average and across years 1.4-2.6 t/ha in agroecological plots versus 1.5-3.6 t/ha in controls), mediated primarily through weeds (standardized estimate of effect size: -0.42) and pollen beetle pressure (st. est effect size: -0.42) (Figure 1). Remarkably, insecticide use did not consistently reduce pollen beetles and rape stem weevils (Figure 1). However, the apparent lack of effect might only reflect an overall high pest pressure that required heavy interventions and cannot be interpreted as a lack of effectiveness. On the other hand, insecticide use reduced the hoverfly population (st. est. effect size: 0.36), implying that chemical control was ecologically costly in this context. However, while agroecological management tended to favor natural enemies, biological and cultural control remained insufficient to suppress pests.

### *Weed – pest – enemy interactions and indirect effects*

Weed biomass was consistently higher in agroecological fields (on average and across years 87.1 to 396.3 g DM/m² versus 25 to 285.6 g DM/m² on control fields) and emerged as a central driver of system performance. Beyond its direct negative effect on yield, increased weed biomass was positively correlated with pollen beetle pressure, apparently independently of insecticide use (Figure 1). This pattern suggests that weeds may provide additional resources for pests (Norris and Kogan, 2005), or indirectly influence pest dynamics by altering trophic interactions. One plausible mechanism is trophic dilution or prey diversion, whereby generalist predators are distracted by alternative prey or resources associated with weeds, reducing predation pressure on pollen beetles (Diehl et al., 2012). Alternatively, the relationship between weed biomass and pollen beetle might be due to the synergistic effect between noxious organisms, particularly relevant for crops that are highly sensitive to early biotic stress such as oilseed rape.

### *Environmental and landscape context*

Beyond management effects, pollen beetle abundance was positively associated with soil clay content (st. est. effect size: 0.48) (Figure 1), suggesting an important role of abiotic context. In contrast with pollen beetle, landscape composition and nitrogen input but not pest management type influenced rape stem weevil pressure, highlighting differences in pest response to agroecological management. The latter was positively influenced by neighboring meadow (st. est. effect size = 0.36), while parasitic wasp abundance also increased with the presence of meadows and hedgerows (st. est. effect size: 0.39). Semi-natural habitats thus played an ambivalent role: while they promoted some beneficial insects (Klinnert et al., 2024), they could also support pests or dilute biological control by providing alternative resources (Delaune et al., 2021; Martin et al., 2013; Tscharntke et al., 2016). Current oilseed rape surface negatively affected both insect pests' abundance or pressure, probably due to a dilution effect.

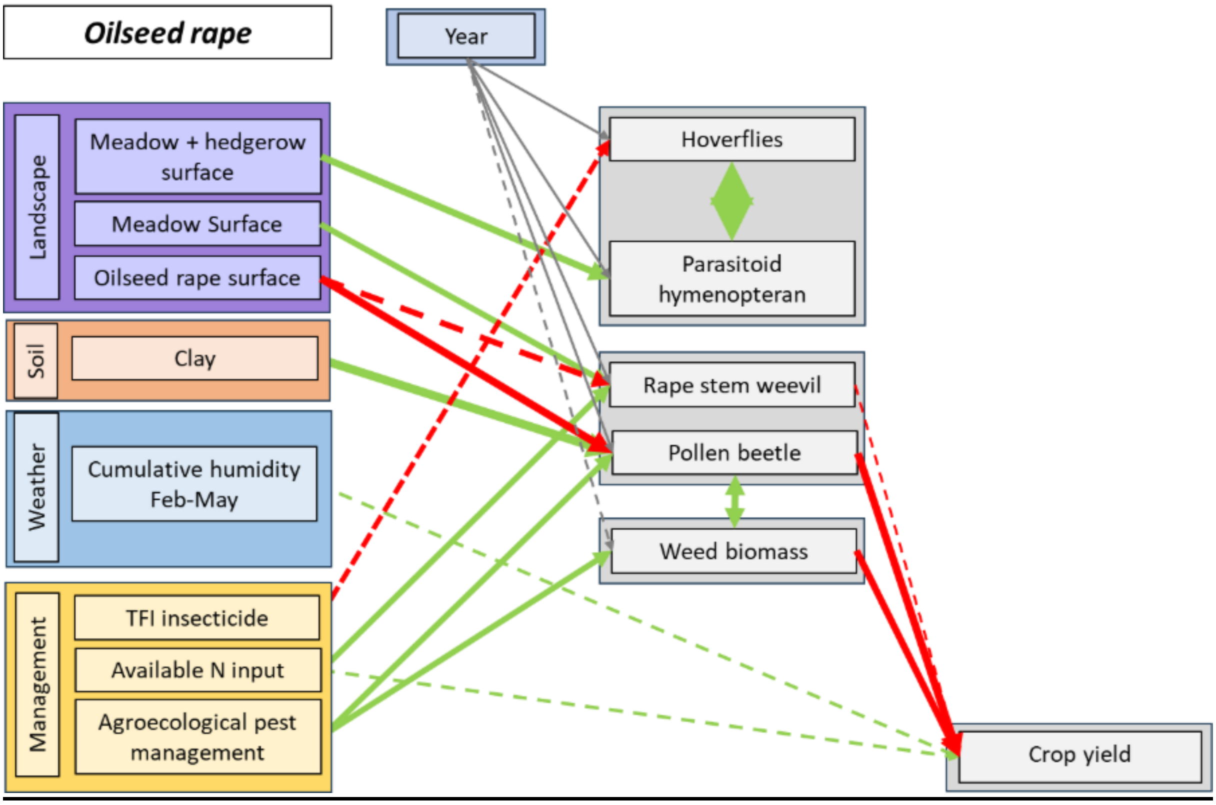

Figure 1. Path diagram showing significant relationships between variables in oilseed rape fields (solid arrows: $p < 0.05$, dashed arrows: $p < 0.1$, marginally significant variables were kept if Aikake Information Criterion (AIC) was lower than without the variable in the model). Red color shows negative effects, green shows positive effect, grey indicates effect of a categorical variable, in the direction of the arrow. The width of the arrow is proportional to the standardized effect size. Arrows going in both directions indicate assumed correlations. Only variables with significant effect are presented. The variable "agroecological pest management" is coded as (1) for agroecological field and (0) for control field.

### *Agroecological crop protection in oilseed rape: implementation and limits*

In line with the project objectives, agroecological crop protection (ACP) was characterized by a substantial reduction in pesticide use in oilseed rape across all sites and years. Herbicide and insecticide applications were absent in 2020 and 2021 and used in low doses in 2022 (TFI of 0.2 and 0.1 for herbicide and insecticide respectively). However, the range of effective alternative weed and insect control measures remained limited in oilseed rape. Ploughing was infrequently implemented possibly due to soil protection considerations and workload (used in 23.5% of the agroecological fields). Neither the combination of agroecological practices including interrow hoeing (used in 29.4 % of agroecological fields and in 35.3 % with camera), harrowing (17.7 %) nor undersowing (58.8 %) appeared sufficient enough to compensate for the near absence of herbicide use. ACP measures aimed at modifying the agroecosystem, such as flower strips (used in 41.2 % of the agroecological fields), push-pull systems (70 %) and undersowing (58.8 %) were not sufficiently effective in attracting natural enemies and regulating insect pests (Figure 1).

***Why oilseed rape is a challenge for agroecological transition***

Overall, oilseed rape emerged as a particularly challenging crop for agroecological transition. The drastic reduction in pesticide use under real farming conditions was accompanied by consistent yield reductions driven by the accumulation of multiple interacting stresses. The crop's high sensitivity to early weed competition, combined with strong dependence on effective insect pest control during flowering, outweighed the mechanical weeding effect and the positive effects observed on natural enemy abundance. These results position oilseed rape as a bottleneck crop for agroecological crop protection and highlight the limits of field-scale approaches alone, pointing to the need for more refined, crop-specific strategies that integrate improved weed management, better synchronization between pest dynamics and control measures, and coordinated actions at the landscape scale to enhance biological regulation.

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# Contribution of semi-natural habitats to predation on tortricid moths in apple orchards

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**Abstract:** In apple orchards, we find several species of tortricid pests of economic importance. However, knowledge about natural enemies of tortricid pests, and the potential of reducing pest pressure through conservation biological control, is limited. Our study aims to gain a better understanding of the contribution of semi-natural habitats to conservation biological control by predatory arthropods in apple orchards. Over two years, insect communities at increasing distances from semi-natural habitats were sampled in 16 apple orchards across two fruit-growing regions in Norway. We used pitfall traps to target ground living predators, as well as beating samples, to target predators and pests present in the canopy. This was conducted four times during the season. Additionally, the plant composition in both the bordering semi-natural habitats and the orchards was assessed, and insect damage on fruits was recorded. There was considerable variation of plant richness in the semi-natural habitat adjacent to the studied orchards, varying from 5 to 28 unique plant genera (not counting Bryophyta or Poaceae). We found that the plant genus richness of the semi-natural habitat differed clearly between the orchards in Eastern Norway and Hardanger, with a higher richness in Eastern Norway. This may be caused by the high intensity of land use for fruit production in Hardanger. Among the most common plant taxa in the semi-natural habitats were *Taraxacum, Ranunculus, Trifolium, Rumex* and *Achillea*, present in 13, 12, 11, 10 and 9 of the 16 semi-natural habitats respectively. Within the orchards *Taraxacum, Epilobium, Trifolum and Stellaria* and *Rumex* were the most common taxa present in 15, 13, 13, 11 and 9 of the orchards respectively. Preliminary results from pitfall traps showed that both the diversity and abundance of ground beetles (Carabidae) were prominently higher closer to the semi-natural habitat. The same tendency was observed for predatory arthropods collected in by sweep-netting in Eastern Norway during the first year of registrations. As the study is ongoing and insect sample identification is still in progress, further analysis is pending.

**Key words:** conservation biological control, natural enemies, semi-natural habitat, insect pests, Tortricidae, orchard

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# Ant management with cover crops in *Citrus* agroecosystems

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**Abstract:** Up to 40 % of global agricultural harvests are lost to pests, representing more than € 240 billion in annual damage. Reducing reliance on chemical control remains a major challenge for sustainable agriculture, especially in perennial systems such as *Citrus*. Landscape management strategies that incorporate semi-natural vegetation and diversified ground covers are increasingly recognized as key drivers of functional biodiversity and natural pest regulation. Ants are among the most abundant arthropods in Mediterranean agroecosystems and play a central role in pest management. While they provide valuable ecosystem services such as pest predation, they can also disrupt biological control by tending honeydew-producing hemipterans. Understanding how habitat diversification practices shape ant communities and ant-mediated processes is therefore crucial for designing effective biodiversity-based pest management at field and landscape scales. In this study, we assessed how two cover-crop types, implemented in *Citrus* orchard alleyways, influence ant communities and ant-driven ecosystem services. We compared a standard grass cover (Poaceae) with a diverse mix of seven wildflower species differing in phenology, a design intended to enhance resource continuity across the season. We evaluated effects on: i) ant community composition; ii) ant activity in the tree canopy; iii) ant – hemipteran mutualisms; and iv) ant-driven predation of pest pupae. Trees embedded within the floral-mix cover crop supported higher ant activity, stronger tending behavior toward hemipteran pests, and higher predation rates compared to the grass-covered plots. These results indicate that local ground-cover diversification can influence ant-mediated interactions with both pests and natural enemies. Our findings highlight that strategic design of herbaceous vegetation within managed landscapes can modulate arthropod functional groups and their contribution to ecosystem services. Integrating functionally diverse cover crops into orchard landscapes may represent a promising pathway to enhance functional biodiversity and promote more resilient pest control in Mediterranean perennial crops.

**Key words:** Functional biodiversity, biological pest control, ant-mediated trophic interactions

## Introduction

Ants are among the most abundant and ecologically influential arthropods in terrestrial ecosystems and play a key role in multitrophic interactions in agroecosystems (Styrsky and Eubanks, 2006). Their impact on crop protection is context-dependent: ants may suppress pests through predation or disrupt biological control by tending honeydew-producing hemipterans (Anjos et al., 2022).

By protecting aphids, mealybugs, or soft scales in exchange for honeydew, ants reduce parasitoid and predator effectiveness, often increasing pest pressure (Plata et al., 2023). This is especially relevant in perennial crops such as *Citrus*, where ant – hemipteran mutualisms can persist year-round. However, as omnivores requiring protein for colony growth, ants can also contribute to pest suppression. Thus, their net effect depends on the balance between mutualistic and predatory behaviors.

Habitat management through cover crops may modulate this balance. By providing alternative carbohydrate resources such as floral nectar, cover crops could reduce ants' reliance on honeydew and weaken ant – hemipteran mutualisms (Blubaugh et al., 2025), although evidence in perennial systems remains limited.

Here, we evaluated two contrasting cover-crop types for ant management in Mediterranean *Citrus* orchards: a standard grass cover and a functionally diverse floral mix.

## Materials and methods

### *Field design*

In a randomized complete block design, two cover crops were sown in the alleyways of *Citrus* trees: a grass cover (*Lolium arundinaceum*) and a seven-species wildflower mix (*Medicago truncatula, Onobrychis viciifolia, Ammi majus, Coriandrum sativum, Achillea millefolium, Calendula officinalis,* and *Lobularia maritima*). Trees and cover crops were established in 2021; *Citrus* trees were drip irrigated, no pesticides were applied, and cover crops were not resown. The field comprised eight blocks (four per treatment), with eight trees per block (32 per treatment). Ant activity and predation services were assessed in May, July, and October 2024.

### *Ant activity*

To evaluate if the type of cover crop affected ant activity on the canopy, the number of ants crossing a section located 20 cm above the base of the tree for two minutes was recorded. As ant activity varies throughout the day, the measurements were taken between 9:00 and 13:00. Ants were identified to the species level in situ.

### *Ant predatory activity*

To evaluate whether cover crops influenced ant predatory activity, we deployed sentinel pupae of *Ceratitis capitata*. We prepared Petri dishes filled with sand containing 10 *C. capitata* pupae and placed one dish in the canopy and another at the base of each experimental tree. Eight 5 mm holes were drilled into the sides of each dish to allow ants to enter while preventing the access by larger predators. Predation activity was visually assessed for 1 minute per dish. When predators were present, they were identified to the species level. Predation rates were quantified in the laboratory after 48 h of field exposure of the sentinel pupae.

## Results and discussion

### *Ant activity*

Across all observations, ants accessing *Citrus* canopies were dominated by the trophobiotic species *Lasius grandis* and *Pheidole pallidula*. From a total of 4,598 ants recorded on 192 trees, *L. grandis* accounted for 1,840 individuals (40 %), while *P. pallidula* accounted for 1,486 individuals (32 %).

Overall ant activity differed significantly between cover crop treatments and among seasons (GLMM; Cover crop: $\chi^2 = 24.54$, $P < 0.0001$; Season: $\chi^2 = 32.24$, $P < 0.0001$; Figure 1). Ant activity was consistently higher in plots with the flower cover crop compared to the grass cover crop across all seasons. Specifically, ant activity in flower cover crops exceeded that in grass cover crops during spring (P = 0.019), summer P < 0.0001), and autumn (P < 0.0001). Seasonal differences in total ant activity were not significant, indicating relatively stable ant foraging levels across spring, summer, and autumn.

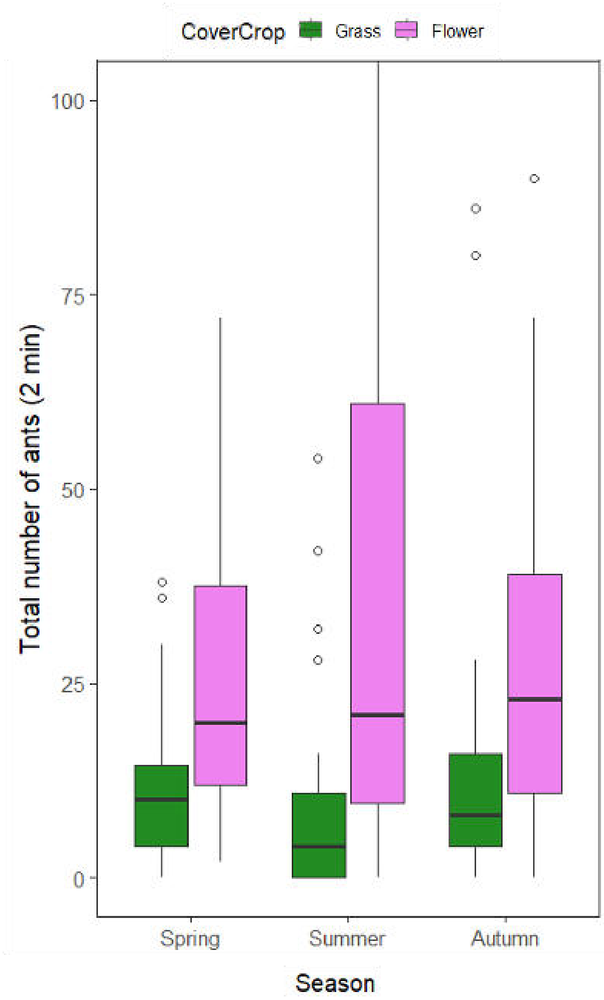

Figure 1. Ant activity across cover crops, seasons. Boxplots showing total ant activity, measured as the number of ants recorded during a 2-min observation period, across two types of cover crops (Grass and Flower) and three seasons (Spring, Summer, Autumn). Boxes represent the interquartile range (IQR), the horizontal line indicates the median, whiskers extend to 1.5 × IQR, and points represent outliers. Ant activity was analysed using a negative binomial generalized linear mixed model including Cover crop, and Season as fixed effects and Block (nested within Year) and Tree identity as random effects. For visual clarity, the y-axis is capped at 100 ants; values above this threshold are not shown.

### *Pest predation in the soil*

Ant-driven pest predation in the soil showed strong seasonal variation (zero-inflated negative binomial GLMM; Season: $\chi^2 = 29.01$, $P < 0.0001$). Overall predation rates did not differ significantly between cover crop treatments when averaged across seasons (Cover crop: $\chi^2 = 0.50$, $P > 0.05$). However, cover crop effects were season-specific.

In summer, soil predation was significantly higher in flower cover crops than in grass cover crops ($P < 0.0001$). No differences between cover crop treatments were detected in spring ($P > 0.05$) or autumn ($P = 0.68$). Seasonal contrasts indicated that soil predation peaked in summer, with higher predation rates compared to both spring ($P = 0.015$) and autumn ($P = 0.003$), while spring and autumn did not differ significantly ($P = 0.92$).

***Pest predation in the canopy***

Pest predation in the tree canopy varied significantly among seasons (zero-inflated negative binomial GLMM; Season: $\chi^2 = 6.11$, $P = 0.047$), whereas no overall effect of cover crop was detected when averaged across the season (Cover crop: $\chi^2 = 2.24$, $P = 0.14$).

Season-specific contrasts revealed that canopy predation was higher in flower cover crops than in grass cover crops during summer ($P = 0.046$). No significant differences between cover crop treatments were detected in spring ($P = 0.14$) or autumn ($P = 0.13$). Seasonal dynamics showed that canopy predation was highest in autumn, exceeding levels observed in summer ($P = 0.0037$), while spring did not differ significantly from either season.

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# Inoculative and conservation biological control: A win-win combination for the effective and resilient management of pests in Mediterranean subtropical crops

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**Abstract:** The results obtained in the SABIOCONTROl project demonstrate that the joint implementation of conservation biological control and augmentative biocontrol strategies has a synergistic effect in improving the establishment of released natural enemies. In addition, the new release formats, as well as the new strains or species of natural enemies evaluated and fine-tuned in the project, have contributed to improving the efficiency of augmentative biocontrol. Although the initial investment in the new proposed strategy was somewhat higher in the first year, costs in the second year were comparable to those associated with conventional control strategies. In the current context, where there is a continuous reduction in authorised active substances, which is significantly affecting the effectiveness and future viability of chemical control strategies, the new strategy developed in SABIOCONTROL is expected to become a key solution for agricultural producers in the Mediterranean region.

**Key words:** *Citrus* fruits, persimmons, ecological infrastructures, natural enemies, supplementary diets

## Introduction

Biological control strategies currently used in the IPM programs of *Citrus* and persimmon crops for new invasive or recently emerged pests are not offering effective solutions. Clearly, inoculative biological control protocols alone are insufficient in intensive agricultural systems. Prevention and low pest pressure are essential, together with the timely arrival of different types of natural enemies (Bouvet et al., 2019; Monzo, 2020; Monzo et al., 2021). The SABIOCONTROL project "SmArt BIOdiversity for Innovative Resilient Pest Control on Mediterranean Subtropical Woody Crops", launched in 2022 and finished in June 2025, aimed to improve spider mites and mealybugs control, *Delottococcus aberiae* in citrus and *Pseudococcus viburni* in persimmon, by combining augmentative and conservation biological control strategies. The rational management of functional biodiversity, including native natural enemies and released predators, and the management of alternative food resources are key elements for pest management. We tested innovative biocontrol strategies based on new release formats, new strains or species of natural enemies, as well as the use of supplementary food. The project involved designing and implementing ecological infrastructures, such as hedgerows, biodiversity islands composed of 2-3 small native shrub species and ground covers, composed of native plants. These plants were selected based on their attractiveness to key natural enemies of the targeted pests and their adaptability to the management of these agroecosystems (Cesar et al., 2023). This study presents the results of two years of management using this approach in commercial *Citrus* and persimmon orchards.

## Materials and methods

During 2023 and 2024 an optimized biocontrol strategy named SABIOCONTROL thesis, combining new inoculative and conservation biological control, was tested and compared to conventional management methods. During the first year of the project, different and complementary types of ecological infrastructures were designed, including hedgerows, biodiversity islands and ground covers. The native shrubs and herbaceous plants that were selected to attract natural enemies were chosen based on botanical, entomological, and technical criteria (Cesar et al., 2023). Four commercial farms participated in the trials: two growing citrus and two growing persimmons, each comprising a conventional plot and a SABIOCONTROL, for a total of eight surveyed plots. Hedgerows and biodiversity islands were set up on all farms in the SABIOCONTROL plot between late March and early May 2023, and cover crops were sown between January and March 2024. To monitor both red spider mites and mealybugs, two leaves and two fruits were sampled fortnightly from 25 trees per treatment. The presence or absence of the pest was noted. For mealybugs, only fruits were sampled, and presence was confirmed when ovisacs, adults or nymphs were detected. The parameters evaluated were the percentage of leaves and/or fruits showing signs of red spider mites and/or natural enemies, and the percentage of fruits showing signs of mealybugs and/or natural enemies. Also, the number of phytosanitary interventions was quantified, and the estimated cost per hectare was calculated for the same period between 2023 and 2024. This calculation considered only interventions related to the control of target pests.

## Results and discussion

No differences in the incidence of red spider mites were observed between treatments in either of the two years for citrus crops (Table 1). However, there was a tendency towards higher populations in the conventionally managed plots (Figure 1). This pest was not present in persimmon crops. The incidence of mealybugs in citrus crops showed significant treatment and interaction with year effects (Table 1). While mealybug populations remained low in SABIOCONTROL *Citrus* crops without any difference between 2023 and 2024, there was a significant increase in populations in conventional crops in 2024 (Figure 1). On the contrary, there was no overall effect of management strategy on mealybugs occurrence in persimmon. However, there was an effect of season as well as an interaction between year and management type (Table 1). The incidence of mealybugs increased significantly from 2023 to 2024, but the increase was significantly higher in the conventional plots (Figure 1). In both crops, SABIOCONTROL strategies appear to be as efficient as conventional management at controlling this pest in the medium term.

Table 1. Type III fixed effects test related to the presence of spidermites, phytoseiids, mealybugs, predators and *Anagyrus* in *Citrus* and persimmon crops in conventional and SABIOCONTROL in 2023 and 2024.

| | Effect | DF Nº | DF Den | Spider mite | | Phytoseiids | | Mealybug | | Predators | | *Anagyrus* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F | F Value | Pr > F |
| *Citrus* | trt | 1 | 93 | 1.32 | 0.25 | 50.44 | <.0001 | 7.87 | 0.01 | 19.41 | <.0001 | 1.09 | 0.30 |
| | year | 1 | 93 | 10.24 | 0.002 | 0.77 | 0.38 | 0.84 | 0.36 | 2.03 | 0.16 | 6.45 | 0.01 |
| | year*trt | 1 | 93 | 0.05 | 0.82 | 0.78 | 0.38 | 17.36 | <.0001 | 0.46 | 0.50 | 0.51 | 0.48 |
| Persimm. | trt | 1 | 78 | - | - | 13.53 | 0.02 | 1.28 | 0.26 | 0.82 | 0.37 | 7.93 | 0.01 |
| | year | 1 | 78 | - | - | 9.11 | 0.04 | 70.12 | <.0001 | 0.21 | 0.65 | 34.63 | <.0001 |
| | year*trt | 1 | 78 | - | - | 2.07 | 0.22 | 15.84 | 0.0002 | 3.96 | 0.05 | 6.01 | 0.02 |

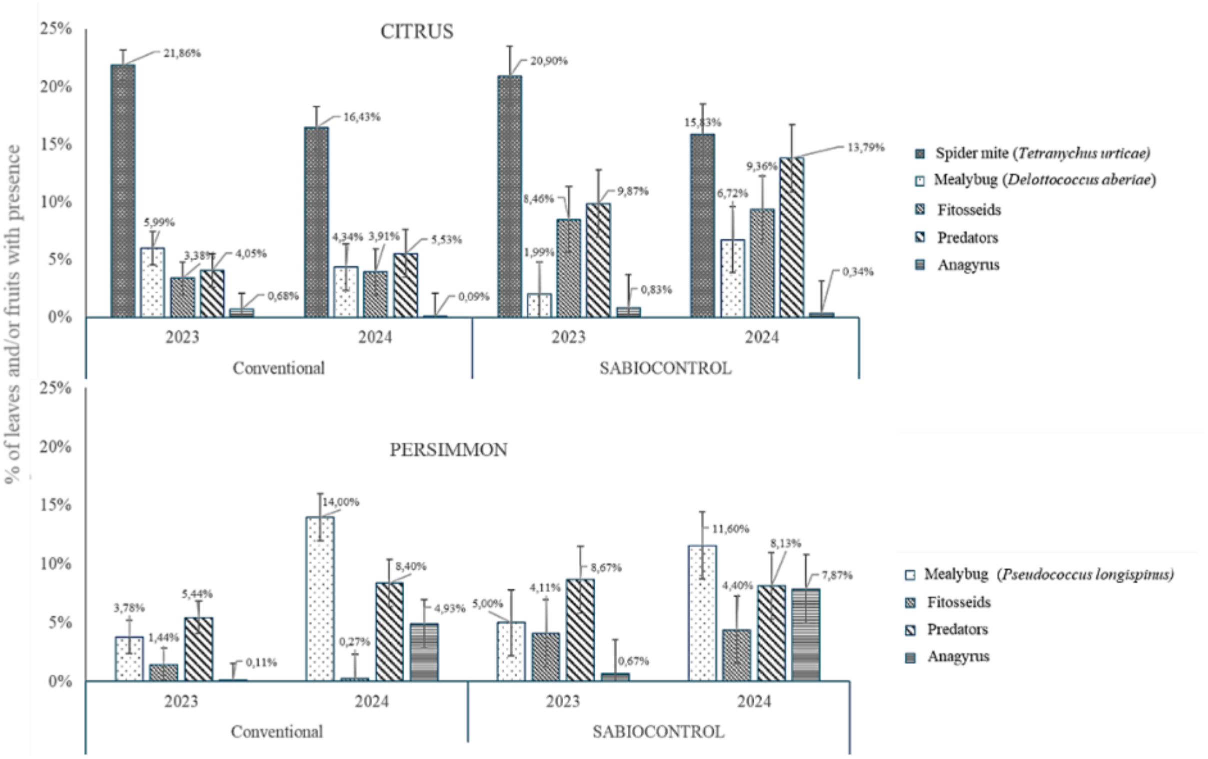

Figure 1. % of fruits and/or leaves with presence of spidermites, mealybugs, phytoseiids, predators and *Anagyrus* in *Citrus* (up) and persimmon (below) crops in conventional and SABIOCONTROL in 2023 and 2024.

Regarding natural enemies, the type of management affected phytoseiid populations in both crops, with significantly higher populations in the SABIOCONTROL strategy (Figure 1). In citrus crops, there were no differences between years, although a tendency toward a higher number of phytoseiids in the second year of the SABIOCONTROL strategy was observed. This was not the case in the conventional management strategy. An effect of management type on predator populations was detected only in citrus crops, where predator abundance was highest in the SABIOCONTROL strategy (Table 1). Regarding the *Anagyrus* population, a year effect was observed in *Citrus*, but no treatment or interaction effect was found (Table 1). However, a general downward trend in populations was apparent between 2023 and 2024 (Figure 1). In persimmon, management type had a significant effect, with higher number of *Anagyrus* in the SABIOCONTROL treatment. The difference was stronger in 2023.

SABIOCONTROL management in *Citrus* resulted in significantly higher costs compared to the conventional strategy, due to the large number of natural enemies released specially in 2023. In 2023, the cost of pest control using the improved strategy was € 2,808/ha, compared to € 1,269/ha using the conventional strategy (Table 2). However, in 2024, the cost of SABIOCONTROL strategy was significantly reduced (€ 1,963/ha), similar to the cost of the conventional strategy (€ 2,160/ha). These results support the initial hypothesis that a combined strategy of inoculative biological control and conservation leads to more resilient crops and allows for a gradual reduction in costs. In persimmon, the SABICONTROL strategy was more expensive in both 2023 and 2024, with € 1,301/ha and € 1,910/ha, respectively, compared to the conventional strategy, with € 828/ha and € 1,065/ha, respectively. Pest control costs were higher in both strategies in 2024 due to the greater presence of mealybugs, requiring more chemical and biological interventions (Table 2). While the percentage of fruit affected by mealybugs was similar in both strategies in 2024, the conventional plot had a high mealybug infestation in each fruit. Consequently, the SABICONTROL plot did not experience significant yield problems because most of the harvested fruits were sold due to a low mealybug infestation in the fruit. In contrast, the conventional required aggressive treatments before harvest and this resulted in the loss of much of the crop production. Therefore, although the SABIOCONTROL strategy entailed a higher economic cost, it resulted in a more profitable crop.

Table 2. Spider mite and mealybugs control interventions carried out in *Citrus* and persimmon crops and management cost of SABIOCONTROL and conventional strategies, in 2023 and 2024.

| | | | *Citrus* | | Persimmon | |
|---|---|---|---|---|---|---|
| | | | Number of releases | | | |
| Biological control | Pest | Natural enemy | 2023 | 2024 | 2023 | 2024 |
| | Whitefly | *A. swirskii* | 0 | 0 | 2 | 2 |
| | Spider mite | *A. andersoni* | 3 | 2 | 0 | 0 |
| | | *A. californicus* | 2 | 0 | 0 | 0 |
| | | *Phytoseiulus persimilis* | 3 | 3 | 0 | 0 |
| | Mealybug | *Anagyrus vladimiri* | 0 | 0 | 0 | 1 |
| | | *Anagyrus aberiae* | 2 | 0 | 0 | 0 |
| | | *Cryptolaemus monstrouzieri* | 1 | 3 | 0 | 2 |
| | | *Crysoperla carnea* | 2 | 1 | 4 | 1 |
| | | *Nephus* sp | 5 | 3 | 0 | 1 |
| | Sup. food | POWERMITE 3.0 | 1 | 0 | 0 | 0 |
| | Cost (€/ha) | | 2.419,7 | 1.963,1 | 1.300,5 | 1.496,7 |
| Chemical control | TESIS | | Number of applications | | | |
| | | | 2023 | 2024 | 2023 | 2024 |
| | | Conventional | 8 | 8 | 3 | 7 |
| | | SABIOCONTROL | 2 | 0 | 0 | 3 |
| | Cost (€/ha) | Conventional | 1.268,7 | 2.160,3 | 828,0 | 1.064,9 |
| | | SABIOCONTROL | 388,5 | 0,0 | 0,0 | 414,0 |

In conclusion, the SABIOCONTROL project's integration of conservation and new augmentative biological control strategies has offered a promising approach to the sustainable management of key pests in subtropical Mediterranean crops. SABIOCONTROL approach improved crop health and increased natural predator populations. Furthermore, combining augmentative and conservation biological control has proven to be as effective as pesticide-based control in *Citrus* and persimmon crops. This method offers a sustainable, long-term alternative that reduces dependence on chemical products and associated pest control costs while promoting sustainability in Mediterranean agriculture.

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# Barn owls as agents of functional biodiversity: Vegetation and landscape effects on pest control in vineyards

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**Abstract:** Predators in agroecosystems can provide valuable ecosystem services by exerting top-down control on pests through direct consumption, perceived predation risk, or both. Harnessing these services for pest management requires understanding how top-down effects are mediated by vegetation structure and landscape complexity, which remain poorly understood, especially for vertebrate pests and their predators. Globally, farmers install nest boxes to attract barn owls (*Tyto* spp.) for rodent control, yet evidence for their effectiveness remains limited and mechanisms largely unresolved. We studied American barn owls (*Tyto furcata*) in winegrape landscapes of Napa Valley, California, USA to quantify (1) rodent removal rates, (2) owl habitat use between vineyards and adjacent habitats, (3) whether owl hunting reduces rodent activity and abundance, and (4) how these effects vary with vegetation, landscape composition, wind, and moonlight, which influence prey detection. On average, each owl family removed 3,466 rodents per year and spent 35-50% of their hunting time in vineyards. As the proportion of natural habitat in the surrounding landscape increased, nest box occupancy also rose, but owls hunted proportionally less in vineyards. Owl hunting reduced gopher (*Thomomys bottae*) and mouse/vole (*Peromyscus* and *Microtus*) activity by 14 % and 36 % in vineyards, respectively, and increased perceived predation risk for mice/voles by 27 %. Results also suggest that dense vegetation favored acoustically oriented barn owls over visually oriented rodent pests. Together, these findings provide strong evidence that barn owls contribute to biological control in agricultural landscapes and that vegetation and landscape composition can be managed to enhance their impact.

**Key words:** pests, diseases, integrated control, rodents, barn owls, top-down, landscape of fear, California

## Introduction

Predators can influence prey through direct consumption, predator-induced changes in behavior arising from perceived risk, or both (Orrock and Fletcher, 2014). Empirical evidence for these top-down effects among vertebrates is variable, with outcomes shaped by ecological context, prey behavior, and predator – prey functional traits. In many systems, predators alter prey space use and activity by creating a heterogeneous "landscape of fear," though the magnitude of these effects depends on habitat structure and the reliability of sensory cues (Laundré et al., 2001).

Vegetation, landscape structure, and abiotic conditions can strongly mediate predator effects by influencing prey detectability and capture success. Dense vegetation may hinder visually oriented predators but favor acoustically oriented hunters such as barn owls. Heterogeneous landscapes that include natural habitats can have myriad effects on top-down control: they may enhance predator impacts by attracting or supporting predators or diminish those impacts if natural habitats function as refugia or population sources for prey. Abiotic factors like wind and moonlight modify sensory conditions for both predators and prey and could therefore influence the relative strength of top-down effects.

Understanding these mechanisms is especially important in agroecosystems, where predators may provide ecosystem services through pest suppression. Although predator impacts on insect pests are well studied, vertebrate pests have received far less attention. Rodents cause billions of dollars in agricultural damage annually, and while predators can reduce rodent abundance through consumption, behavioral effects that reduce crop damage remain poorly understood.

Barn owls (*Tyto* spp.) are widely promoted for rodent control through nest box programs, yet evidence for their effectiveness and underlying mechanisms remains limited. Previous studies document owl predation on voles, gophers, and rats (Hansen and Johnson, 2022), but most focus on prey remains or abundance and rarely distinguish between consumptive and non-consumptive effects. How vegetation and landscape context mediate these effects is largely unknown.

Here, we evaluate whether American Barn Owls (*Tyto furcata*) contribute to rodent suppression in a California vineyard agroecosystem and how these effects are shaped by vegetation, landscape composition, wind, and moonlight. Specifically, we quantify nest box occupancy, owl habitat use, rodents killed, and owl-induced changes in rodent activity, abundance, and perceived predation risk.

## Materials and methods

### ***Study system***

Napa Valley, California (~ 100 km north of San Francisco), has a Mediterranean climate and extensive winegrape agriculture (~ 20,000 ha) embedded within oak woodlands, grasslands, forests, and riparian habitats. Barn owls are dietary generalists commonly attracted to agricultural landscapes via nest boxes (Roulin, 2020). They hunt primarily near nesting sites and prey opportunistically on locally abundant rodents (Castañeda et al., 2021). We studied the American Barn Owl (*Tyto furcata*), following recent taxonomic revisions. Rodents in Napa Valley vineyards include deer mice (*Peromyscus* spp.), house mice (*Mus musculus*), California voles (*Microtus californicus*) and pocket gophers (*Thomomys bottae,* Hansen and Johnson, 2022). Barn owl diets in the region include mice, voles, and gophers, with composition varying by local habitat.

### ***Owl monitoring***

We monitored 250-330 owl nest boxes in Napa Valley from 2015-2024. Boxes were inspected using a pole-mounted camera system that allowed remote viewing from the ground, minimizing disturbance during nesting. A box was considered used if eggs or nestlings were observed at any point during the breeding season. Monitoring schedules varied slightly among years, but surveys were timed to coincide with peak breeding activity. We deployed surveillance video cameras on 26 nest boxes to quantify prey delivery rates (for details see St. George and Johnson, 2021), and we attached GPS tracking devices (Ecotone, Uria 300) to 18 adult owls to document how much time they spent hunting in vineyard versus natural habitats (for details see Castañeda et al., 2021).

### *Rodent monitoring*

We quantified rodent abundance and behavior using complementary field indices across six vineyards spanning a gradient of anticipated barn owl hunting pressure based on presence and density and past occupancy of nest boxes (Johnson et al., 2025). Grids were ≥ 200 m apart and sampled twice: late winter (February-March), when owl hunting pressure was low, and late spring (May-June), when nestling provisioning increases hunting activity (St. George and Johnson, 2021). Gopher activity was indexed using the open-hole method (Engeman et al., 1993). Grids were subdivided into subplots, holes were opened into active tunnel systems, and the proportion of holes plugged after 48 hours was used as an index of gopher activity (see Hansen and Johnson, 2022, for details). Relative abundance of above-ground rodents was indexed using chew blocks (wax-seed cubes), a standard method in which visitation rates increase with rodent density. Each grid contained 36 blocks scored for presence or absence of bite marks after four days, with motion-triggered cameras used at a subset to confirm species identity. Perceived predation risk was assessed using giving-up density (GUD) experiments conducted at the same grid locations but separated from chew block sampling by ≥ 20 days. GUD trays contained sand mixed with a fixed quantity of seeds; higher remaining seed mass indicates earlier patch abandonment under higher perceived risk (Jacob and Brown, 2000). Each grid contained 12 trays run for six nights, with a subset monitored by cameras to verify species identity.

### *Vegetation and landcover*

Landscape composition of 7 landcover types (vineyard, grassland, oak savannah, riparian, forest, urban, and water) was quantified within 2.81 km of each nest box (mean maximum distance travelled by an owl based on telemetry). In addition, we quantified the local vegetation in the vineyard, combining measurements of vine canopy cover, cover crop height, grass height in vine row, and percent cover of vine debris into a scaled score of zero to four.

### *Analyses*

We used a variety of generalized linear models (in some cases with random effects) to quantify the effect of habitat and landscape composition on six response variables: (1) prey delivery rate, from which we calculated an estimated total number of rodents killed by a barn owl family per year (see St. George and Johnson, 2021 for details), (2) the probability of nest box occupancy (Johnson et al., 2025) (3) the probability tracked adults hunted in vineyard versus natural habitats (based on resource selection functions, see Castañeda et al., 2021), (4) gopher activity (from open-hole method; Hansen and Johnson, 2022), (5) above-ground rodent abundance (from chew blocks), and (6) rodent perceived predation risk (from GUD trays).

## Results and discussion

### *Owls*

Landscape composition strongly influenced barn owl ecology in this system. Nest box breeding occupancy ranged from 22 % (2022) to 52 % (2018 and 2024), with a long-term mean of approximately 40 %. Nest box occupancy increased significantly with the proportion of natural habitat within 2.81 km of nest boxes, particularly grassland. Based on videography, barn owl families (1 adult male, 1 adult female, and an average of 3.5 young) killed a mean (± 1 SE) of 3,466 ± 465 rodents per year. Voles comprised the majority of identifiable prey (49.6 %), followed by mice (22.0 %) and gophers (17.5 %), with prey composition varying across landscapes. Oak savannah was positively associated with the proportion of gophers and negatively associated with voles, whereas grassland was positively associated with vole consumption. Tracking data indicated that approximately one-third of owl hunting locations occurred in vineyards, even though vineyards comprised roughly 50 % of the area surrounding nest boxes. Vineyard use increased as the availability of preferred uncultivated habitats declined. Thus, nest box occupancy was highest in landscapes with greater amounts of natural habitat, but owls hunted proportionally less in vineyards in these settings. From a pest control perspective, this reveals a clear trade-off: increasing natural habitat may enhance owl occupancy while reducing hunting effort within vineyards. Future work should explicitly evaluate landscape configurations that maximize rodent suppression in agricultural fields.

### *Rodents*

Results from the open-hole method indicate that barn owls exert top-down effects on pocket gophers. Of 2,816 subplots surveyed, 868 holes were opened and 550 (63 %) were plugged by gophers within 48 hours. Modeling results showed that gopher activity declined by 14 % on vineyards with owl nest boxes, but increased by 18 % on vineyards without boxes. Chew block results further supported the hypothesis that barn owl hunting pressure directly reduced mouse and vole abundance. Across the observed range of hunting pressure, from nearly no owls to approximately three occupied nest boxes (six adults and eight chicks) within a 1-km radius, rodent abundance declined by 38 % to 52 % (upper and lower 95 % confidence limits, respectively). The proportion of chewed blocks increased with wind but showed little variation with habitat or landscape composition, suggesting that wind may mask rodent movements or reduce owls' ability to detect prey acoustically. Top-down effects of barn owls also extended to rodent behavior. Giving-up density experiments showed that, across the observed range of hunting pressure, owls increased rodent perceived predation risk by 16 % to 38 % (lower and upper 95 % confidence limits, respectively). Vegetation cover was positively associated with perceived predation risk, suggesting that dense vegetation may increase rodents' detectability by acoustically hunting owls rather than providing effective cover. As expected, rodents also exhibited higher perceived risk on moonlit nights.

### *Pest control implications*

Together, these results indicate that American barn owls in Napa Valley function as effective agents of rodent pest control, removing enough rodents to reduce their abundance in winegrape vineyards. In addition to direct predation, owl hunting increased perceived predation risk in rodents, which may further reduce crop damage, though this mechanism warrants further study. The strength of these top-down effects varied with environmental conditions. Landscape composition influenced owl nest box occupancy and vineyard hunting in partially opposing ways: greater surrounding grassland increased occupancy but reduced time spent hunting in vineyards. This suggests a potential "optimum" amount of natural habitat that maximizes pest control services, a hypothesis deserving further study. Local vegetation and abiotic factors also shaped prey vulnerability. Rodents were more abundant on windy nights and more fearful in taller vegetation. Because barn owls locate prey acoustically, tall vegetation and still nights may increase rodent vulnerability to this specialized predator.

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# A species-centered structural equation model reveals predator subsets driving biological control of *Chilo sacchariphagus*

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**Abstract:** Pest species are embedded in complex multitrophic networks that shape their dynamics. Systemic approaches integrating environmental covariates with multitrophic interactions are therefore needed to link biodiversity to agroecosystem functioning and design agroecological cropping systems. However, these approaches face methodological challenges, particularly when the focal herbivore occupies a narrow trophic module and the ecological processes shaping interactions remain poorly understood. We applied a species-centered structural equation modeling approach to identify drivers of sugarcane borer *Chilo sacchariphagus* infestation in sugarcane agroecosystems on Reunion Island. An intensive two-year survey at 60 sampling points disentangled direct and indirect effects of environmental factors while highlighting the role of generalist predators within a broader multitrophic context. A filtering procedure identified key predator species before constructing a tailored structural equation model. Our results show that a refined predator aggregate comprising 11 morphospecies with diverse functional profiles exerted a strong negative effect on pest damage ($\beta = -0.7$). Additionally, the two dominant invasive ant species (*Pheidole megacephala* and *Solenopsis geminata*) exhibited a nonlinear, dome-shaped relationship with herbivory ($\beta_1 = 0.5$, $\beta_2 = -0.6$), suggesting a strong regulatory role. This study highlights the value of systemic approaches for understanding natural pest control. It underscores the importance of focusing on key predator groups while considering broader trophic interactions. Future research should clarify how predator functional traits complement each other and interact with the wider community to enhance pest regulation within the environmental context.

**Key words:** biological control, structural equation modeling, generalist predators, functional identity, tropical agroecosystems

## Introduction

Herbivore regulation by natural enemies represents a central ecosystem function in both natural and managed ecosystems, contributing to the stability of trophic webs and the control of arthropod pests. In agroecosystems, generalist predators are often considered key agents of natural pest suppression, as functional complementarity and redundancy may provide ecological insurance and promote the persistence and stability of pest regulation services over time and space. Although specialist natural enemies (e. g., parasitoids) are emphasized because of their tight associations with pest species, yet their effectiveness relies on specific, host-synchronised, and environmentally sensitive mechanisms, whereas generalist predators may provide consistent background regulation through broad prey spectra, numerical stability, and persistence across heterogeneous landscapes, underscoring the need to better understand their effective role in pest regulation.

However, despite their recognized importance, a net effect of generalist predator assemblages on herbivory pressure may remain difficult to detect and frequently yields neutral relationship outcomes. Mechanisms contributing to this pattern include multiple positive (facilitation) and negative (interference, competition, intraguild predation) interactions among predators, as well as confounding averaging effects that obscure predator – pest relationships (Letourneau et al., 2009). Detecting natural regulation is particularly difficult in understudied agroecosystems, where limited prior knowledge and a focus on a single herbivore can obscure control confined to a small, previously unknown subset of predators. Another challenge lies in narrowing down the appropriate taxonomic perimeter. Broad predator categories based on assumed trophic roles are often imprecise and largely speculative when targeting a specific pest species. In such contexts, working from morphospecies and upscaling information may be more relevant.

While predator – prey relationships can be addressed using univariate approaches, such frameworks fail to capture strong indirect effects on predator communities mediated by bottom-up cascades from alternative prey and abiotic contexts. Structural equation models (SEM) offer a powerful systemic approach to integrate multitrophic interactions and abiotic drivers across spatial scales, while revealing indirect, actionable drivers (e. g., agronomic practices) for pest management. However, the selection and aggregation of diversity facets within each trophic level remain constrained by the focal research question. A narrow focus on a target herbivore inevitably restructures the multitrophic framework, privileging pathways most relevant to that species.

Following the absence of an overall predator regulatory effect reported in a previous study (Guinjard et al., in press), we present here, for the first time in sugarcane agroecosystems a modelling workflow focused on the specialist moth *Chilo sacchariphagus*. This approach aims to refine the taxonomic scope and construct a tailored multitrophic structural equation model while accounting for environmental covariability. We hypothesize that: (i) a subset of predators may exert additive or synergistic regulatory effects on *C. sacchariphagus*; (ii) two omnivorous ants (*Pheidole megacephala* and *Solenopsis geminata*) play a disproportionate role due to their high foraging efficiency and eusocial behavior, potentially suppressing other predatory arthropods.

## Materials and methods

### ***Study area***

Sixty plots were monitored in 20 sugarcane fields in Petite-Île (southern Reunion Island) from 2022 to 2023. Fields covered a strong altitudinal gradient (90-968 m, mean 544 m) and varied in surrounding landscape diversity (Simpson index 0-0.9, mean 0.4).

### ***Arthropod sampling devices***

Each plot was equipped with two passive traps: an aerial interception trap (Polytrap) and a ground pitfall trap (Barber). Arthropods were collected weekly and identified to the taxonomic level required for assignment to four trophic guilds (predators, herbivores, decomposers, parasitoids). At the end of each growing season, damage by *C. sacchariphagus* was quantified as the mean proportion of perforated internodes per plot, used as a proxy for larval population dynamics (0-0.18, mean 0.05). When cropping changes occurred, plots were relocated within or near the same field to maintain comparable environmental contexts.

### *Environmental context*

Environmental context was characterized using agronomic practices (grower surveys), meteorological data (regional stations), and landscape structure derived from land-use maps (2022-2023). Landscape composition and configuration metrics were calculated within buffers ranging from 100 to 1000 m and averaged. To reduce dimensionality, a principal component analysis was performed, and the first four axes and their quadratic terms were retained as predictors.

### *Trophic compartment construction*

To identify key predators potentially regulating *C. sacchariphagus*, a two-step filtering procedure was applied prior to SEM construction. First, a classification tree predicting damage classes was built using predator morphospecies abundances and environmental covariates; morphospecies with importance values above the median were retained. Second, generalized linear mixed models tested all possible combinations of candidate species as aggregate predictors of damage. After Bonferroni correction, morphospecies occurring in more than 20 % of significant models were retained. The two dominant ant species (*P. megacephala* and *S. geminata*) exhibited strong spatial exclusion. Their abundances were therefore combined into a single metric included in the SEM as linear and quadratic terms. For remaining predator species and for herbivore, decomposer, and parasitoid compartments, community-level descriptors (total abundance, Pielou's evenness, and second-order jackknife alpha diversity) were calculated separately for aerial and ground assemblages. This step resulted in 20 candidate endogenous variables.

### *Navigation map*

Given the exploratory nature of the study, a navigation map was built to guide SEM development. For each candidate endogenous variable, generalized linear mixed models were fitted with broad predictor sets, excluding only implausible trophic links. Multicollinearity was controlled using variance inflation factors, and residuals were checked for distributional assumptions and spatial autocorrelation. Model selection relied on multimodel inference, restricting candidate models to four to six predictors. Variables with cumulative Akaike weights > 0.5 in models with ΔAICc < 4 were retained for SEM conceptualization.

### *Chilocentric SEM*

The SEM was constructed using a piecewise approach. Preliminary exploratory analyses guided model conceptualization, which was ultimately centered on *C. sacchariphagus* infestation dynamics. The causal structure was iteratively extended upstream to avoid structural issues, resulting in a final model describing infestation dynamics across three causal levels. Model fit structural coherence was evaluated. Conditional independence of all non-hypothesized paths was assessed using the d-separation test. Path coefficients were standardized. The model was assessed using jackknife resampling to examine the stability of its structure and estimates.

## Results and discussion

### *SEM reliability*

The SEM showed good structural coherence (Fisher's C = 86.929, p = 0.279), as directed separation tests indicated that relationships were adequately represented and no missing paths were detected. Resampling further supported the stability of model structure and estimates.

### *Core of the regulation*

Results revealed a clear regulatory signal, as shown in Figure 1, exerted on the focal pest, *C. sacchariphagus*, which occupies a central position within our structural model. To our knowledge, this is the first study providing robust evidence of predator-mediated regulation of this pest within a tailored multitrophic framework, implemented through a customized methodological pipeline. Importantly, this regulation does not arise from the predator community as a whole but from the specific interaction between *C. sacchariphagus* and a subset of predators that was largely unknown a priori. Community-level, aggregate measures would have obscured this effect, as effective control is concentrated within this discrete module. First, among predator assemblages, the abundant predator aggregate had the strongest negative effect on pest damage ($\beta = -0.7$, Figure 1 a), emphasizing the importance of the identity and functional traits of a specific predator subset leading the regulation service (Straub and Snyder, 2006). The effective predator aggregate, identified through the filtering procedure, comprised 11 predator morphospecies, including predatory Hemiptera (*Tytthus* sp.), ant species (*Tetramorium bicarinatum*, *Tapinoma melanocephalum*, *Paratrechina longicornis*), pseudoscorpions, Blattodea, harvestmen (Sclerosomatidae), and several spider taxa (Pholcidae, *Theridion melanostictum*, *Coleosoma floridanum*). The taxa encompass a wide range of functional traits, including active foraging predators, web-building spiders, and cryptic microhabitat specialists such as pseudoscorpions. Their spatial complementarity within the study system area may play a crucial role. These organisms can also operate across multiple strata and act at different developmental stages of the moth. Second, the two numerically dominant ant species (i. e., *P. megacephala* and *S. geminata*) exhibited a nonlinear, dome-shaped relationship with pest damage ($\beta_1 = 0.5$, $\beta_2 = -0.6$, Figure 1 b), indicating that plots dominated by either species experienced reduced herbivory, while plots where neither species was dominant (generally characterized by very low abundances of both) had the highest pest damage. As previously reported in literature, the aggressive behavior, high recruitment efficiency, omnivory of these two invasive ants explain their key role in regulating *C. sacchariphagus.* Future work will leverage the approach outlined above to deploy a systemic understanding of infestation damage by the focal moth. A major perspective would also be to look in more detail at the environmental drivers (e. g., agroecological levers) associated with each relevant natural enemies morphospecies.

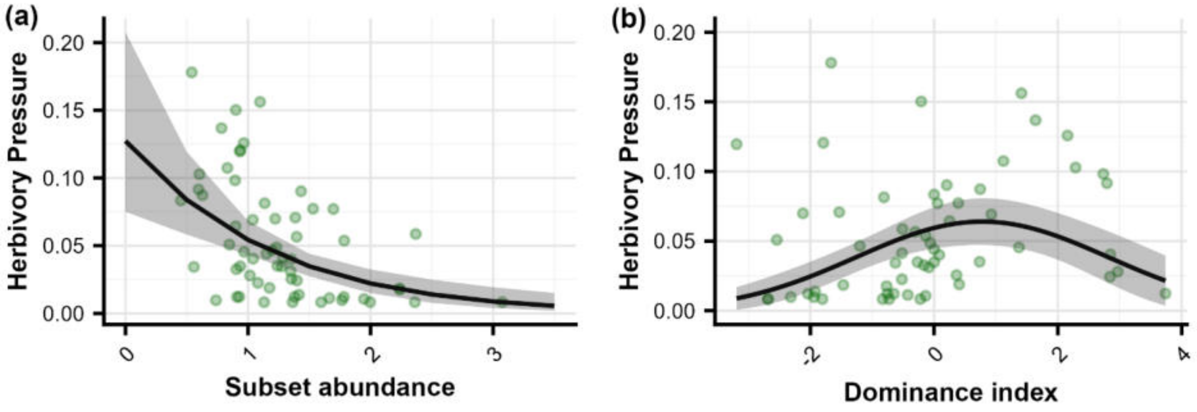

Figure 1. Effects of (a) aggregated predator subset abundance and (b) the dominance index on herbivory pressure. For the dominance index, negative values indicate *S. geminata* dominance, while positive values indicate *P. megacephala* dominance.

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# Assessing the impact of agroecological practices on ecosystem services and crop productivity in open-field tomatoes in Greece

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**Abstract:** Tomato is an important crop both globally and in Mediterranean countries. Agroecological farming practices aim to enhance functional biodiversity to support ecosystem services and reduce reliance on synthetic inputs. Our study investigates the impact of agroecological practices and boosting functional biodiversity, on the population dynamics of major tomato pests and important natural enemies, and the productivity of the tomato crop in open-field cultivation systems in Greece. Over three years we evaluated agroecological practices based on companion plants – phacelia (*Phacelia tanacetifolia*) and buckwheat *(Fagopyrum esculentum*) planted alongside tomatoes – and the application of the soil beneficial fungus, *Trichoderma harzianum* T22. In addition, we compared the agroecological approach with the conventional approach. Throughout the growing season, insect sampling was conducted in both the agroecological and the conventional experimental fields using Malaise traps and visual observations. Data collection focused on parasitoids, wasps, bees, syrphid flies (Syrphidae), and predatory insects of the family Miridae. Simultaneously, populations of the main tomato pests were recorded. In the agroecological system, the individual and combined effects of the companion plants and fungus on tomato plant physiology and growth were also assessed. Our results suggest that the agroecological approach enhanced functional biodiversity, increased the abundance and diversity of beneficial insects, and reduced pest pressure, while also boosting tomato growth and crop productivity. This study aims to develop an agroecological tomato cultivation model that utilizes and strengthens functional biodiversity in order to enhance ecosystem services and crop productivity with minimal inputs.

**Key words:** agroecology, tomato, companion plants, soil symbionts, conservation biological control, pests, yield

## Introduction

Tomato is a key crop worldwide, particularly in the Mediterranean Basin. Its market value in the EU amounts to approximately 7 billion euros, with Italy, Spain, Greece, and Portugal accounting for over 90 % of EU production (Eurostat, 2025). Regardless of the cultivation system (open-field or greenhouse) or the duration of the production cycle, increasing quantities of external inputs – such as pesticides, fertilizers, and herbicides – are required to ensure satisfactory levels of crop protection and yield. Major insect pests, spearheaded by *Tuta absoluta*, whiteflies, and mites, cause significant yield losses in tomato crops and substantially increase production costs (Wakil et al., 2018).

Agroecological approaches that focus on the conservation and enhancement of functional biodiversity, both above- and belowground, aim to increase and exploit ecosystem services such as pest regulation, nutrient cycling, and pollination, offering a potential alternative to the use of external synthetic inputs (Palomo-Campesino et al., 2022). However, their adoption relies on their validation experimentally.

Plant diversity in non-crop habitats can lead to reduced herbivore abundance and crop damage, accompanied by increased diversity and abundance of beneficial taxa that suppress economically important insect pests (Wan et al., 2020). The establishment of flowering plants is a key component of habitat management through plant diversity integration within the context of conservation biological control (Gurr et al., 2017). In addition, bottom-up effects –such as the disruption of host-finding and feeding behavior of herbivorous insects – play an important role in shaping pest population dynamics in agroecosystems. However, two critical factors must be considered: first, companion plants may also serve as hosts for insects and pathogens that can negatively affect the main crop; second, increases in natural enemy assemblages resulting from enhanced plant diversity are not always directly linked to effective pest suppression.

Several studies have documented increased biodiversity of beneficial pollinators and entomophagous insects promoted by diverse flowering plant mixtures, along with the ecosystem services they provide (Balzan et al., 2017; Kati et al., 2021). Popular flowering plants that provide food resources to beneficial insects and pollinators include, among others, alyssum (*Lobularia maritima* (L.) Desv., Brassicaceae), buckwheat (*Fagopyrum esculentum* Moench., Polygonaceae), coriander (*Coriandrum sativa* L., Apiaceae) and phacelia (*Phacelia tanacetifolia* Bentham, Hydrophyllaceae) (Pontin et al., 2006). Nevertheless, significant knowledge gaps remain regarding pest population dynamics and crop productivity under such systems.

Furthermore, the conservation and enhancement of soil biodiversity, particularly beneficial soil symbionts, can promote plant growth and strengthen plant defenses. Fungi of the genus *Trichoderma* are among the most extensively studied plant-associated microorganisms and are known to trigger induced resistance against a wide range of pests and diseases (Woo et al., 2022; Flors et al., 2024). Of particular relevance to tomato cultivation is the ability of *Trichoderma* spp. to enhance crop productivity and resistance to the leaf-mining pest *T. absoluta* in greenhouse systems (Minchev et al., 2024, 2026).

In this study, we implement agroecological practices in open-field tomato crops and evaluate both their individual and combined effects. Specifically, we assess how these practices, alone and in synergy, influence functional biodiversity, insect pest populations, and tomato plant growth and productivity.

## Materials and methods

### *Experimental plots*

Activities took place in a conventional open-field tomato crop in Epanomi, Thessaloniki, and an experimental tomato field in Aristotle University of Thessaloniki (AUTH) farm during 2023-2025. The two crops were 15 km apart. The conventional commercial field encompassed an area of ca. 30 × 15 m and there was frequent use of pesticides and fertilizers. In the AUTH farm, the experimental tomato field had three treatment plots: 1) tomato plot with phacelia (*Phacelia tanacetifolia*) as companion plant and application of *Trichoderma harzianum* T22, 2) tomato plot with buckwheat (*Fagopyrum esculentum*) as companion plant and application of *Trichoderma harzianum* T22 and 3) control tomato plot. Within the two companion plant treatments, *T. harzianum* T22 was applied to half of the tomato plants to assess the individual and combined effects of companion plant proximity (plants located close to or far from companion plants) and fungal application on arthropod communities, pest populations, and crop development. Each plot containing companion plants measured 12 × 3 m. Adjacent tomato plots measured 10 × 12 m, with a total of 216 tomato plants established. The internal control plot was 5 × 7 m, with 70 tomato plants. No pesticides or fertilizers were applied in the AUTH farm. Crops in the two fields consisted of determinate tomato varieties (Mountain fresh in AUTH farm and Zinnia in Epanomi).

***Evaluation of functional biodiversity***

Throughout the growing season over all three years (2023-2025), insect sampling was conducted in both the agroecological AUTH farm and the conventional commercial fields using Malaise traps to compare the diversity of Hymenopterans and Syrphidae. For the years 2024-2025 we also compared populations of beneficial Miridae between the conventional and agroecological fields and furthermore, within the two agroecological plots with the companion plants (plot 1 and 2) to assess the effect of the companion plant and the beneficial fungi and its combination. Lastly in year 2025 we did visual observation of mainly pollinators for 10 consecutive days during the flowering period of the companion plants at the AUTH farm.

***Monitoring pest populations***

Key pests such as *Tuta absoluta*, whiteflies (primarily *Bemisia* spp.) and tetranychid mites were monitored every 10-15 days across all experimental tomato plots.

***Assessing treatments on yield and quality of the crop***

Growth and productivity of tomato plants were evaluated in the two agroecological plots and the internal control plot in the AUTH farm by recording fruit weight and quality of the first fruits reaching harvest and classifying them into three size- and quality-based categories for the years 2024 and 2025.

## Results and discussion

First analyses indicate that agroecological practices substantially influenced functional biodiversity, pest dynamics, and crop performance. Hymenoptera communities in the AUTH farm where the two agroecological plots were located showed greater family richness and a more even taxonomic distribution compared to the conventional field, suggesting enhanced ecosystem stability. Syrphidae abundance was consistently higher in agroecological plots, particularly during fruit development. Miridae populations were lower in the conventional system across all samplings within the crop season, whereas in agroecological plots they were initially more abundant near companion plants and gradually dispersed into the crop, indicating the role of companion plants as reservoirs for beneficial arthropods. Companion plants supported distinct insect visitor assemblages: phacelia was primarily visited by honeybees (≈ 60 % of visits), followed by syrphids, while buckwheat was mainly visited by syrphids, wasps and wild bees.

*Tuta absoluta* populations persisted and increased toward harvest despite continuous pesticide applications in the conventional field, while no whitefly or mite infestations were recorded in this system. In contrast, no infestations of *T. absoluta* or whiteflies were observed in the AUTH farm encompassing the agroecological plots. Spider mite infestations occurred in agroecological plots; however, in plants treated with *Trichoderma harzianum* T22, mite populations were significantly reduced, indicating a suppressive effect of the beneficial fungus.

Regarding crop productivity and quality, the two agroecological plots consistently showed higher tomato yield and fruit number per plant compared to the internal control. Moreover, in 2025, fruit quality improved in the agroecological crop with phacelia, with a higher proportion of fruits classified in the highest quality category. Our results suggest that agroecological practices enhanced functional biodiversity, improved biological regulation of pests, increased yield and improved fruit quality. The combined use of companion plants and *T. harzianum* T22 appeared to act synergistically, contributing to greater stability and resilience of the tomato agroecosystem and supporting agroecology as a sustainable approach to tomato crop management.

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# Co-designing agroecological fruit production areas: a multi-scale and multidimensional approach

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**Abstract:** Diversification at different scales is a way to reinforce ecosystem services. However, the implications of such diversification are seldom considered comprehensively in design processes. We analyzed, over the 2017-2024 period, the design process of an experimental pesticide-free agroecological area for fruit production, located at INRAE Gotheron. Diversification of crop species, cultivars, companion plants and habitats was the basis of the approach, and co-design involved a diversity of stakeholders (farmers, advisers, researchers, teachers, naturalists). The design embedded interconnected scales that were worked on simultaneously or successively depending on the objectives and the design step. The approach mainly targeted ‘pest suppressive’ processes. At the plot scale, resource sharing in time and space between productive and associated plants as well as ergonomics were also considered. The supra-plot scale (10 ha) encompassed the spatial distribution of crops and habitats that contributed to the local agroecological landscape, as well as workload, allocation and organization. Finally, at the territory scale, the socio-technical system related to the marketing of fruit was embedded. Evaluation encompasses various criteria to account for different dimensions, scales, and a range of ecosystem services. First results attest to the need for methodological developments in the design-management-evaluation of complex agroecological systems and the importance of co-design to achieve the tradeoff between agronomic, ecological, organizational and socio-technical dimensions. Further research is still required but the present analysis opens avenues for agroecological design in perennial crops.

**Key words:** agroecology, co-design, diversification, orchard, pest control, upscaling

## Introduction

Diversification at different scales is a way to reinforce ecosystem services (Vialatte et al., 2025). However, the implications of agroecosystem diversification are rarely considered comprehensively in design processes due to (i) their complexity (i. e., a range of components such as crop species, cultivars, companion plants and habitats are involved); (ii) the occurrence of processes underlying ecosystem services at larger scales than that of the plot; and (iii) the single perspective in some research work, usually that of pest suppression in agroecological trials. But diversification entails many changes in other areas, such as decision making, work organization, marketing, etc. (Deguine et al., 2023; Vialatte et al., 2025). This is especially challenging in perennial (i. e., difficult to modify) and specialized crops such as orchards where plant diversity is very low (a cultivar corresponds to a clone), and practices heavily rely on input use at the expense of many ecological processes (Simon et al., 2010).

The aim of the ‘Zero pesticide’ project carried out in South-Eastern France at the INRAE Gotheron experimental unit was to design a fruit production area using plant diversification to reinforce ecosystem services towards pesticide-free orchards. Beside ecological considerations, the present paper aims to disentangle the dimensions and scales that were embedded through such diversification aimed at pest control.

## Materials and methods

The analysis is based on the case study of the ‘Zero pesticide’ multi-actor project carried out by the team SaVAGE (Agroecological Orchard Systems) at INRAE Gotheron since 2016. A first orchard prototype (P1) was co-designed in 2017 with farmers, advisers, researchers, trainers and naturalists (Penvern et al., 2018) and planted in 2018. It consisted of a highly diversified circular orchard of 1.8 ha comprising 33 fruit cultivars of 15 species and a range of service plants and habitats for biodiversity (Simon et al., 2025). Pest control only relied on cultivar choice, sanitation, mechanical practices and a pest-suppressive design through within-row and between-row fruit tree mixtures and diverse plant assemblages, to achieve barrier-dilution effects, and bottom-up and top-down processes mediated by plants and natural enemies, respectively. Attention was paid to ergonomics through work distribution throughout the year and how to circulate within the plot. No economic objectives were set in this breakthrough design. In 2023, the whole 10 ha-experimental area, already structured by historical hedgerows and P1, was enriched by a pond and service plants, and organized in homogeneous areas according to soil and plant context. At the same time, a new orchard prototype (P2) was co-designed under the same constraints as P1, but also including adaptation to climate change (i. e., facing extreme temperatures and water scarcity). Workload and organization were considered at this ‘small farm’ supra-plot scale. The resulting prototypes were an agroecological farmscape and the P2 agroforestry orchard recently planted. Finally, the marketing of diverse and low-volume fruit production is involved in the third design step currently underway. We analyzed this design process for the period 2017-2024 in terms of challenges, framework and constraints, scale of the objects designed, dimensions embedded and stakeholders involved in the process.

## Results and discussion

### *Several dimensions embedded in the approach beyond the biotechnical fields*

The approach mainly targeted ‘pest suppressive’ processes which are the basis of the approach towards pesticide-free fruit production (Figure 1). At the plot scale (P1, P2), three dimensions were involved in the design choices: pest control, resource sharing in time and space between plants, whether productive or service plants, and work organisation in time (i. e., throughout the year) and space (i. e., movements of workers and machinery within the plots). The supra-plot design step created an agroecological farmscape through the spatial distribution of crops and habitats to promote ecological processes involved in pest control. It also integrated work load, its allocation and organization, and movements of workers and machinery within and between plots. Finally, at the territory scale, the socio-technical system (i. e., the “collective of stakeholders, their networks, their practices and knowledge, the technologies they use, their collective representations and the standards and rules they adopt” (Meynard et al., 2017, after Rip and Kemp, 1998) related to the marketing of fruit from such diversified orchards is involved. This implied understanding and taking into account the constraints and objectives of the downstream stakeholders, that were not involved in Steps 1 and 2.

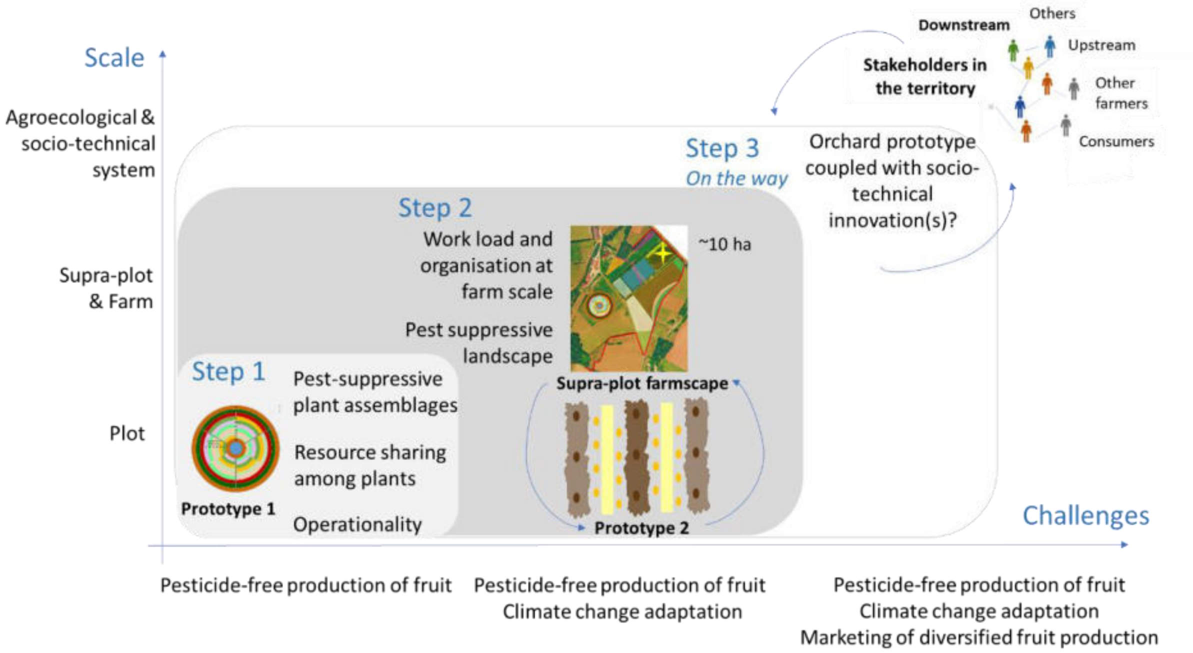

Figure 1. Dimensions embedded in the design process of orchard prototypes within the ‘Zero pesticide’ project at INRAE Gotheron. Each step includes all the dimensions considered in the previous step which are not reported for sake of clarity. Blue arrows represent back and forth steps between the concerned entities.

### *Levels considered in the approach*

The design embedded interconnected scales that were worked on simultaneously or successively depending on the objectives and the design step (Figure 1). The challenge relied in making consistent choices for all these interconnected scales. This was made through steps back and forth between scales (see arrows in Figure 1), satisfying the constraints identified at each scale to achieve the multi-scale design: between the plot (P2) and supra-plot (farmscape) spatial scales at Step 2, and the agroecological and the socio-technical systems at Step 3 (Figure 1). Beside stakeholders of Steps 1 and 2, Step 3 also included downstream stakeholders who work in the same territory and with the same products (i. e., fruit), but whose professional world greatly differed. Many research questions are worked on in the experimental design: Did we increase functional and common biodiversity, and predation and parasitism rates? Did we control pests and limit pest damage? Did we produce fruit? What did diversification entailed for work nature and organization? For fruit marketing? What are the economic performances of such prototypes in the current marketing systems? What about knowledge building? Issues related to the agricultural sector and the agrifood system and their lock-in effects that hinder the development of diversified agroecological orchards were also identified (Rosiès et al., 2025).

Consistently with Prost et al. (2023) and Cardona et al. (2025 a), first results attest to the need for innovative approaches in multi-dimension and multi-scale design and new benchmarks in the management of complex agroecosystems. Co-design as well as interdisciplinarity (mainly agronomy, agroecology, ergonomy, social sciences) were important to achieve the tradeoff between agronomic, ecological, organizational, economic and socio-technical dimensions and to consider interactions (whether agroecological or social) and complexity. To face the scarcity of stabilized knowledge on diversified systems in fruit production, open innovation was also very helpful through interactions with stakeholders such as ‘Cafés Agro’ (Cardona et al., 2025 b) for experience sharing among researchers and farmers to explore innovations. Finally, the evaluation of these diversified systems encompassed various criteria to address the different dimensions, levels, and a range of ecosystem services: methodological developments and formats to report the results (e. g., Alaphilippe et al., 2023) are also still underway. Further research is still required on the above-mentioned issues but the present analysis opens avenues for agroecological design in perennial crops.

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# Effects of agroecological practices expansion on biodiversity and ecosystem service multifunctionality in agricultural landscapes

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**Abstract:** Many studies conducted in controlled conditions or natural ecosystems demonstrated that biodiversity enhances multiple functions and ecosystem services. However, evidence from highly anthropized ecosystems, such as agricultural fields, remains scarce. Moreover, most of existing studies have focused on biodiversity – multifunctionality relationships at the local scale, often overlooking how these relationships emerge at larger spatial scales. At the landscape scale, habitat complementarity can enhance biodiversity and ecosystem functioning, and several ecosystem services depend on spatial dynamics. Yet our understanding of these spatial processes in intensively managed agricultural landscapes is still limited. This PhD thesis aims to identify how the large-scale deployment of agroecological practices affects biodiversity, ecosystem services, and multifunctionality (i. e., the capacity of an ecosystem to provide multiple ecosystem services simultaneously) quantified at the landscape scale. To do so, we will collect data on biodiversity and ecosystem services across different habitats along a landscape gradient of increased share of agroecological farming, in two study-regions dominated by vineyards or cereal fields in the South-West of France. Different provisioning, regulating, supporting and cultural services will be considered, with the objective of quantifying ecosystem services supply and multifunctionality at the landscape scale. By explicitly working in managed landscapes, this design will allow us to quantify how landscape-scale multifunctionality responds to the deployment of agroecological farming. This work will produce theoretical knowledge on the role of biodiversity spatial dynamics in sustaining multifunctionality, as well as operational insights for the spatial management of agricultural landscapes facing multiple and sometimes competing demands.

**Key words:** multifunctionality, ecosystem services, landscape, agroecology, functional diversity

## Introduction

While the expansion of agroecological practices is now often advocated for in agriculture, a key challenge remains to identify land-use strategies that protect biodiversity and simultaneously deliver multiple ecosystem services while still reaching sufficient production rates. Addressing this challenge requires moving beyond single-service approaches and considering how different services trade off with one another. In this regard, research on ecosystem service multifunctionality has developed, highlighting the need for a better understanding of the relationships between biodiversity and ecosystem service supply (Manning et al., 2018).

Since agroecological practices are implemented through management decisions across farms and landscapes, and because ecosystem services are collectively demanded and used by human societies at this same spatial scale, it has been emphasized that multifunctionality must be characterized and quantified at the landscape scale. To date, however, relatively few studies have explicitly quantified ecosystem service supply at this scale (but see Neyret et al., 2023) and the upscaling of landscape-scale multifunctionality is most often estimated by aggregating field-scale values weighted by the relative area of different habitat types. Such approaches implicitly assume spatial independence among landscape units and therefore overlook key ecological interactions, including flows of organisms, matter, and energy across habitats. Given these limitations, recent studies highlight the need to conceptualize and model multifunctionality at broader spatial scales by explicitly accounting for interactions among landscape units and cross-habitat processes (Boesing et al., 2024).

Quantifying ecosystem service multifunctionality at the landscape scale requires an explicit understanding of how local- and landscape-scale drivers interact to shape ecosystem service supply. Studies investigating landscape-scale drivers of biodiversity and ecosystem functioning have largely focused on metrics of landscape configuration or composition, which reflect the habitat-matrix heterogeneity of landscapes. While informative, such approaches overlook variation in habitat quality within a given habitat type, implicitly assuming that all patches contribute equally to biodiversity and ecosystem functioning (Fahrig et al., 2011). To account for this within-habitat heterogeneity, plant diversity has emerged as a robust proxy for habitat quality, as the composition and diversity of plant communities affect both above and belowground biodiversity and overall ecosystem service delivery (Le Provost et al., 2023).

This PhD thesis ultimately aims to model and quantify landscape ecosystem service multifunctionality in agricultural landscapes. Achieving this objective requires several intermediate steps, involving complementary analytical approaches, which together structure the different research axes of the thesis. The three main steps of this work are to: (i) assess how local practices and the landscape context modulate functional diversity of ecological communities in different habitats and at different spatial scales, using plants communities as a study system, (ii) analyze the effects of local practices, the landscape context and biodiversity on the supply of multiple ecosystem services at the local scale and (iii) upscale ecosystem service supply at the landscape scale and model ecosystem service multifunctionality in agricultural landscapes.

## Presentation of the study sites and design

Two agricultural territories will be considered, both located in the south-west of France: one dominated by vineyards, near Bordeaux, the other dominated by wheat fields, near Poitiers. Inside those territories, 18-20 landscapes (1 km-radius circles) are selected along two uncorrelated gradients: a gradient of proportion of organic farming, and a gradient of proportion of semi-natural habitats. Inside each of those landscapes, data will be collected in 4 different habitats: a conventional and an organic field of the studied crop, a grassland and a forest. In each of those habitats, surveys have been or will be conducted, to characterize multiple communities (plants, arthropods, birds) and ecosystem services (e. g., food production, pest control, climate regulation, organic matter recycling).

## Axis 1 - Drivers of plant functional diversity across habitats in vineyard landscapes

### *Introduction*

As community patterns are shaped by local and landscape scale processes, functional approaches have been increasingly called to better elucidate the impact of those processes on community assembly (Lavorel and Garnier, 2002; Spasojevic and Suding, 2012). Although these approaches have been applied in a range of habitats, both cultivated, natural or semi-natural, few studies have assessed functional diversity patterns at the landscape scale, in both crop and non-crop habitats. The first axis of this thesis aims to explore the impacts of local practices and the landscape context on plant alpha-, beta-, and gamma trait-diversity. By considering different traits associated with plant functional strategies, we aim here at disentangling the metacommunity processes shaping plant communities in agricultural landscapes, and estimate the relative importance of local and landscape factors in shaping the composition of plant communities (Spasojevic and Suding, 2012).

### *Materials and methods*

Using GLMM and RLQ analyses, this axis will mobilize plant community surveys in different habitats within contrasted agricultural landscapes, plant trait databases and landscape heterogeneity metrics that characterize landscape composition and configuration. We will select plant traits that provide information about how plants respond to environmental changes and that determine interactions with other trophic levels (e. g., herbivore, pollinator and predator arthropods, birds) and ecosystem service provision.

### *Results and discussion*

At the local (alpha) scale, we expect higher plant diversity in landscapes with high proportions of organic farming and semi-natural habitats. However, local practices may modulate these relationships, and more intensively managed habitats may harbor more ruderal species that colonize fast. At the landscape scale, we expect overall gamma functional diversity to be driven by both landscape composition and configuration, where a high habitat diversity and many interfaces between them promote plant gamma diversity. We further expect that very heterogeneous landscapes will be associated with a higher beta trait-diversity compared to more homogeneous landscapes, where flows of species are facilitated, in more similar communities between habitats.

## Axis 2 - Effects of local and landscape management on the relationships between biodiversity and ecosystem service supply

### *Introduction*

Habitat complementarity at the landscape scale underpins ecosystem multifunctionality, as habitats deliver different services and interact through organism and matter flows (Le Provost et al., 2023). This axis aims at investigating how ecosystem service supply at the local scale is modulated by local practices, landscape variables and by local and landscape scale plant diversity, considered as a proxy of habitat quality.

### *Materials and methods*

At the field scale, across the four different habitat types in both study areas, data collection will inform on provisioning, regulating, supporting and cultural service supply. This data will be coupled to plant biodiversity surveys and landscape metrics mobilized in the first axis. Using statistical models such as Structural Equation Modelling, we will identify the main drivers of ecosystem service supply within each habitat along landscape gradients and biodiversity.

#### *Results and discussion*

We expect that biodiversity and associated regulating and cultural services will be higher in organic fields compared to conventional fields but that provisioning services will be lower, resulting in trade-offs between ecosystem services at the local scale. As semi-natural habitats in the landscape have been shown to improve local regulating and cultural services via the spillover of beneficial species, and because semi-natural habitats act as shelters for biodiversity, we further expect that local biodiversity, as well as regulating and cultural services will increase with the proportion of semi-natural habitats in the landscape.

### Axis 3 - Upscaling ecosystem service multifunctionality at the landscape scale

#### *Introduction*

Assessing ecosystem multifunctionality at the landscape scale offers a comprehensive framework to capture the full range of benefits that agricultural landscapes and biodiversity provide to society (Manning et al., 2018), and inform land-use planning and agricultural management policies aimed at balancing production, conservation, and human well-being. Landscape-scale assessments of multifunctionality can therefore support the design of integrated management strategies that move beyond single-service optimization. While a limited number of studies have quantified landscape-scale multifunctionality, even fewer have explicitly considered the interactions among habitat patches within landscapes. The goal of this third axis is to model landscape-scale multifunctionality, considering the influence of landscape metrics and surrounding biodiversity on ecosystem service supply.

#### *Materials and methods*

Using the relationships established in the 2$^{nd}$ axis, we will model ecosystem service supply within different habitat patches in the landscapes, and upscale ecosystem service multifunctionality assessment at the landscape scale (Boesing et al., 2024), which will provide us information on landscape structures promoting multifunctionality (Neyret et al., 2023).

#### *Results and discussion*

Overall, we expect landscape-scale multifunctionality to be higher in highly heterogeneous landscapes, composed of multiple, complementary habitats that supply a wide range of ecosystem services, and are well connected, thereby facilitating positive interactions between habitat patches.

## Conclusions

By integrating field-based data analyses and landscape-scale modelling, this thesis will generate important ecological knowledge about spatial dynamics of biodiversity, and its influence on the supply of ecosystem service across cultivated and semi-natural habitats. Landscape-scale multifunctionality assessment will then be coupled with data on the ecosystem services requirements by different stakeholder groups within the study areas (Neyret et al., 2023).

Such analysis would ultimately provide operational insights about how the large-scale adoption of agroecological practices in agricultural landscapes can meet stakeholder needs and promote the coexistence of multiple activities within agricultural landscapes.

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# Soil physicochemical properties and soil microbiota affect abundance and prevalence of entomopathogenic fungi in soil

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**Abstract:** Entomopathogenic fungi (EPF) are naturally occurring antagonists of insect pests, offering a promising approach to replace or complement synthetic insecticides. Supporting survival or proliferation of applied EPF in agricultural soils via soil management practices could increase biocontrol efficacy but requires data-driven analyses on which EPF are suitable in particular soil conditions. These soil conditions not only comprise physicochemical soil properties but also soil microbiota, which may support, coexist with, or antagonize EPF in soil. Using a global amplicon dataset containing EPF presence/absence data, we modelled global cropland suitability for *Metarhizium* and *Beauveria* as a function of soil and climatic properties. Furthermore, we compared the inferences obtained from global data analyses to inferences from a local dataset on EPF abundance. With a subset of soil variables correlating with EPF abundance, we conducted lab experiments using sterilized and non-sterilized field soil to assess whether the tested variables directly affect EPF or are microbiota-mediated. Similar results could be obtained using global and local soil microbiome datasets. Natural *Metarhizium* occurrence is higher in regions with high primary productivity, while *Beauveria* appears to be more frequent and in higher relative abundances in drier, more mountainous regions. In *Metarhizium*, we observed species-specific effects of soil sulphur content on growth, which were at least partially mediated by microbiota. Our findings identify key soil chemical components that may be instrumental in promoting EPF populations in agricultural soils to support functional biodiversity.

**Key words:** *Metarhizium*, *Beauveria*, environmental competence, realized niche, agroecosystem

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# Trade-offs and synergies between ecosystem services in agricultural landscapes – a multiservice modelling approach

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**Abstract:** Exploring how landscape changes affect multiple ecosystem services is key to design agroecological landscapes that would foster a bundle of ecosystem services. In this study, we focus on pollination, pest control and surface water quality (nitrate concentration). We simulated two agricultural watersheds, in the Living Lab Gascogne in South-West of France, and five scenarios of land-cover changes: (i) a landscape in accordance to the Ten Years For Agroecology in Europe scenario ("Sustainable Development"), (ii) an increase in legume crops (replacing cereal crops) ("Trend"), (iii) an increase in the cultivation of cereal crops ("Liberal"), and (iv) two breakup scenarios in which all cereal crops were converted to either grasslands or forests. Spatially-explicit models were used to evaluate the impacts of the five scenarios on the levels of services delivered. At the watershed level, all three services were on average improved with the breakup scenarios, while they were reduced with the Liberal scenario. Results were contrasted for the Sustainable Development scenario, with higher potential for pest control and water quality, but lower for pollination. An analysis at a smaller spatial scale might unravel synergies and trade-offs between services linked to changes in the surrounding landscape. These results suggest that only changing land cover without changes in associated agricultural practices such as pesticide use or mineral fertilization, might not be sufficient to foster sets of ecosystem services. This modelling approach can be used to promote concerted action between stakeholders using maps, and to help design agroecological landscapes that fosters bundles of ecosystem services.

**Key words:** pollination, pest control, water quality, land-cover scenarios, agriculture transition

## Introduction

The agroecological transition will rely on ecosystem services (ES) such as pollination and pest control to reduce the use of chemical inputs. Such a switch in practices will reduce agriculture current negative impacts on the environment, such as water pollution. Fostering these ES requires a landscape approach, as pollinators, pests, and natural enemies are mobile organisms over the landscape (Kremen, 2007). Similarly, water quality of a river is impacted by the practices implemented throughout the entire watershed. Predicting the impacts of management scenarios in various ES is not straightforward. Once calibrated and validated, models can be used to evaluate landscape management scenarios and help local stakeholders to design their landscape and practices (Hossard, 2013). We used three different models to assess the potential impacts of land-cover scenarios on pollination (Invest), pest control (Chloe – landscape metrics) and water quality (SWAT), and conducted a preliminary assessment of the potential economic impact on farms.

## Materials and methods

### *Study area and scenarios*

The study took place in two watersheds (Touch and Louge) in the Living Lab Gascogne, part of the LTSER PYGAR long-term socio-ecological research site in south-western France. The area of about 450 km$^2$, is a mix of crops and extensive livestock farming system composed of 27 % woods, 24 % cereal crops, 22 % meadows, 7 % protein crops and 6 % legume crops. Five landscape scenarios were elaborated during participatory workshops: (i) a landscape in accordance to the Ten Years For Agroecology in Europe scenario (“Sustainable Development”, with an increase of grain and fodder legumes, protein crops, and a decrease in meadows), (ii) a 50 % increase in legume crops according to the expected trend (“Trend”), (iii) a conversion of all grasslands to cereal crops (“Liberal”), and (iv) two breakup scenarios in which all cereal crops were converted to either grasslands or forests. The actual landscape in 2016 (Baseline scenario) was simulated with a resolution of 3 m using spatial data: agricultural land cover (Registre Parcellaire Graphique), urban, forest and water areas (BD Topo from the French national mapping agency IGN) completed by OCS-GE data (IGN) providing complete coverage of the French territory, and soil characteristics at 1/250000 resolution (IGCS). The baseline scenario map was modified to generate the maps of the landscape scenarios using R software. We used climate data from 2009 to 2020 (from Météo-France) to include climatic variability. Long-term data on biodiversity and water (Ouin et al. 2021; Petit et al., 2023) collected on the study area were used to parameterize the models.

### *Modelling*

Three ecosystem services were studied using spatially-explicit models. We used the InVEST® platform to assess pollination services. The pollination model estimates, for each pixel of the landscape, (i) an index of wild pollinators supply based on nests and nearby floral resources availability, and (ii) an index of crop visitation rate based on nearby pollinator supply and floral resources. We modelled the visitation rates of sunflower and rapeseed fields, the most frequently cultivated pollinator-dependent crops in the study area. Pest control potential was assessed using “Chloe – landscape metrics” software (Boussard et al., 2025). For each pixel, the model predicts an index of pest control level by taking into account meteorological data, local data on land cover and practices (Treatment Frequency Index – TFI), and surrounding landscapes using Shannon diversity and cumulative TFI. Water quantity and quality was assessed with the use of the SWAT model (Arnold et al., 2012), a process-based river basin model used to predict the impacts of management on water resources. Daily data on water discharge and chemical parameters were measured at the outlet of each basin, during more than a year, to calibrate the model. Finally, an economic evaluation of the scenarios was made (except for the two breakup scenarios), with the use of a bio-economic model (Kleftodimos et al., 2021). Four farm-types were identified through personal interviews and with the local extension services (Chambre Régionale d'Agriculture d'Occitanie): specialization in cereal and oilseeds rotation system (A), specialization in maize rotation (B), specialization in polyculture (C), and a livestock-oriented system with permanent and temporary grassland dominated land-use (D).

***Analysis***

Output indexes from the pollination and the pest control models were analysed at the pixel level, while SWAT outputs were analysed at the watershed outlets. In order to compare the outputs of the scenarios with those of the baseline scenario, we quantified the percentage change for each index as follows:

$$\Delta Index(scenario) = 100 \times \frac{Index(scenario) - Index(baseline)}{Index(baseline)}$$

For each index we compared the scenarios' percentage change using a Kruskal-Wallis test with multiple comparison posthoc test and the Bonferroni correction. For each scenario we tested if the percentage change was significantly different than zero ± 2.5 using a Wilcoxon test.

## Results and discussion

Both breakup scenarios show gains for indicators, as indexes for pest control and pollination are significantly higher compared to the baseline scenario, while nitrate load and concentration are significantly lower (Figure 1). The Liberal scenario on the other hand shows a worsening in all indicators except water flow, with less pest control and pollinator supply and visit, and higher nitrate load and concentration in the water. As for the Trend and Sustainable development scenarios, only the pollinator supply index shows an increase compared to the baseline, but we do not see similar improvements in crop visitation rates. Regarding the economic evaluation, only the Liberal scenario leads to improved incomes for farm-types A and B.

Model outputs show that breakup scenarios give significant increase or decrease in multiple services. This is not the case for more realistic scenarios (Trend and Sustainable Development) for which only small differences were observed on average. These results suggest that land-cover modification without changing the agricultural practices in a systemic way (e. g., including the economic conditions for implementation, see Vialatte et al., 2025) is not sufficient to foster these ecosystems services, which aligns with known negative impacts of agricultural practices on ecosystem services (Geiger et al., 2010, Knauer et al., 2025). Such a modelling approach may be used in a participatory process with stakeholders to co-design and evaluate scenarios of transition, helping decision-making and action (Poggi et al., 2021).

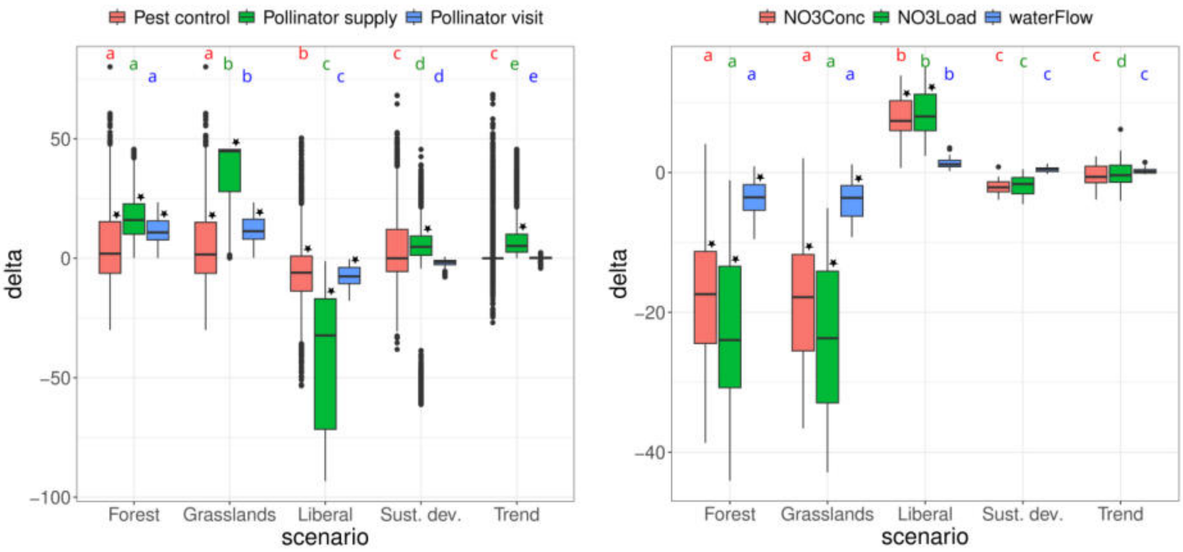

Figure 1. Comparison of model outputs for the five scenarios for pest control and pollination at the pixel scale (left) and water quantity and quality at the watershed scale (right, with values for both watershed and 10 years of simulation). All values are the gain or loss (%) compared to the baseline scenario. Letters indicate the results of the Kruskal-Wallis test for each index, while the stars indicate that the scenario outputs are significantly 2.5 % greater and lower than the baseline scenario.

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# FutureScapes – The Centre of Excellence for Sustainable Land Use

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**Abstract:** The Centre of Excellence for Sustainable Land Use (FutureScapes) is a seven-year initiative (2024-2030) designed to uncover how biodiversity and carbon flows interact in diverse environmental conditions across Estonia. The project develops innovative approaches to simultaneously address biodiversity loss and climate change. Its core objective is to identify the complex linkages and co-benefits between biodiversity, carbon stocks, and carbon fluxes, and to incorporate this knowledge into large-scale spatial models that support evidence-based land-use decisions.

We will quantify and integrate the relationships between biodiversity patterns and functions, ecosystem carbon storage, sequestration, and greenhouse gas emissions from local to national scales. Using geospatial datasets – including satellite observations – and machine-learning-based spatial modelling, we aim to upscale these insights to the regional level and embed them into spatially explicit land-use planning and management. This process will also account for the socioeconomic context of landowners and land users to ensure practical and socially relevant outcomes.

**Key words:** biodiversity, climate change, spatial models, machine learning, land-use planning

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# Pest control in the Baltic Sea Region via the PestSpace common data platform

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**Abstract:** The PestSpace system aims at the improvement of pest and disease control by identifying crop diseases and insect pests based on images sent via a mobile app. Pathogens and insects are identified using environmental DNA and machine learning, and the data is stored in a shared database on the PlutoF platform. The far goal of this system is to notify growers about pathogens and insect pests and provide guidance on crop protection. Currently, research is focused on the health of winter wheat and faba beans, but guidelines will ultimately be developed for further expansion of the system to include other crops. At present the PestSpace system is being developed in the Baltic Sea Region and covers Estonia, Finland, Latvia, Lithuania and Poland.

**Key words:** pests, diseases, integrated control, PlutoF, Baltic Sea Region

## Introduction

As the climate changes, pests previously unable to survive in the Baltic Sea Region (BSR) will become viable and may survive and develop in new conditions. Therefore, it is necessary to collect and monitor data on the diversity of insect pests and plant diseases in common, shared data space, especially during the growing season of agricultural crops. Detailed data on the presence and the diversity of pests and pathogenic fungi is a crucial prerequisite to develop possible future scenarios of their spread. This data is also necessary to prepare the relevant recommendations for the farmers. At present such precise and digitally available monitoring schemes are not available in the BSR region. There is a challenge to collect a large amount of data, integrate it with the existing data and analyze it to find the patterns of pest occurrence and harmfulness. Moreover, the data should be easily obtained by farmers, advisers, officials, and researchers across countries to ensure that threats are identified and responded to as quickly and comprehensively as possible.

The new Interreg funded project PestSpace, started in March 2025. It uses existing technologies to create a system that identifies pests in the field using environmental DNA (eDNA) sequencing and photos uploaded via a mobile app. Machine-learning algorithms will be used to identify the pests and diseases (pathogenic fungi) based on photos, using a mobile app. The data is stored in a common data space on the PlutoF platform (https://plutof.ut.ee/). The system intends to quickly notify plant growers about the threats and provide guidance on how to respond to them. The plan is to develop guidance materials on the use of the system and engage all stakeholders along the value chain. We will validate the system using two important crops to the BSR (faba beans and winter wheat) and create guidelines on how the system could be further expanded to cover other crops in the other countries of BSR in the future. Link to project website: https://interreg-baltic.eu/project/pestspace/

## Materials and methods

### *Project partnership*

PestSpace unites researchers, officials, entrepreneurs, consultants, journalists, and farmers in five countries of the BSR – Estonia, Finland, Lithuania, Latvia and Poland. The project is led by the University of Tartu (UTARTU), one of Europe's leaders in developing digital tools for biodiversity research. UTARTU is responsible for the solution developed in WP1, piloted in WP2, and transferred in WP3. Researchers from all 5 countries contribute data and support dissemination. University of Warsaw (UW) contributes experience in taxonomy, systematics, and biodiversity research. It will share its knowledge in using DNA analysis in the field. Institute of Plant Genetics, Polish Academy of Sciences (IPG PAS)' Pathogen Genetics and Plant Resistance Team specializes in resistance assessment, early detection of pathogens, and operates the Polish System for Forecasting Disease Epidemics. Vytautas Magnus University (VMU) contributes plant protection specialists skilled in safeguarding crops and enhancing agricultural productivity. Latvia University of Life Sciences and Technologies (LBTU) performs R&D in agriculture together with industrial partners, including farmers and consultants. The Finnish Museum of Natural History at the University of Helsinki (UH) offers the country's largest infrastructure in biodiversity research with expertise in taxonomy and DNA-based species identification. The Centre of Estonian Rural Research and Knowledge (METK) and the Natural Resources Institute Finland (Luke) as well as LBTU in Latvia represent sectoral agencies researching, monitoring, and reporting plant diseases to their national governments. Together, they ensure that the solution is adopted by government agencies across the region. HR Smolice is a Polish seed and breeding company with its own glasshouses and molecular laboratory equipped for molecular studies. Beyond participating in development and piloting, they will make sure that the developed solution also fits the needs of large agribusinesses. The partnership is supported by a wide range of organizations representing key stakeholders of the project. LATRAPS is the largest farmers' cooperative in the Baltics with their own advisory department responsible for knowledge transfer and implementing new tools and technologies. APRA is Poland's leading publisher and printing house specialized in agriculture. The Kuyavian-Pomeranian Agricultural Advisory Center (KPODR) is the leading extension service for farmers in Central Poland with access to educational infrastructure and to the field. Innvigo, Väätsa Agro, and ProAgria represent small and medium-scale farmers and agribusinesses in Poland, Estonia, and Finland. The training will be provided to Poland's Main Inspectorate of Plant Health and Seed Inspection, which will then further disseminate the method and the results.

***Data collection***

The monitoring and collection of pests and diseases (fungal pathogens) is carried out for two years of faba bean cultivation (2025 and 2026) and two seasons of winter wheat cultivation (2025/2026 and 2026/2027) for 10 cultivars, two being chosen by each of the five participating countries (EE, FI, LT, LV and PL) (Figure 1). Field study is performed at 18 locations (Table 1). Each specimen and sample is assigned an individual QR code which is then matched to the results of visual and molecular identification. The data is stored at the data storage platform PlutoF.

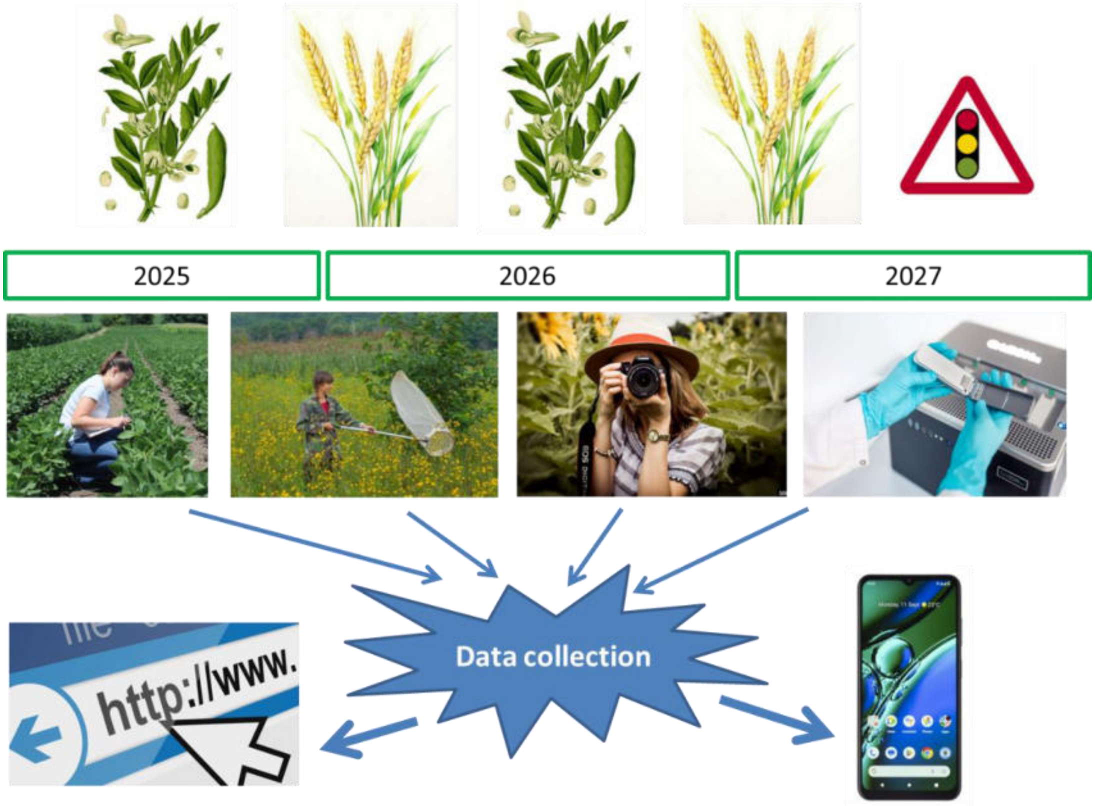

Figure 1. Scheme of the PestSpace project with two years of data collection from field experiments on faba beans and winter wheat, followed by DNA sequencing, bioinformatic analysis of the data and creation of the warning system for the farmers.

Table 1. Number and names of locations of the field experiments in the PestSpace project.

| Country | No. of locations | Names of locations |
|---|---|---|
| Estonia | 4 | Jõgeva, Kuusiku, Viljandi, Võru |
| Finland | 1 (+2) | Inkoo, (Jokioinen, Isokyrö - only Finnish cultivars) |
| Lithuania | 3 | Grinkiškis, Noreikiškės, Verėduva |
| Latvia | 3 | Kurzeme, Vidzeme, Zemgale |
| Poland | 5 | Chrząstowo, Radostowo, Rarwino, Smolice, Wrócikowo |

### *Data storage platform PlutoF*

PlutoF is an online data management platform and computing service provider for biology and related disciplines. Registered users can enter and manage a wide range of data, e. g., taxon occurrences, metabarcoding data, taxon classifications, traits, and lab data. It features an annotation module where third-party annotations (on material source, geolocation and habitat, taxonomic identifications, interacting taxa, etc.) can be added to any collection specimen, living culture or DNA sequence record. It also features an analysis module by providing digital services for molecular sequence identification and species discovery from eDNA samples (Abarenkov et al., 2010).

## Results and discussion

### *Transnational value of the project*

The PestSpace system will consist of a shared data space, a mobile app for disease and pest identification through image analysis, and an early warning system that will notify farmers and other interested end-users from various countries about the emergence of new threats to crop health in a given area. The spread of pests due to climate change is inherently international: pathogenic and parasitic species tend to shift northwards with rising temperatures. To simplify, the pests affecting Poland today could threaten Finland tomorrow. The policies and action of actors in one country can significantly affect others – allowing or hindering the spread of (invasive) pests. Thus, no single country can solve this problem alone. This is even more so for smaller countries such as the Baltic countries whose monitoring is geographically limited. For this reason, we involved partners from countries of different sizes along the North-South pathway: PL, LT, LV, EE, and FI. The PestSpace project brings together scientific organisations, farmers' cooperatives and businesses, public agencies, and other stakeholders in each country to map existing biodiversity data to determine how to integrate the PestSpace system into national monitoring systems as well as possible. A transnational approach is also needed to enable regular communication between farmers, public agencies, agricultural companies, and researchers across borders, so knowledge is spread, solutions are shared, and best practices introduced. Although natural ecosystems are similar among BSR countries, they are not identical. Involving actors from different countries will help account for this local variability. Beyond this, a joint effort will be more effective to gain the expertise in the domains covered by this project (biodiversity, AI, agriculture, public policy). We focus on a crop of high current importance to the BSR: wheat, of which over 5 million tons are produced each year in the BSR and is a major export crop. We also focus on a crop of future importance: faba beans, which can serve as climate-friendly alternative to importing soybeans. In the future, additional crop species and countries beyond the Baltic Sea region can be added to PestSpace, to further increase the impact and effectiveness of the system.

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