



HAL
open science

Weed control provided by seed predators saves 20 % crop yield in cereal fields

Lucile Muneret, Benjamin Carbonne, Bruno Chauvel, Alexandre Dosset, Chantal Ducourtieux, Nicolas Henon, Émeline Felten, Emilien Laurent, Annick Matejicek, Sandrine Petit

► **To cite this version:**

Lucile Muneret, Benjamin Carbonne, Bruno Chauvel, Alexandre Dosset, Chantal Ducourtieux, et al.. Weed control provided by seed predators saves 20 % crop yield in cereal fields. *Agriculture, Ecosystems and Environment*, 2026, 400, pp.110196. <10.1016/j.agee.2025.110196>. <hal-05453827>

HAL Id: hal-05453827

<https://hal.science/hal-05453827v1>

Submitted on 13 Jan 2026

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

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



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



Weed control provided by seed predators saves 20 % crop yield in cereal fields

Lucile Muneret^{a,b,*} , Benjamin Carbonne^{a,c}, Bruno Chauvel^a, Alexandre Dosset^b ,
Chantal Ducourtieux^a, Nicolas Henon^a, Emeline Felten^a, Emilien Laurent^a, Annick Matejcek^a,
Sandrine Petit^a 

^a Université de Bourgogne Europe, Institut Agro Dijon, INRAE, UMR Agroécologie, Dijon, France

^b Université Paris-Saclay, AgroParisTech, UMR Agronomie, 22 Place de l'agronomie, Bâtiment F, CS 20040, Palaiseau cedex 91123, France

^c IGEPP, INRAE, Institut Agro, Univ. Rennes, Angers 49045, France

ARTICLE INFO

Keywords:

Weed control
Quantification
Crop productivity
Natural enemy
Arable land
Conservation agriculture
Exclusion cages
Carabids
Rodents

ABSTRACT

Although many herbicide active substances have been banned, and while weed infestation is a major threat to crop productivity, the extent to which natural weed control provided by seed predators can help farmers manage weed communities remains unknown. The contribution of seed predators to crop productivity through weed control was quantified, and it was assessed whether farming systems such as conservation agriculture played a role in bolstering their impact. A total of 112 seed predator-exclusion cages were set up in 28 cereal fields in France (14 pairs of plots, in which one plot was managed under conservation agriculture and the other under conventional agriculture). Weed emergence and biomass were surveyed, crop yield was measured, and the main seed predators—carabid beetles and rodents—were sampled. A 20 % reduction in yield loss due to weeds was found to be caused by seed predator activity, which was extrapolated to an economic gain of 285 €/ha. However, a whole 60 % of the maximum crop yield potential reached in the absence of weeds remains lost. Moreover, while conservation agriculture enhances weed control, this does not translate into increased crop yield. This study demonstrates the tangible importance of considering seed predators for weed control but highlights the need to combine this approach with other weed control practices or to substantially redesign cropping systems to enhance the beneficial effects of biodiversity on crop productivity.

1. Introduction

In industrialized countries, crop yield is highly dependent on synthetic fertilizers and pesticides (Tilman, 2002). However, due to their negative impacts on the environment and biodiversity worldwide, their use is increasingly challenged and many pesticide substances are now prohibited (Jacquet et al., 2022; Chauvel et al., 2022). As an alternative paradigm, the ecological intensification of agriculture relies on ecological processes supporting intermediate ecosystem services to — at least partially — replace the use of external inputs to enhance crop yield (Bommarco et al., 2013; Dainese et al., 2019). Yet, this new paradigm comes with its share of uncertainties. First, agrobiont biodiversity has suffered from agricultural intensification for decades, altering the provision of efficient regulating ecosystem services such as pollination or pest control potential (Rigal et al., 2023; Sánchez-Bayo et al., 2019).

Second, efforts to enhance biodiversity in agricultural fields, either through agroecological practices or by maintaining semi-natural habitats, could also lead to a better development of damaging crop pests or of weeds, to the detriment of crop yield (Muneret et al., 2018; Delaune et al., 2021). Thus, harnessing biodiversity to provide efficient regulating services that limit pest outbreaks and foster crop yield through the implementation of biodiversity-friendly practices is still very challenging.

The implementation of biodiversity-friendly practices or systems is expected to enhance biodiversity and the provision of regulating ecosystem services (Wittwer et al., 2021). For example, reducing pesticide use is beneficial for the carabid community in general (Muneret et al., 2023); and the presence of grassy margins can be positive for some granivorous species like the Carabid species *Amara similata* (Labruyere et al., 2018). However, adopting an agroecological system can also

* Corresponding author at: Université de Bourgogne Europe, Institut Agro Dijon, INRAE, UMR Agroécologie, Dijon, France.
E-mail address: lucile.muneret@inrae.fr (L. Muneret).

<https://doi.org/10.1016/j.agee.2025.110196>

Received 7 October 2025; Received in revised form 14 December 2025; Accepted 24 December 2025

Available online 10 January 2026

0167-8809/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

result in crop yield losses, since regulating services may take time to become effective or may not fully compensate for the absence of external inputs required to achieve productivity goals. For example, conservation agriculture is on average 5 % less productive than conventional agriculture (Pittelkow et al., 2015). Conservation agriculture has been expanding rapidly worldwide since the 2000s and is based on three principles: no or minimal soil tillage, soil cover with biomass mulch, and crop diversification (Kassam et al., 2019). This farming system is generally beneficial for biodiversity (Henneron et al., 2015). Nevertheless, the increased complexity of trophic interactions under this management can dilute their effect on the provision of pest control services (Carbonne et al., 2023). Further measures of the efficacy of alternative systems such as conservation agriculture in enhancing regulating services remain necessary to guide the agroecological transition.

In this context, weeds remain the main biotic threat to crop yield (Oerke et al., 2006). The biomass of dominant weeds is a strong driver of yield loss in arable fields (Adeux et al., 2019). It might be especially significant in contexts of ecological intensification due to the weed seedbank's persistence and to its species diversity, which enables it to respond to a variety of environmental conditions. Many macro-organisms like carabids, ants, voles and granivorous birds have been identified as weed seed predators (Sarabi, 2019). For example, the carabid community can influence weed seed bank enrichment as well as weed demography (Westerman et al., 2005; Bohan et al., 2011). These effects depend on several parameters, such as carabid species composition, weed species (due to differences in lipid content and seed size), or the presence of alternative prey (e.g. Petit et al., 2014; Carbonne et al., 2022; Gaba et al., 2019). In fallow plots, they can reduce weed emergence by 38 % and weed biomass by 81 % (Blubaugh and Kaplan, 2016). However, due to their compensation mechanisms, weeds are likely to grow better and produce more seeds when they are scarce (in addition to being released from competition). The actual impact of weed seed predators on crop productivity through weed control therefore remains to be verified and assessed (Pannwitt et al., 2021). Moreover, if seed predators significantly contribute to weed control, determining which taxonomic group—especially carabids or voles—has the strongest impact would be crucial for designing nature-based weed management strategies. Thus, vague and presumptive claims about the effect of biodiversity on weed dynamics highlight a knowledge gap that should be addressed by quantifying the potential of natural weed control and clarifying its tangible benefits for farmers.

A small-plot experiment was conducted in commercial fields to quantify the contribution of seed predators to crop yield. This is the first attempt to measure the genuine effect of seed predation on yield. Our

experiment involved the installation of 112 exclusion cages across 28 cereal fields. First, we hypothesized that both invertebrate and vertebrate seed predators reduce weed emergence and biomass, which in turn should enhance crop yield (Fig. 1). Specifically, we expected that a more abundant and complementary natural enemy community would mitigate the negative impact of weed biomass on crop yield. Second, we hypothesized that conservation agriculture promotes the presence of invertebrate and vertebrate seed predators, thereby strengthening the positive effect of weed control on crop yield.

2. Materials and methods

Experimental design. Our experiment was carried out in 14 pairs of cereal fields in a cropland-dominated area around Dijon, in the East of France (47°19'19.369" N, 5°2'29.328" E) between 2021 and 2022. Cereals included winter wheat (24 fields), winter and spring barley (three fields), and Escourgeon (one field). Each pair was composed of one field farmed under conservation agriculture and the second under conventional agriculture. The pairs covered a gradient of proportional cover of conservation agriculture in a buffer of 1 km radius around fields (a range from 3.1 % to 37.5 %). This metric was not correlated with the proportion of semi-natural habitats (Supplementary Figure S1). The landscape was documented using the French Graphic Parcel Register, superimposed on the CORINE Land Cover map 2000 in ArcMap 10.8. The land use and the farming system of the parcels were also recorded through field and farmer surveys. The mean distance between neighbouring field pairs was 9.6 km. Field sizes ranged from 1.94 to 38.7 ha, with the exception of two smaller experimental plots in a laboratory site. In each field, we set up four cages with different weed seed predator-exclusion treatments at 20–50 m from field margins, except for the two experimental fields (i.e. 112 cages in total). Cages were aligned, spaced 30 cm apart and enclosed together using a wire fence positioned about 1 m around the line of cages to protect them from wild animals (Fig. 2). The enclosed plots were maintained free from any agricultural intervention throughout the experiment, whereas farmers continued to apply their usual management practices in the surrounding fields, contouring the fenced areas.

The cages were hand-crafted according to the author's design and comprised both a buried component and an above-ground component. The buried part was a box measuring 0.30 × 0.30 × 0.15 m (L×W×H). The four sides were made of wood and the bottom was made of a perforated steel sheet (diameter 2 mm) to allow for water exchange with the field soil. The boxes were filled with sterilized sandy loam soil (®SONOFEP company) and buried into the soil to have their soil surface

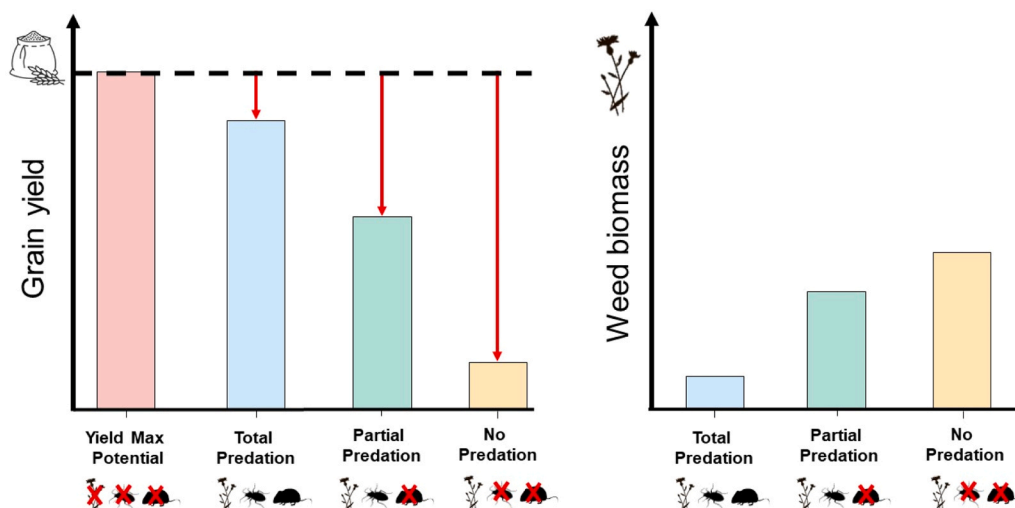


Fig. 1. Hypothesized effects of seed predators on weed biomass and crop yield at harvest.



Fig. 2. Overview of the experiment's timeline and settings. **A)** The experiment started in March 2021 with the burial of four hand-made cages in the soil (15 cm depth) of each field. The cages were spaced 30 cm apart and surrounded by a wire fence to prevent damage from large mammals. Weed seed rain was simulated in May and June, coinciding with carabid and rodent captures. Wheat was sown in October, and both crop yield and weed biomass were measured a few days before harvest, in late June or early July 2022. **B)** Picture 1 provides a close-up view of the different types of weed access allowed to natural enemies. Picture 2 shows the experimental setup at the beginning of the study. Pictures 3 and 4 illustrate two examples of cages under the "Total predation" and "Control" treatments, respectively. Pictures 5, 6, and 7 show the evolution of the setup over time until harvest.

level with the field's (Fig. 2). The aerial part was 1.0 m tall and framed by a structure made of 8 mm steel bars. The cages' differentiating features were located in this part's lower 0.15 m, just above the soil. This part was bordered by wood frames that were either closed off using a plastic net that left seed predators no access to the cage (the *Control* and *No predation* cages were like this), or using a chicken wire with 0.012 m holes, only giving invertebrate predators access to the cage, or they were left open, so that both vertebrate and invertebrate predators could access the cage. Above this 0.15 m strip, all the cages were covered by a plastic net (with 600 μ m perforations) to ensure that micro-climatic conditions were the same in all four cages regardless of their seed

predator treatment.

All cages were installed in sets of four. The first cage only contained wheat, excluding weeds and seed predators, and served to measure the maximum crop yield potential: this was our *Control* cage. The second cage contained wheat and weeds, but totally excluded seed predators, to measure weed harmfulness to crop yield. This was the *No Predation* cage. The third cage contained wheat and weeds and gave access to invertebrates only. This was the *Partial Predation* cage, which allowed us to measure the extent to which invertebrates mitigate weed harmfulness. The fourth cage contained wheat and weeds, and gave total access to all seed predators, to measure weed harmfulness mitigation by

invertebrates and vertebrates. This was the *Total Predation* cage.

These cages were set up in late March and early April 2021 to minimise impact on the field crop. The experiment's full chronology is laid out in Fig. 2 (all setting-up and sampling dates are featured in Table 1). In the three cages that included weeds, we placed 104 seeds from four annual weed species (i.e. *Geranium dissectum*; *Stellaria media*; *Veronica hederifolia*; *Viola arvensis* – N = 26 for each species) evenly distributed in a grid at the soil surface of the cage in Mid-May. In Mid-June, we also evenly distributed 130 seeds from five annual weed taxa (i.e. *Alopecurus myosuroides*; *Galium aparine*; *Anisantha sterilis*; *Lolium* sp.; *Cyanus segetum* – N = 26 for each species). Weed seeds came from Arbiotech (<http://www.arbiotech.com/>). Weed species were chosen either because farmers in the area deemed them harmful (based on agronomist's expertise in the lab) or because they were a well-studied biological model for weed control (e.g., *V. arvensis*). The seeds were placed into the cages when their seed rain naturally occurs in the area. In the four cages, 20 wheat seeds were manually sown along two lines drawn 0.17 m apart (as in the field, on average) in the middle of the cage at a depth of 0.02 m in November. This corresponds to a density of 222 wheat seeds/m², which is about what can be expected of farmers in France.

Plant surveys. Weeds were surveyed nine times throughout the cropping season to remove all unsown plants. The number of emerged plants was counted. At harvest in late June 2022, all vegetation in the cage was cut by hand just above the soil surface, and the dry biomass of the weeds and the wheat was measured. The number and weight of wheat grains were also measured to assess the crop yield of each cage. Plant biomass was obtained by drying in an oven at 80 °C for 72 h. Finally, to compare crop yields measured inside the cages with those from the surrounding fields, field yield estimates were provided by the farmers.

Weed seed predator samplings. Carabids (Coleoptera: Carabidae) were sampled using three pitfall traps per field. Each trap was composed of a plastic beaker (10 cm height, 8 cm diameter), filled with 150 mL of a preservative solution of brine and a few drops of odourless soap. A plastic cover was placed above each trap to avoid rain flooding. The traps were collected once in May and once in June 2021, each time after seven days (see sampling dates in Table 1). Carabids were identified at the species level (Coulon et al., 2011, Appendix S1). They were then assigned to a trophic group: carnivorous, omnivorous or granivorous (Homburg et al., 2013), and we only kept the omnivorous and granivorous groups for further analyses. The total number of omnivorous and granivorous carabids collected in each field corresponds to the measure of activity density (abundances of both sampling sessions were

summed). The number of specimens per species was multiplied by their specific body mass ($Body\ mass = 0.0237 \times Body\ size^{2.7054}$; Barnes et al., 2014). The body size of each carabid species was extracted from the literature (see Appendix S1).

Rodents were captured using INRA traps (16 cm long, 5 cm tall, 5 cm wide — BTM company) connected to 500 mL boxes containing hay, a gel water ball and a food pellet (beef-based cat food and peanut butter) to meet the captured individuals' needs (this ensures they can stay alive). The traps were placed in two lines of 25 traps spaced at 3 m intervals. The two lines were placed near tractor wheel paths, 20–30 m apart. The traps were left over three consecutive days and checked for captures every 24 h. Rodent sampling on all fields was conducted over a single period between late May and early June. Captured individuals were carefully identified, weighed, marked and released immediately after. All captures made over these 3 days were pooled to obtain a total abundance figure and multiplied by the average individual body mass measured in field to obtain the rodent biomass. Catching methods for invertebrates and vertebrates were approved by INRAE, a signatory of the Transparency Charter on the Use of Animals (<https://www.inrae.fr/nous-connaitre/institut-responsable/inrae-institut-responsable-matiere-dexperimentation-animale>).

Statistical analyses. First, to compare crop yield (absolute values) and weed biomass between the types of cages, paired *t*-tests were used (112 observations and 84 observations, respectively). Second, to calculate economic gains of natural weed control due to increased wheat yield at the hectare scale, the crop yield obtained in the cage was multiplied by 11 111.1, as the cage area was 0.09 m² and wheat seeds were sown at a commercial density to mimic farmers' sowing. The resulting value in tonnes of wheat grains was then multiplied by the mean price of a tonne of wheat grain between July 2014 and July 2023 (FranceAgriMer). Third, to examine the effect of weed biomass on crop yield loss, we ran a linear mixed-effect model including crop yield loss as the response variable, weed biomass as the fixed term and field as a random term. Crop yield loss corresponded to the crop yield's response ratio between each cage and the *Control* cage: $\ln((Y_{fk} + 1) / (Y_{fc} + 1))$ with *Y* as the crop yield, *f* as a field, *k* as a cage, either *No Predation* or *Partial Predation* or *Total Predation*, and *c* as the *Control* cage. Fourth, two Piecewise Structural Equation Models (PSEM, Lefcheck, 2016) were developed to investigate causal links between farming system (conventional vs. conservation agriculture), seed predator biomass, weed emergence, weed biomass at harvest and crop yield. One PSEM was based on data from *Partial Predation* cages and invertebrate seed predator communities. The second one was based on data from *Total Predation* cages and vertebrate and invertebrate communities. The homoscedasticity and normality of all model residuals were checked visually. The overall fit of both PSEMs were assessed with D-separation tests and Fisher's C statistic (Lefcheck, 2016) and AIC. All the analyses were performed using R-Core team (V 4.3.1), PSEMs were performed by the piecewise SEM package (Lefcheck, 2016), and direct and indirect links were summarized using semEff (Murphy, 2022).

3. Results

Responses of crop yield and weed biomass to weed seed predator exclusions. The crop yield measured in all our sets of four seed predator-exclusion cages varied significantly between cages, except between the *Partial Predation* and *Total Predation* cages (paired *t*-test based on a total of 112 observations, Fig. 3 A; Table 2). The maximum crop yield was reached in the *Control* cage, with 73.3 g of wheat grains on average (Standard Deviation (SD) 59.2). In contrast, the *No Predation* cage produced 14.7 g (SD 24.5) of wheat grains on average, 80 % less than the *Control* cage. The *Partial Predation* and *Total Predation* cages produced 39.8 g (SD 40.8) and 29.6 g (SD 35.6) of wheat grains on average respectively. Crop yield was therefore reduced by 46 % and 60 % respectively in comparison to the *Control* cage. This also showed a slight negative influence of vertebrate predators on crop productivity.

Table 1

Sampling, sowing, counting, and harvesting periods. The number of wheat plants and the number of tillers per plant in the cages were counted nine times during each period.

		Start	End
Carabid sampling	Sampling period 1	May-3 2021	May-5 2021
	Sampling period 2	June-2 2021	June-4 2021
Rodent sampling	Sampling period 1	May-26 2021	June-8 2021
Wheat seedling	Sowing period 1	November-24 2021	November-29 2021
Weed seed raining mimic	Date 1	May-17/19 2021	
	Date 2	June-14/16 2021	
Counting number of wheat plants and number of tillers per plant in the cages	Counting period 1	June-7 2021	April-28 2022
Harvesting wheat and weeds in cages and counting plants and tillers	Harvesting period 1	June-17 2022	June-30 2022

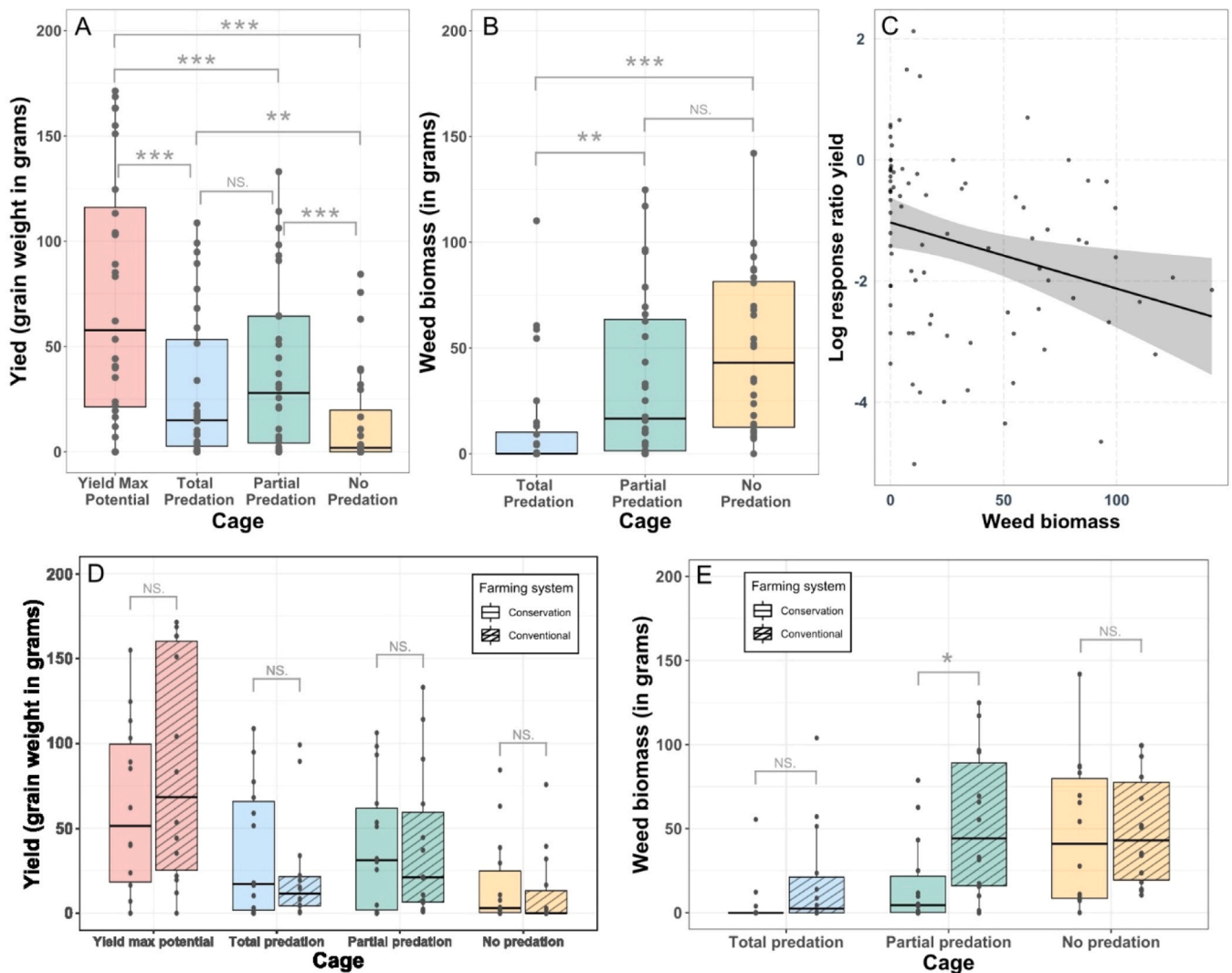


Fig. 3. Responses of (A) crop yield and (B) weed biomass at harvest to weed seed predator exclusions and (C) relationships between weed biomass at harvest (in grams) and crop yield response ratio (a lower log response ratio indicates a greater yield loss). Effects of conservation agriculture on (D) crop yield and (E) weed biomass.

Table 2 | Paired *t*-tests for crop yield and weed biomass comparisons between the different types of cages.

Type	Comparison	t statistic	p value	Confidence intervals	df
Yield	Partial Predation - Total Predation	1.34	0.19	(-5.40; 25.83)	27
Yield	No predation - Total Predation	-2.95	0.01	(-25.28; -4.56)	27
Yield	Control (Max Crop yield) - Total Predation	4.92	0.00	(25.45; 61.79)	27
Yield	Partial Predation - No predation	4.17	0.00	(12.77; 37.50)	27
Yield	Partial Predation - Control (Max Crop yield)	-4.40	0.00	(-48.98; -17.82)	27
Yield	Control (Max Crop yield) - No predation	6.45	0.00	(39.93; 77.14)	27
Weed biomass	Partial Predation - Total Predation	1.34	0.19	(-5.40; 25.83)	27
Weed biomass	No predation - Total Predation	-2.95	0.01	(-25.28; -4.56)	27
Weed biomass	Partial Predation - No predation	4.17	0.00	(12.77; 37.50)	27

Alternatively, crop yield was multiplied by 2.7 and 2.0 respectively in the *Partial Predation* and *Total predation* cages compared to the *No Predation* cage.

By extrapolation, at the hectare scale and without any other weed control measures than natural weed seed predation, crop yield reached 8.1t/ha, 1.6t/ha, 4.4t/ha and 3.3t/ha in the *Control*, *No predation*, *Partial predation* and *Total Predation* cages respectively. Based on these experimental conditions, considering the price of winter soft wheat over the last decade (167€/t between July 2014 and July 2023, source: [FranceAgriMer](#)), the value added by seed predators reached 285€·hectare⁻¹·year⁻¹ (based on the difference in yield per hectare between the *No Predation* cage and the *Total Predation* cage to represent real conditions because it is unrealistic to exclude only vertebrate seed predators in commercial fields). For comparison, the average crop yield reported by farmers in the commercial fields where the experiment was conducted was 7.0 t/ha.

In the three cages that contained weed seeds (84 observations, excluding the *Control* cages), the paired *t*-test revealed significant differences in weed biomass at harvest (Fig. 3B; Table 2). The *Total Predation* cages contained significantly smaller amounts of weed biomass than the other two types of cages, *Partial Predation* and *No Predation*. While the *Partial Predation* cages contained an intermediate amount of weed biomass and the *No Predation* cages had the largest amounts of

weed biomass, the amounts found in these two types of cages were not significantly different.

Relationship between weed biomass and crop yield loss. Based on linear mixed-effect models, a slight negative relationship between weed biomass and the response ratio of crop yield was detected (estimate = -0.01, $t(82) = -2.614$, $p\text{-value} = 0.01$, Fig. 3 C). This means that smaller weed biomass values correlate with crop yield being closer to the maximum crop yield potential measured in the *Control* cage.

Effect of conservation agriculture on weed biomass and crop yield loss. Conservation agriculture does not influence the response of crop yield to treatment inside each cage (Fig. 3D; Supplementary Table 1), neither weed biomass at harvest except in the cage with *Partial predation* (Fig. 3E; Supplementary Table 1). In this treatment, weed biomass is higher in cages located in conventional fields.

Effect of conservation agriculture and seed predator communities on weed biomass and crop yield loss. Two PSEM revealed the links between farming systems, seed predators, weed emergence, weed biomass and crop yield loss for the *Total Predation* and *Partial Predation* cages independently (each one based on 28 observations; see Fig. 4,

conceptual framework). When both carabids and rodents were considered (*Total Predation* cages) the PSEM performed poorly at explaining the crop yield loss ($R^2 = 0.04$; Supplementary Table 2). All the intermediate links between farming systems, predator biomass (carabid beetles and rodents), weed emergence, weed biomass and crop yield response ratio were consistent with the hypotheses but insignificant (Fig. 4). Specifically, conservation agriculture tended to increase carabid and rodent biomasses, which tended, in turn, to reduce weed emergence. Weed emergence tended to increase weed biomass, in turn reducing crop yield loss.

When only carabids were considered (in *Partial Predation* cages) causal links explained the crop yield loss better than in the previous model ($R^2=0.23$; Fig. 4, Supplementary Table 3). All the links detected were coherent with our hypotheses. Conservation agriculture tended to increase carabid biomass (ns, standardized coefficient (std. est.) = 0.29, $R^2=0.09$), carabid biomass reduced weed emergence (std. est. = -0.52, $R^2=0.27$) and cuts in weed biomass reduced crop yield loss in *Partial Predation* cages (std. est. = -0.48, $R^2=0.23$). A significant direct negative link between conservation agriculture and weed biomass was

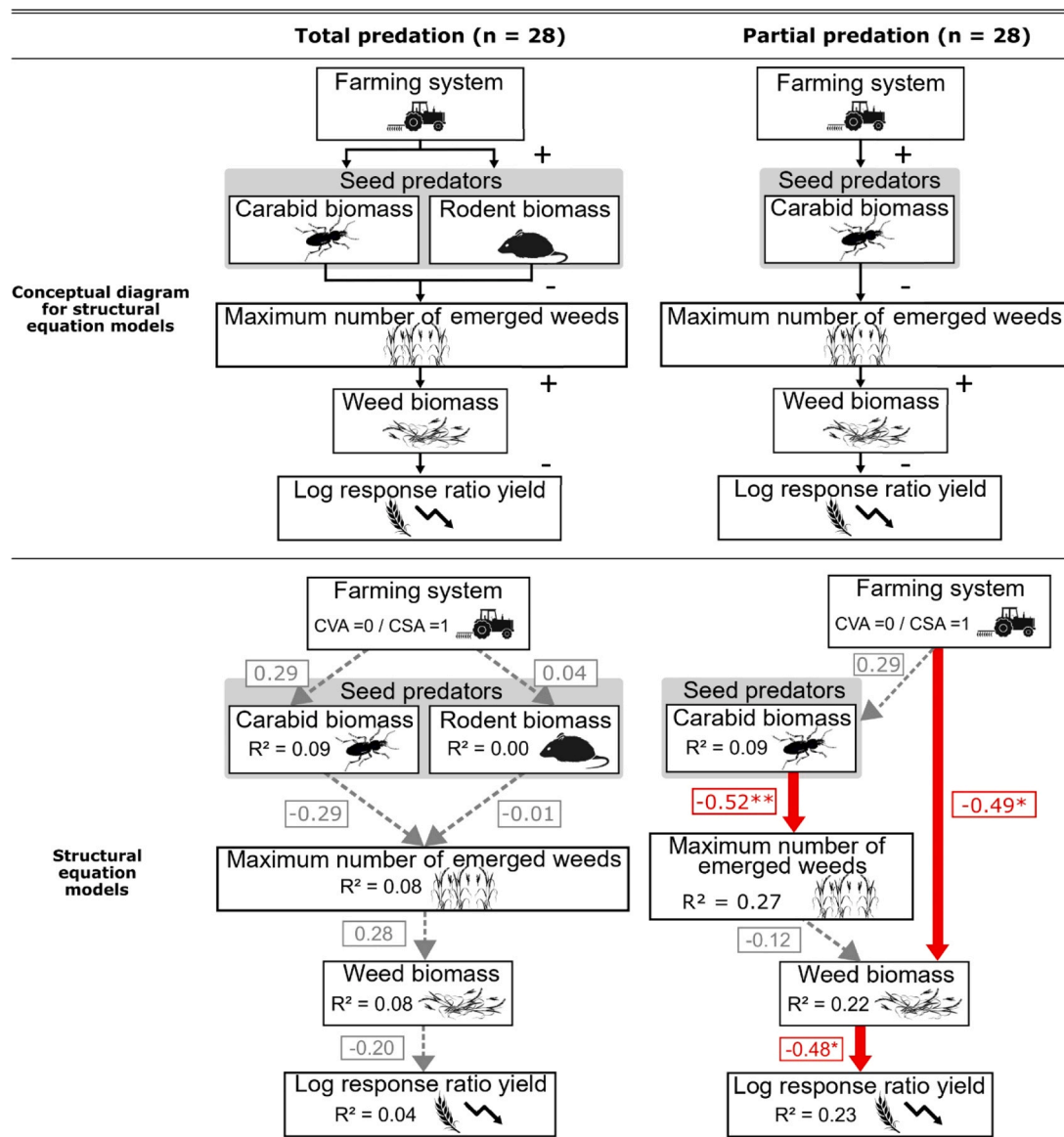


Fig. 4. Conceptual frameworks and results of both PSEMs used to investigate how farming systems affect crop productivity through natural enemies and weed development. A lower log response ratio indicates a greater yield loss. Solid red arrows represent significant negative links and dashed grey represent insignificant links. Standardised coefficients are shown for each path. The numbers of asterisks indicate the level of significance ($p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

detected (std. est. = -0.49 , $R^2=0.22$) leading to a positive cascading effect of conservation agriculture on crop yield through weed biomass reduction (Supplementary Table 3).

4. Discussion

To our knowledge, this is the first quantification of the effects of seed predators on crop yield through their impact on weed biomass. It was found that crop yield loss due to weeds was reduced by 20 % through seed predation. Specifically, yield loss decreased from 80 % in the absence of seed predation to 60 % when all seed predators had access to and consumed weed seeds. Extrapolating our cage-scale results to the field scale, this control by seed predators would correspond to an economic gain of €285 per hectare per year. However, even with seed predation, yield loss due to weeds still amounted to 60 % of the maximum yield potential. Our results therefore highlight both the importance of accounting for weed seed predation in field management. It also shows the need to either combine it with complementary techniques or substantially redesign cropping systems to enhance seed predator activity—while acknowledging that vertebrate as well as other invertebrate seed predators may also have adverse effects on crop yield (Boetzel et Knapp, 2024). Finally, it was observed that weed control tended to be enhanced under conservation agriculture through an increase in seed predator biomass, which reduced weed emergence but did not translate into higher crop yields.

As was expected, crop yield responded positively, and weed biomass negatively, to weed seed predators having access to the cages (Fig. 3). The 20 % reduction in weed-induced crop yield loss afforded by the presence of seed predators means that weed compensation mechanisms – individual weed plants being able to produce more biomass and more seeds when they are isolated than when they are part of an abundant weed community – do not mitigate the limiting effect of seed predators on weed biomass. This is the first demonstration of the genuine effect of seed predators on crop yield. Other research has shown that they could reduce weed emergence by up to 38 % in fallow plots (Blubaugh et Kaplan, 2016). However, with invertebrate and vertebrate seed predators contributing to weed seed removal, crop productivity remains 60 % lower than its full potential. This aligns with results from modelling approaches showing that seed predators need to consume at least 78 % of seeds at peak seed shedding to suppress *Alopecurus myosuroides* growth (Daouti et al., 2022). This threshold was clearly not reached here, which shows that effective weed control requires a combination of multiple measures. Natural weed control constitutes a partial but important lever among several others to reduce pesticide applications, thereby contributing to the management of herbicide resistance and the mitigation of agriculture's environmental impacts.

A rough economic evaluation of the service provided by seed predators was carried out; 285 €/hectare⁻¹ year⁻¹ were saved in terms of crop yield. To our knowledge, this is the first economic valuation of the weed control service provided by seed predators, whose regulatory role was already known (e.g. Carbonne et al., 2019; Lami et al., 2020) but without any economic valuation. Previous studies showed that pest control provided by bats and birds can save between 44\$ and 730 \$/hectare-year⁻¹ depending on the study and its location and agroecosystems (Kellermann et al., 2008; Maas et al., 2013; Karp et al., 2013). Our estimation falls within this range. This work has the added benefit of reconsidering the way productivity is measured in fields to include the contribution of biodiversity (Seppelt et al., 2020). However, this economic valuation has to be taken with caution, both due to price fluctuations and because efforts to maximise the provision of regulating services do not systematically mean biodiversity conservation goals are met (Adams et al., 2014; Kleijn et al., 2015). In addition, extrapolating small-scale results (0.09 m² within the cage) to the hectare scale constitutes a limitation of this study, as does the fact that it was conducted over a single year.

Comparing cages that gave access either to invertebrate predators

only or to invertebrate and vertebrate predators did not show a significant difference in crop yield. However, yield losses were lower when only invertebrate predators were involved (-46 %) than when both invertebrate and vertebrate predators were at play (-60 %). This result shows that invertebrate and vertebrate seed predators do not control weeds in a complementary way, and that invertebrates are the main contributors to this service in this context. This corroborates the idea that while vertebrates, and voles especially, are seed predators, they also have negative effects on crop plants (Krijger et al., 2017). In addition to weed control, crop yield loss mitigation requires that ways to control them be considered.

Conservation agriculture had a positive but insignificant effect on the biomass of seed predators such as carabid beetles and rodents. This result is due in part to the choice of dataset used in the PSEM. Here, granivorous and omnivorous species were considered together, whereas a previous work on this dataset reported that a positive effect of conservation agriculture on the activity density of granivorous carabid species, as well as on other taxonomic groups, had been found (Carbonne et al., 2023). Moreover, a clear correlation between conservation agriculture and reduced weed biomass was detected. This link suggests that other taxonomic groups not included in the PSEM can actively contribute to weed control (Sarabi, 2019; Lami et al., 2020). It is possible that ants, collected from many fields, played a role in controlling weeds here. While implementing conservation agriculture stimulates weed control services, these do not reach a level at which yield loss due to weed biomass interference can be prevented.

5. Conclusion

Our study provides the first quantitative evidence that seed predators can effectively reduce weed-induced crop yield losses. Seed predation decreased yield loss by 20 %, translating into an estimated economic gain of €285 ha⁻¹ yr⁻¹. This finding highlights the potential of biodiversity to contribute directly to agricultural yield. However, even with active seed predation, yield losses remained substantial (60 % of potential yield), underscoring the limits of relying solely on natural weed control. The results suggest that effective weed management requires combining biological control with complementary agronomic practices. Moreover, vertebrate seed predators, while beneficial for weed seed removal, may also negatively affect crops, calling for balanced management strategies. Conservation agriculture tended to promote weed control through increased seed predator biomass, yet without improving yield. Overall, integrating biodiversity-based regulation into crop management can enhance sustainability, provided it is accompanied by system redesign to optimize multiple ecosystem services.

Authors' contributions

LM and SP designed the first version of the study. LM, CB, AM, EL, EF, NH, CD, BC, SP contributed to build the experimental design, collect and manage the data. LM and AD analysed the data. AD wrote the open access scripts. SP secured the funding. LM wrote the first draft and all the authors contributed significantly to the final version of the manuscript.

CRediT authorship contribution statement

Alexandre Dosset: Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation. **Bruno Chauvel:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Chantal Ducourtieux:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Matějček Annick:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Emilien Laurent:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Emeline Felten:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data

curation. **Nicolas Henon**: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Benjamin Carbonne**: Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation. **Lucile Muneret**: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sandrine Petit**: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Funding

This research was funded by the EIP-AGRI project RegGAE (funds from the EU Rural development 2014–2020 programme for Operational groups and the Region Bourgogne-Franche-Comté).

Declaration of Competing Interest

We declared no conflict of interest.

Acknowledgements

We warmly thank all the farmers who kindly gave us access to their fields and agreed to let us carry out our experiment. We would also like to thank Stéphane Cordeau, Guillaume Adeux and the colleagues at the Pole “Gestion durable des Adventices” for the valuable advice they provided us with in the study’s design stage. Finally, we extend our gratitude to Rodolphe Hugard, Mathieu Siol, Charly Pouillot, Luc Biju-Duval, Anne-Lise Goumon, Philippe Aubert and Pascal Farcy who helped us to build our experimental design and our cages, and helped us with the surveys.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2025.110196](https://doi.org/10.1016/j.agee.2025.110196).

Data availability

We have already shared the data and codes

References

- Adams, W.M., 2014. The value of valuing nature. *Science* 346 (6209), 549–551. <https://doi.org/10.1126/science.1255997>.
- Adeux, G., Vieren, E., Carlesi, S., Bärberi, P., Munier-Jolain, N., Cordeau, S., 2019. Mitigating crop yield losses through weed diversity. *Nat. Sustain.* 2 (11), 1018–1026.
- Barnes, A.D., Jochum, M., Mumme, S., Haneda, N.F., Farajallah, A., Widarto, T.H., Brose, U., 2014. Consequences of tropical land use for multitrophic biodiversity and ecosystem functioning. *Article 1. Nat. Commun.* 5 (1). <https://doi.org/10.1038/ncomms6351>.
- Blubaugh, C.K., Kaplan, I., 2016. Invertebrate seed predators reduce weed emergence following seed rain. *Weed Sci.* 64 (1), 80–86.
- Boetzel, F.A., Knapp, M., 2024. On the ambivalence of granivorous carabids: Weed seed bank regulators, potential crop pests or both? *Agric. Ecosyst. Environ.* 376, 109226. <https://doi.org/10.1016/j.agee.2024.109226>.
- Bohan, D.A., Boursault, A., Brooks, D.R., Petit, S., 2011. National-scale regulation of the weed seedbank by carabid predators: Carabid seed predation. *J. Appl. Ecol.* 48 (4), 888–898. <https://doi.org/10.1111/j.1365-2664.2011.02008.x>.
- Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: Harnessing ecosystem services for food security. *Trends Ecol. Evol.* 28 (4), 230–238.
- Carbonne, B., Bohan, D.A., Charalabidis, A., Petit, S., 2019. Weed seed availability, carabid intraspecific interference and their interaction drive weed seed consumption by carabid beetles. *Agric. For. Entomol.* 21 (4), 396–406. <https://doi.org/10.1111/afe.12346>.
- Carbonne, B., Bohan, D.A., Foffová, H., Daouti, E., Frei, B., Neidel, V., Saska, P., Skuhrovec, J., Petit, S., 2022. Direct and indirect effects of landscape and field management intensity on carabids through trophic resources and weeds. *J. Appl. Ecol.* 59 (1), 176–187. <https://doi.org/10.1111/1365-2664.14043>.
- Carbonne, B., Muneret, L., Laurent, E., Felten, E., Ducourtieux, C., Henon, N., Matejček, A., Chauvel, B., Petit, S., 2023. Conservation agriculture affects multitrophic interactions driving the efficacy of weed biological control. *J. Appl. Ecol.* 60 (9), 1904–1916. <https://doi.org/10.1111/1365-2664.14475>.
- Chauvel, B., Gauvrit, C., Guillemin, J.-P., 2022. From sea salt to glyphosate salt: A history of herbicide use in France. *Adv. Weed Sci.* 40, e020220015. <https://doi.org/10.51694/AdvWeedSci/2022;40:seventy-five008>.
- Coulon, J., Pupier, R., Quéinnec, E., Ollivier, E., & Richoux, P. (2011) « Coléoptères carabiques Compléments et mise à jour ». *Faune de France* 95, Volume 2, 337 pages. <https://faunedefrance.org/faune-95/>.
- Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A., 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* 5 (10), eaax0121.
- Daouti, E., Jonsson, M., Vico, G., Menegat, A., 2022. Seed predation is key to preventing population growth of the weed *Alopecurus myosuroides*. *J. Appl. Ecol.* 59 (2), 471–482. <https://doi.org/10.1111/1365-2664.14064>.
- Delaune, T., Ouattara, M.S., Ballot, R., Sausse, C., Felix, I., Maupas, F., Chen, M., Morison, M., Makowski, D., Barbu, C., 2021. Landscape drivers of pests and pathogens abundance in arable crops. *Ecography* 44 (10), 1429–1442. <https://doi.org/10.1111/ecog.05433>.
- FranceAgriMer (<https://visionet.franceagrimer.fr/Pages/accueil.aspx>).
- Gaba, S., Deroulers, P., Bretagnolle, F., Bretagnolle, V., 2019. Lipid content drives weed seed consumption by ground beetles (Coleoptera, Carabidae) within the smallest seeds. *Weed Res.* 59 (3), 170–179. <https://doi.org/10.1111/wre.12354>.
- Henneron, L., Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Girardin, C., Blanchart, E., 2015. Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. *Agron. Sustain. Dev.* 35 (1), 169–181. <https://doi.org/10.1007/s13593-014-0215-8>.
- Homburg, K., Schuldt, A., Drees, C., Assmann, T., 2013. Broad-scale geographic patterns in body size and hind wing development of western Palaearctic carabid beetles (Coleoptera: Carabidae). *Ecography* 36 (2), 166–177. <https://doi.org/10.1111/j.1600-0587.2012.07488.x>.
- Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022. Pesticide-free agriculture as a new paradigm for research. *Agron. Sustain. Dev.* 42 (1), 8. <https://doi.org/10.1007/s13593-021-00742-8>.
- Karp, D.S., Mendenhall, C.D., Sandí, R.F., Chaumont, N., Ehrlich, P.R., Hadly, E.A., Daily, G.C., 2013. Forest bolsters bird abundance, pest control and coffee yield. *Ecol. Lett.* 16 (11), 1339–1347. <https://doi.org/10.1111/ele.12173>.
- Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of Conservation Agriculture. *Int. J. Environ. Stud.* 76 (1), 29–51. <https://doi.org/10.1080/00207233.2018.1494927>.
- Kellermann, J.L., Johnson, M.D., Stercho, A.M., Hackett, S.C., 2008. Ecological and economic services provided by birds on Jamaican Blue Mountain Coffee Farms. *Conserv. Biol.* 22 (5), 1177–1185. <https://doi.org/10.1111/j.1523-1739.2008.00968.x>.
- Kleijn, D., Winfree, R., Bartomeus, I., Carvalheiro, L.G., Henry, M., Isaacs, R., Klein, A.-M., Kremen, C., M'gonigle, L.K., Rader, R., 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nat. Commun.* 6 (1), 7414.
- Krijger, I.M., Belmain, S.R., Singleton, G.R., Groot Koerkamp, P.W., Meerburg, B.G., 2017. The need to implement the landscape of fear within rodent pest management strategies. *Pest Manag. Sci.* 73 (12), 2397–2402. <https://doi.org/10.1002/ps.4626>.
- Labryere, S., Petit, S., Ricci, B., 2018. Annual variation of oilseed rape habitat quality and role of grassy field margins for seed eating carabids in arable mosaics. *Agric. For. Entomol.* 20 (2), 234–245. <https://doi.org/10.1111/afe.12250>.
- Lami, F., Boscutti, F., Masin, R., Sigura, M., Marini, L., 2020. Seed predation intensity and stability in agro-ecosystems: Role of predator diversity and soil disturbance. *Agric. Ecosyst. Environ.* 288, 106720. <https://doi.org/10.1016/j.agee.2019.106720>.
- Lefcheck, J.S., 2016. piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods Ecol. Evol.* 7 (5), 573–579.
- Maas, B., Clough, Y., Tschamtké, T., 2013. Bats and birds increase crop yield in tropical agroforestry landscapes. *Ecol. Lett.* 16 (12), 1480–1487. <https://doi.org/10.1111/ele.12194>.
- Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E.A., Pétilion, J., Plantegenest, M., Thiéry, D., Rusch, A., 2018. Evidence that organic farming promotes pest control. *Nat. Sustain.* 1 (7), 361–368.
- Muneret, L., Ricci, B., Vialatte, A., Aviron, S., Ducourtieux, C., Biju-Duval, L., Petit, S., 2023. Carabid beetles have hump-shaped responses to disturbance and resource gradients within agricultural landscapes. *J. Appl. Ecol.* 60 (4), 581–591. <https://doi.org/10.1111/1365-2664.14357>.
- Murphy, M.V., 2022. Automatic calculation of effects for piecewise structural equation models. *R. Package semEff. Compr. R. Arch. Netw. (CRAN)*.
- Oerke, E.-C., 2006. Crop losses to pests. *J. Agric. Sci.* 144 (1), 31–43.
- Pannwitt, H., Westerman, P.R., De Mol, F., Gerowitz, B., 2021. Demographic processes allow *Echinochloa crus-galli* to compensate seed losses by seed predation. *Agronomy* 11 (3), 565.
- Petit, S., Boursault, A., Bohan, D.A., 2014. Weed seed choice by carabid beetles (Coleoptera: Carabidae): linking field measurements with laboratory diet assessments. *Eur. J. Entomol.* 111 (5). (<https://pdfs.semanticscholar.org/f603/5c31a73dba4d2f4cd6716db99faa59404cb.pdf>).
- Pittelkow, C.M., Liang, X., Linquist, B.A., Van Groenigen, K.J., Lee, J., Lundy, M.E., Van Gestel, N., Six, J., Venterea, R.T., Van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517 (7534), 365–368.
- Rigal, S., Dakos, V., Alonso, H., Auniş, A., Benkő, Z., Brotons, L., Chodkiewicz, T., Chylarecki, P., De Carli, E., Del Moral, J.C., Domşa, C., Escandell, V., Fontaine, B., Foppen, R., Gregory, R., Harris, S., Herrando, S., Husby, M., Ieronymidou, C., Devictor, V., 2023. Farmland practices are driving bird population decline across Europe. *Proc. Natl. Acad. Sci.* 120 (21), e2216573120. <https://doi.org/10.1073/pnas.2216573120>.

- Sánchez-Bayo, F., Wyckhuys, K.A., 2019. Worldwide decline of the entomofauna: a review of its drivers. *Biol. Conserv.* 232, 8–27.
- Sarabi, V., 2019. Factors that influence the level of weed seed predation: A review. *Weed Biol. Manag.* 19 (3), 61–74. <https://doi.org/10.1111/wbm.12186>.
- Seppelt, R., Arndt, C., Beckmann, M., Martin, E.A., Hertel, T.W., 2020. Deciphering the biodiversity–production mutualism in the global food security debate. *Trends Ecol. Evol.* 35 (11), 1011–1020.
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418 (6898), 671–677. <https://doi.org/10.1038/nature01014>.
- Westerman, P.R., Liebman, M., Menalled, F.D., Heggenstaller, A.H., Hartzler, R.G., Dixon, P.M., 2005. Are many little hammers effective? Velvetleaf (*Abutilon theophrasti*) population dynamics in two-and four-year crop rotation systems. *Weed Sci.* 53 (3), 382–392.
- Wittwer, R.A., Bender, S.F., Hartman, K., Hydbom, S., Lima, R.A.A., Loaiza, V., Nemecek, T., Oehl, F., Olsson, P.A., Petchey, O., Prechsl, U.E., Schlaeppli, K., Scholten, T., Seitz, S., Six, J., Van Der Heijden, M.G.A., 2021. Organic and conservation agriculture promote ecosystem multifunctionality. *Sci. Adv.* 7 (34), eabg6995. <https://doi.org/10.1126/sciadv.abg6995>.