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Context dependency and differential arthropod responses belie simple agro-ecological management solutions

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ABSTRACT

Policies promoting agroecological management aim to counteract the adverse effects of agricultural intensification on biodiversity, and ecosystem health with varying effectiveness. This study evaluates the effects of agroecological management practices and environmental heterogeneity on biodiversity, pest control services, and crop yields in winter wheat, barley, and oilseed rape fields in Switzerland. We assessed plant species diversity, pest and predator populations, and crop yield across 44 agricultural fields managed with either conventional or agroecological practices, including the establishment of wildflower strips (WFS) and reduced pesticide use. Vegetation diversity was higher in agroecological fields compared to conventional fields, but this did not lead to an increase in predator populations. While ground-dwelling beetles are potentially enriched, neither spiders or parasitoids, nor pest abundances were higher in agroecological fields. Pest pressure was not affected by predator abundance, while yields were significantly higher in conventional fields, with the differences attributed to farming practices rather than the influence of vegetation diversity or pest presence. The effect of environmental heterogeneity varies across taxa and depends on the landscape feature considered.

Synthesis and applications: Our findings indicate that while agroecological practices can enhance vegetation diversity and support a diverse arthropod community, these benefits do not necessarily lead to improved pest control or increased yields. The variability in responses suggests that the effectiveness of such measures is highly context dependent. Therefore, tailored strategies that consider specific crop and landscape characteristics are needed to optimize pest management and maintain productivity in sustainable farming systems.

1. Introduction

Agricultural intensification, characterized by extensive agrichemical use, dense planting, monocultures, genetic uniformity, and loss of seminatural habitats, has significantly enhanced crop yields over recent decades. However, these practices have also led to reduced biodiversity, increased pest pressure, environmental pollution, adverse health effects, and the depletion of soil organic matter (Matson et al., 1997). The decline in biodiversity associated with intensive agricultural practices compromises key ecosystem services, such as natural pest control, which rely on diverse species assemblages (Dainese et al., 2019).

Recognizing these challenges, the European Union (EU) has implemented policies to promote biodiversity in agricultural landscapes. The Agri-Environment Schemes (AES), introduced in the 1990s as part of the Common Agricultural Policy, provide financial incentives for farmers to adopt environmentally friendly practices. These include organic farming, integrated pest management, reduced pesticide and fertilizer inputs, crop rotation, habitat enhancement for wildlife, buffer strips, and the conservation of agricultural genetic resources (European Commission Directorate-General for Environment, 2017). More recently, the EU launched the Biodiversity Strategy for 2030, a framework aimed at restoring ecosystems, strengthening protected areas, and establishing biodiversity governance mechanisms with clear indicators for monitoring progress (European Commission Directorate-General for

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Abbreviations: AES, Agri-Environment Schemes; AIC, Akaike information criterion; BPA, Biodiversity Promotion Areas; CLB, cereal leaf beetle; ÖLN, Ökologischer Leistungsnachweis; PFT, Pitfall trap; SNH, Seminatural habitat; SEM, structural equation modelling; FOAG, Swiss Federal Office for Agriculture; FOEN, Swiss Federal Office for the Environment; TFI, Treatment Frequency Index; CLB, Cereal Leaf Beetle; CSFB, Cabbage stem flea beetle; TSW, Weight of 1000 seeds; WFS), wildflower strip.

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Environment, 2020).

Switzerland, though not an EU member, has implemented its own biodiversity conservation policies that align with EU strategies for sustainable agriculture. The Proof of Ecological Performance" (PEP) serves as a baseline requirement for farmers to qualify for direct payments, mandating compliance with environmental standards such as maintaining Biodiversity Promotion Areas (BPA) and adhering to sustainable farming practices. Additional Swiss policies, such as regional biodiversity programs and landscape quality contributions, further support biodiversity conservation in agricultural landscapes (Swiss Federal Office for Agriculture FOAG, 2023; Swiss Federal Office for the Environment FOEN, 2023). Despite national differences in policy implementation, both the EU and Switzerland emphasize the need for sustainable farming practices that enhance habitat quality and biodiversity to maintain essential ecosystem services.

Biodiversity is critical for sustaining ecosystem services at both local and landscape scales (Birkhofer et al., 2018; Karp et al., 2018; Landis et al., 2000; Martin et al., 2019). At the field level, structurally diverse field margins provide essential resources, such as food, shelter, and breeding sites, for beneficial organisms, such as pollinators and natural enemies of pests, (Diehl et al., 2013; Tscharntke et al., 2005; Tschumi et al., 2016a). Additionally, adjacent seminatural habitats, including wildflower strips (WFS), contribute to biological control by supporting natural enemy populations (Diehl et al., 2013; González et al., 2022; Tscharntke et al., 2005; Tschumi et al., 2016a, 2016b). At broader spatial scales, landscape heterogeneity—comprising seminatural patches and varied land cover—can further enhance pest control services by maintaining populations of beneficial arthropods, mitigating the negative effects of intense in-field management (Bianchi et al., 2006; Concepción et al., 2008; Feit et al., 2019a, 2019b; Gámez-Virués et al., 2015).

Agroecology integrates ecological principles into farming systems to enhance sustainability and resilience. By promoting practices such as crop diversification, agroforestry, and organic farming, agroecology reduces reliance on chemical inputs while improving biodiversity-driven ecosystem services, such as pest regulation and pollination (Altieri et al., 2015; Jeanneret et al., 2021). Yet the effectiveness of agroecological interventions at the field scale are affected by the surrounding landscape composition and configuration. While organic farming has been shown to enhance carabid species richness (Kromp, 1989), other studies report limited biodiversity benefits from AES (Kleijn et al., 2001). For instance, a study in Sweden found that species richness in cereal fields, grass-clover leys, and pastures increased with landscape heterogeneity, whereas organic farming alone did not significantly enhance biodiversity (Weibull et al., 2003). These findings underscore the importance of implementing conservation measures at both local and landscape scales to support biodiversity in agricultural systems (Weibull et al., 2003).

In this study, we investigate how field-scale management practices and landscape composition influence biodiversity, pest control services, and crop yield. Our research focuses on two major agricultural pests of winter wheat, barley, and oilseed rape: the cereal leaf beetle (CLB) (*Oulema melanopus)* and the cabbage stem flea beetle (CSFB) (*Psylliodes chrysocephela*), and control by their most relevant predators, including spiders, and ground-dwelling beetles.

In view of this, we expect that AES designed to promote biodiversity, particularly WFS and reduced pesticide use, will enhance localized pest control services in intensive agricultural settings, but this will be mediated by habitat structure at landscape scales. On this basis we hypothesize that: a) Agroecological management (e.g., field margin vegetation diversity) interacts with high environmental heterogeneity to increase plant species abundance and diversity within fields; and (b) High plant diversity within fields enhances the abundance and diversity of arthropod communities by providing resources such as shelter, habitat, and food. We further expect that this would reflect pest services such that: (c) insect predator abundances decrease pest pressure in crop fields; and (d) natural pest control is sufficient to mitigate reduced use of pesticides with respect to crop yields. A conceptual framework illustrating these relationships is provided in Figure1.

2. Methods

2.1. Study design and management

All monitoring has been conducted on fields that are part of a larger project ("PestiRed", www.pestired.ch). The project framework leverages the principles of agroecological management, relying on co-innovation and participation of farmers and other stakeholders. In a pairwise setting, agroecological fields, monitored in terms of populations of noxious organisms and natural enemies of pests, yield, and detailed agronomic and economic parameters (e.g., pesticide use), can be compared to conventionally farmed fields (Jeanneret, et al., 2021). The project aims to reduce pesticide use by at least 75 % while maintaining productivity (maximum 10 % yield reduction) (Wirth et al., 2020). This setup offers a powerful framework to relate management practices to biodiversity and its link to ecosystem service delivery, and to understand how local management effects are moderated by landscape-scale processes.

The experimental design involved 30 agricultural fields, arranged as pairs (in close proximity) of one agroecologically and one conventionally managed field belonging to 15 farms. In each year we sampled from 22 fields belonging to 11 farmers as, due to crop rotation, some fields were cultivated with different crops (i.e., maize, potato, green manure) in one of the years (see Supplementary Table 2). Thus, we had a total of 44 field-treatment combinations over the two years. All plots included in the study were in the same lowland Swiss agricultural landscape of Canton Solothurn. In the agroecological treatment farmers revert to pesticide only as a last resort, and indeed, during the two years considered in this study, all agroecological fields were free from pesticide (i.e. fungicide, insecticide, herbicide, adjuvants and growth regulators). The agroecological management further includes 24 measures such as adapted crop varieties, undersowing and mechanical weeding to regulate weeds. It also included the sowing of annual WFS at field margins to support natural pest regulation. It became apparent that the quality of these WFS varied across agroecological fields, as some strips were more developed than others (see Supplementary Table 3 for detail). In the conventional treatment pesticides were used. All actions conducted by the farmer were recorded. The sampling was carried out in 2022 and 2023. The fields are part of a crop rotation system, where winter wheat is followed by winter barley, oilseed rape, then winter barley, followed by maize, spelt, and grassland (green manure) or potatoes (see Supplementary Table 2). We do not explicitly address the effect of soil, and climatic conditions as the fields were selected to be close together to limit variability in such conditions.

We selected variables we considered to be relevant given our hypotheses. They are summarized in Table 1.

The Treatment Frequency Index (TFI) quantifies pesticide use by comparing the applied dose to the permitted dose per crop, adjusted for the treated area (FAIRWAY Project, 2003; PAN Europe, 2003). A TFI of 1 indicates that the full recommended dose was applied over the entire field, while values above 1 reflect applications exceeding the allowed dose. The TFI is additive across pesticide categories, allowing comparisons across crops and management systems.

We use the TFI because it is a standardized metric widely applied in agricultural monitoring (Gravesen, 2003). However, it does not account for pesticide toxicity or environmental impact (Ongley and others, 1996), meaning a lower TFI does not necessarily indicate lower ecological risk (Barzman and Dachbrodt-Saaydeh, 2011). The permitted pesticide doses vary by product and crop, as detailed by Bundesamt für Lebensmittelsicherheit und Veterinärwesen BLV (2024).

Table 1
Summary of variables assessed to quantify differences and intensity across the two management types (agroecological and conventional).

Variable	Description	Measurement
Number of pesticide applications	Number of times pesticides (fungicide, herbicide, insecticide, growth regulators) are applied.	Count
Amount of synthetic inputs (TFI)	Index quantifying amount of pesticide used ("Treatment Frequency Index"). Quantified as the amount applied per amount allowed according to federal regulations (Bundesamt für Lebensmittelsicherheit und Veterinärwesen BLV, 2024) multiplied by the surface treated per total surface.	Scaled index (0–1 per product additive across product; can exceed 1 if more pesticide than allowed is applied)
Amount of nitrogen (Ndisp)	Nitrogen disposed by fertilizers, differentiated between mineral and organic (manure).	Kilograms per hectare (kg/ha)
Number of soil management interventions	Number of mechanical interventions conducted on the soil after harvest of the previous crop, before the seeding, such as rolling, stubble cultivation, false seed preparation, not including weeding or ploughing	Count
Number of weedings	Number of manual weeding plus mechanical interventions conducted on the soil after seeding conducted.	Count
Number of ploughing passages	Number of ploughing passages.	Count

2.2. *Relevant background on biology and ecology of pest and pest control agents*

This study focuses on major pests of winter wheat, barley, and oilseed rape, namely, the cereal leaf beetle (CLB) (*Oulema melanopus*), and the cabbage stem flea beetle (CSFB) (*Psylliodes chrysocephela*), and control by their most relevant predators, including spiders, and ground-dwelling beetles. The sampling protocol and timing are adjusted to the life cycles of the respective pests (Meindl et al., 2001) (Supplementary Figure 3a and b).

The cereal leaf beetle (CLB) causes economically important yield losses in crops such as winter wheat and barley (Schubiger, F. X., 2024). It is widespread in Europe, Asia, and Northern America, with its importance increasing with warming climate. In early spring, adult beetles emerge from their overwintering habitats in meadows, forest edges, or hedgerows in proximity to crop fields, and start feeding on wild grasses for maturation. They begin laying their eggs in May, preferably on wheat, barley, or oat. After 8–10 days, the larvae emerge and cause major damage to crop leaves. A few weeks later, they drop to the ground for pupation. The second generation of beetles emerges in July and continues to feed on crops and grasses until they retreat to their overwintering shelters again (Schubiger, F. X., 2024, 2024; Tschumi et al., 2016a) (Supplementary Figure 3a).

Natural enemies of CLBs include generalist predators such as ladybirds, lacewing larvae, carabids, and staphylinids (Kheirodin et al., 2022, 2020a, 2020b) as well as parasitic wasps.

The cabbage stem flea beetle (CSFB) is a major pest of oilseed rape in Europe (Ortega-Ramos et al., 2022; Schubiger, 2024; Ulber et al., 2010). Since the ban of neonicotinoids in 2018, pyrethroid use to control CSFB has increased in Switzerland. Both adult and larval life stages of the CSFB are damaging. Upon rape seeding in September, adults infest the fields and feed on germ leaves. Approximately 10–15 days later, females lay their eggs in the soil next to the seedlings. In early spring, neonate larvae tunnel into the plants and feed on plant petioles until June. Third instar larvae drop to the ground where they pupate a few centimeters below the soil surface. Pupation lasts 2–3 months until the new generation of adults emerge and continue to feed on the plants until harvest. They migrate to shelters such as hedgerows or woodlands for a period of inactivity until September (Breitenmoser et al., 2020; Franz Xaver Schubiger, 2024; Ortega-Ramos et al., 2022; Ulber et al., 2010) (Supplementary Figure 3b).

2.3. *Arthropod sampling*

Pest (i.e. CLB in winter wheat and barley, and CSFB in oilseed rape), predator, and parasitoid abundances were monitored using sweepnetting, pan traps, vacuum suctioning and tillermonitoring at 20 m from the field border (or WFS in agroecological fields). This distance was chosen as a compromise between being sufficiently close to detect potential spillover effects from field margins, yet far enough to primarily capture conditions within the crop rather than at the edge. Studies have shown that the impact of adjacent AES and semi-natural habitats (SNH) on natural pest control often follows a distance decay pattern, with the strongest effects occurring near field edges and diminishing further into the field (Boetzl et al., 2020). While margin effects can extend up to 30 m, they decline rapidly within the first few meters, making 20 m an appropriate distance to balance detecting these effects while focusing on within-field processes. After the first year of sampling in 2022, the protocol was adapted to improve comparability, feasibility, and focus (reduction of the number of transects from 3 to 1, exclusion of rarely observed additional species (lacewings, syrphids, ladybirds), strengthening of ground-dwelling arthropod sampling).

The reworked sampling protocol focuses on a complete picture of the spider community in all vegetation strata (using 3 different sampling methods). All spiders were identified at species level by a confirmed arachnologist.

Sweepnetting in cereals targeted adult CLB and parasitic wasps. Tillers were searched for CLB eggs ("tillermonitoring"). Pan traps were used to monitor arrival and approximate abundances of parasitic wasps and CSFBs. Abundances of ground-dwelling spiders, carabids, and staphylinids were captured using pitfall traps (PFT, only 2023).

Additionally, in order to assess CSFB larval infestation levels, a Berlèse extraction was performed on 9 × 3 plants per field cut on three sampling occasions from the end of February until mid-March. Plants were hung up in mesh bags over bottles filled with saline solution in which larvae were collected once they left the dying plants to find more suitable hosts. Infestation levels were calculated by relating the plant dry mass to the number of larvae collected.

A visual representation of the sampling protocol is provided in Supplementary Figures 3a and b, and the sampling set up in the field is visualized in Supplementary Figure 4.

Arrival and occurrences of adult parasitoids were additionally (to tillermonitoring and sweepnetting in cereals) monitored using pan traps.

2.4. *Parasitism rates*

CLB larvae were collected in the field during three weeks from the end of May until mid-June when abundances peaked. CSFB larvae were collected by the Berlèse extraction described above. All larvae were transferred into individual tubes containing lysis buffer for DNA extraction. Larvae containing hymenopteran DNA were identified using diagnostic PCR.

2.5. *Vegetation*

Vegetation was sampled in 8 quadrants (1 m^2) spaced 7 m along the margin (control or WFS) and into the field from the border to the center (Supplementary Figure 4). In 2022, all samplings were carried out in the two weeks from 16.04. to 23.05., while in 2023 the sampling was done between 19.04.23 and 02.05.23. The percentage share of each occurring plant species was recorded as well as the share of bare soil, so that all the shares added up to 100 % per plot. In WFS, the state of the plant (e.g., flowering, budding, etc.) was recorded, and whether the species had been sown. This further served to evaluate the quality of WFS (Supplementary Table 3). The percentage coverage values were transformed to an ordinal scale according to Maarel to allow abundance estimates (der Maarel, 1979). We from now on refer to the plants that have not been sown (i.e. not crop, undersowing or WFS) as “weedy vegetation”. To sample control strips, the most diverse adjacent border was selected. If multiple options were available, a grass strip was prioritized over paths or other non-vegetated field borders. In cases where no grass strip was present, the next most vegetated border was chosen, ensuring that some form of vegetation was always sampled.

2.6. Yield

Farmers reported the yield harvested from their fields. To further assess productivity, we conducted detailed measurements in both experimental and control units just prior to harvest.

For OSR, plant density was estimated by counting plants in 10 × 1 m^2 quadrats, placed from the field border to the center at 5–10 m intervals, depending on field width. Fruiting rate was determined from one plant per quadrat, calculated as the ratio of pods to flowers per branch. These plants were collected and stored in linen bags for further analysis. In the lab, five pods per plant were examined to count seeds per pod. Seeds were standardized for hygrometry in a climate chamber at 60°C for one hour, and the weight of three randomly selected seeds per branch was measured to the nearest 0.01 mg.

For cereals, yield biomass and grain protein content were assessed in 10 × 0.25 m^2 quadrats per plot, spaced approximately 5 m apart from the field border to the center. Sampling was conducted one week before the farmers’ harvest. Grain and plant sward were separated, and samples were oven-dried at 60–80°C for 48 h before weighing. Additional grain characteristics, including grain protein content, humidity seed length, width and area, and the weight of 1000 seeds (TSW), were measured

2.7. Environmental heterogeneity

Environmental heterogeneity was assessed as a compound measure (Table 2).

Table 2
Environmental heterogeneity was assessed as a compound variable. Landscape heterogeneity quantifies aspects at landscape scale, while directly adjacent structures are in immediate proximity to the field (visually recorded).

Variable	Description	Index/ Measurement
Landscape Heterogeneity: Assessed using swisstopo data in QGIS; land use elements within a 500 m radius categorized into seven categories: arable, built-up, other natural, BPA, woody, rocky, and water.		
Landscape Diversity	Quantified variance in the proportion of area covered by each of the seven habitat categories	Exponential Shannon Index
Landscape Patchiness	Assessed using the mean patch size irrespective of landscape type.	Mean Patch Size
Directly Adjacent Structures: recorded in the field and categorized into Artificial land, Crops, Woodland, Shrubland, Grassland, Bare Land and Lichens/moss, Water Area, and Hedgerows.		
Percent Edge shared with semi-natural Habitats (SNH)	Woodland, Shrubland, Grassland, Water Area, and Hedgerows were counted as SNH.	percent edge / field boundary length
Forest	Presence of a forest next to the field (no forest = 0, forest = 1).	Factor (0/1)

2.7.1. Landscape heterogeneity

Landscape heterogeneity was assessed using swisstopo data (Bundesamt für Landestopografie swisstopo, 2023) and analyzed in QGis (QGIS.org, 2023). Land use elements within a 500 m radius polygon centered on each field were classified into seven categories: arable, built-up, other natural (mostly permanent meadows), BPA (Biodiversity Promotion Areas, officially accepted and financially compensated biodiversity-rich landscape elements in two quality categories defined as parts of the Swiss AES), woody, rocky, and water. Landscape heterogeneity was quantified within each polygon in two different ways: as a measure of landscape diversity, we calculated the exponential Shannon to quantify variance in the proportion of area covered by each of the seven habitat categories (Feit et al., 2019a, 2019b), and landscape patchiness was assessed using the mean patch size irrespective of landscape type (Concepción et al., 2008).

2.7.2. Directly adjacent structures

Directly adjacent structures were recorded by visually identifying the land use types bordering each field. This was done in addition to the QGis landscape analysis of the 500 m radius polygons described above under the assumption that directly adjacent landscape structures have the highest impact on plants and arthropods of a field and account for spill-over effects (Concepción et al., 2008). These structures were categorized into artificial land, crops, woodland, shrubland, grassland, bare land and lichens/moss, water area, and hedgerows, based on a standardized classification scheme with further subcategories. For woodland, we observed broadleaved (four elements occupying a total area of 88’590 m^2) and mixed (10 elements occupying a total area of 563’751 m^2). For grassland, we differentiated between extensively managed, species rich grassland (20 elements occupying a total area of 115’990 m^2), fertile grassland (878’866 m^2 in 71 elements), grassland with sparse tree/shrub cover (5 elements, 30’199 m^2), and spontaneously re-vegetated surfaces (3 elements 2436 m^2). Woodland, shrubland, grassland, water area, and hedgerows were further aggregated under “semi-natural habitats” (SNH) for analysis.

We used the percent edge (rather than the area of the structure to avoid quantifying the same elements twice, see *2.7.1. Landscape heterogeneity*) shared with SNH to serve as an explanatory variable to explain vegetation and arthropod abundances and diversity variables. Anecdotal observations suggested significant effect of forests in proximity to fields on pest pressure. Hence, we further included the presence of an adjacent forest as a factor.

2.8. Data analysis

2.8.1. Statistical analysis and model selection

All analyses were performed using the statistical software R (R Core Team, 2024). Linear mixed models were generally first fitted as "full models" including all explanatory variables and then simplified according to Akaike information criterion (AIC), and interactions were tested. Model selection followed the approach of Zuur et al. (2009). The full model contained the environmental explanatory variables (landscape diversity, mean patch size, and either percent edge shared with SNH and forest). To account for multiple measurements within the same field (i.e., shared environmental conditions and management), field was included as a random term. Year was included as a fixed term if there were significant differences between the two years, i.e. including it improved the model fit. Otherwise, it was included as a random term. Management was included as a categorical factor (control vs agroecological treatment). The models were fitted using lme4 (Bates et al., 2015) and refitted robustly using rlmer() from the package robustlmm (Koller, 2016), or, if no random structure was required, or rlm() from robustbase (Maechler et al., 2024) with default tuning parameters. No outliers were excluded. Response variables were the vegetation (cover and diversity), the predators (abundance), the parasitoids (abundance), the pests (abundance), the yield (quantity and quality). To improve the normality of residuals and model fit, response variables were log-transformed (for abundances) or log10-transformed (for ratios). Explanatory variables were standardized (centered and scaled). Only if the total number of datapoints did not allow fitting all the explanatory variables jointly without overfitting the model (i.e. separate models testing the effects of predators, and environmental and management variables on pest abundances (CLB and CSFB)), separate models testing effects of different explanatory variables were fitted. Further, whenever possible and ecologically meaningful, we aimed to fit one model across all crops. However, in some cases, this was not feasible due to differences in sampling methods, timing, or target species (e.g., parasitoids). In such cases, separate models were fitted. An overview of all explanatory variables and the final models, including the output is given in Supplementary Table 5).

Although we established a causal framework for ecological interactions (Fig. 1), we did not use structural equation modeling (SEM) due to inconsistencies in sampling resolution across datasets. Harmonizing the data structure would have reduced the dataset to 44 data points, which was insufficient for fitting a complex SEM.

All model outputs including the final models and eliminated terms eliminated from model selection, are provided in Supplementary Table 5. All figures were created in R using “ggplot2” and “interactions” to visualize interactions (Long, 2019; Wickham, 2016).

2.8.2. *Vegetation diversity*

Vegetation diversity was quantified using the Shannon Index (package “vegan” (Oksanen et al., 2023). Percent cover values were transformed into an ordinal abundance scale before calculating the Shannon Index (*see 2.5. Vegetation*). To explain vegetation abundance within fields, we used the Shannon Index of field margin vegetation as an explanatory variable. In models analyzing pest and predator abundances within fields, we used the Shannon Index of in-field vegetation diversity as an explanatory variable.

2.8.3. *Factors affecting predator and parasitoid abundances*

We chose to use in-field diversity describing the habitat quality as the explanatory variable for arthropod abundances, as we consider this to be a more direct explanation of arthropod abundance. Data from oilseed rape (OSR) and cereals were analyzed separately due to differences in sampling protocols, timing, and target species. Analysis of factors affecting parasitoid abundances followed methods described in *2.8.1 Statistical analysis and model selection*. Each sampling method targeted a different ecological community. Consequently, effects on predator abundances were assessed by conducting separate analyses for: 1) ground-dwelling predators monitored using PFT (2023 only), i.e. staphylinids, carabids, spiders, 2) spiders sampled by sweepnetting, and 3) spiders sampled by vacuum suctioning. We chose not to pool all spider data to analyze the effects of management and environment per functional group (i.e. spiders vs beetles) because PFTs were installed only in 2023, and the absolute abundances measured with each method differed by an order of magnitude. Combining data from all methods would have required extensive scaling, hampered interpretability and introduced methodological bias.

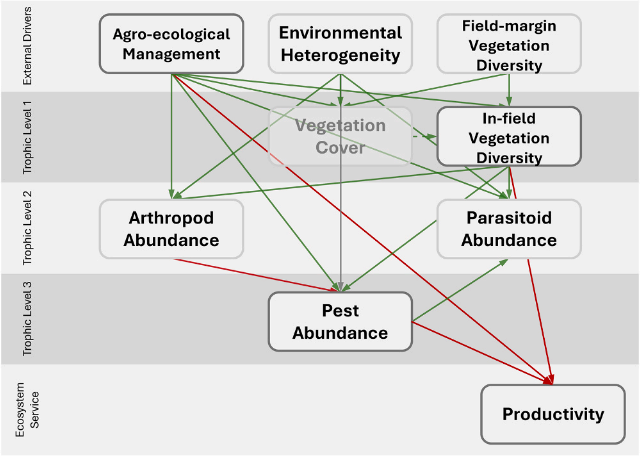

Fig. 1. Overview over the conceptual study set-up, visualizing positive (i.e. increasing / fostering; green arrows) and negative (i.e decreasing / diminishing; red arrows) effects across trophic levels on productivity. “Vegetation cover” is greyed out because it does not serve as downstream explanatory variable. The relationship between environmental heterogeneity and pest pressure is shown as neutral (grey arrow), reflecting that the effect may be either positive (e.g. by providing habitat, overwintering sites, and food resources that support pest populations) or negative (e.g. by increasing overall species richness, which may stabilize populations and reduce the dominance of individual pest species). As these opposing mechanisms are both plausible, no directional hypothesis is stated.

2.8.4. *Predator abundances affecting pests*

To evaluate the influence of predator abundances on pest abundance, mean predator abundances per field (and season) were used as explanatory variables. These included: a) mean spider abundances in cereals, sampled using vacuum suctioning, sweepnetting, and PFT, as well as b) mean beetle abundances (staphylinids and carabids) in PFT.

2.8.5. *Factors affecting yield*

Lastly, to test whether reduced management intensity in agroecological management affects crop yields through increased weed and pest abundances, we included mean pest abundances per field (CLB larvae from tiller monitoring), CSFB larval infestation levels from Berlèse extractions) and vegetation Shannon diversity as explanatory variables. Again, was included as a binary variable (conventional vs. agroecological).

We further assessed how differences in management intensity—specifically, the number of field operations and amount of synthetic inputs—relate to yield quality measures.

We used Principal Component Analysis (PCA) to summarize the primary differences in management practices between agroecological and conventional fields. PCA was performed separately for barley, OSR, and wheat, as well as across all crops combined, using scaled and centered data. The first two principal components (Dim1 and Dim2) were extracted to visualize variation in management intensity, with a particular focus on pesticide use (TFI) in conventional fields and mechanical weeding in agroecological fields.

3. Results

3.1. *Agroecological management and high environmental heterogeneity increase vegetation cover within fields*

The percent cover of weedy vegetation is significantly higher in agroecological compared to conventional fields ($p < 0.005$). However, the effect of high diversity of the field margin vegetation on in-field vegetation cover is not consistent across managements and crop types.

Notably, there is no overall significant effect of field margin vegetation diversity on in-field vegetation cover ($p > 0.5$, see Fig. 2a), despite the fact, that field margin vegetation diversity is consistently higher in WFS (i.e. agroecologically managed fields) as compared to conventional field margins (Supplementary Figure 1). The interactive effect of field margin vegetation diversity and OSR is strongly positive ($p < 0.005$). This effect is more pronounced in conventional fields. Similarly, the interaction of field margin vegetation diversity in wheat also suggests a positive association, though not significant ($p > 0.1$).

The presence of forests adjacent to the field did not significantly affect in-field vegetation cover ($p > 0.1$). Similarly, landscape diversity had no significant effect on in-field vegetation cover ($p > 0.1$). There was, however, a difference between years—with significantly more

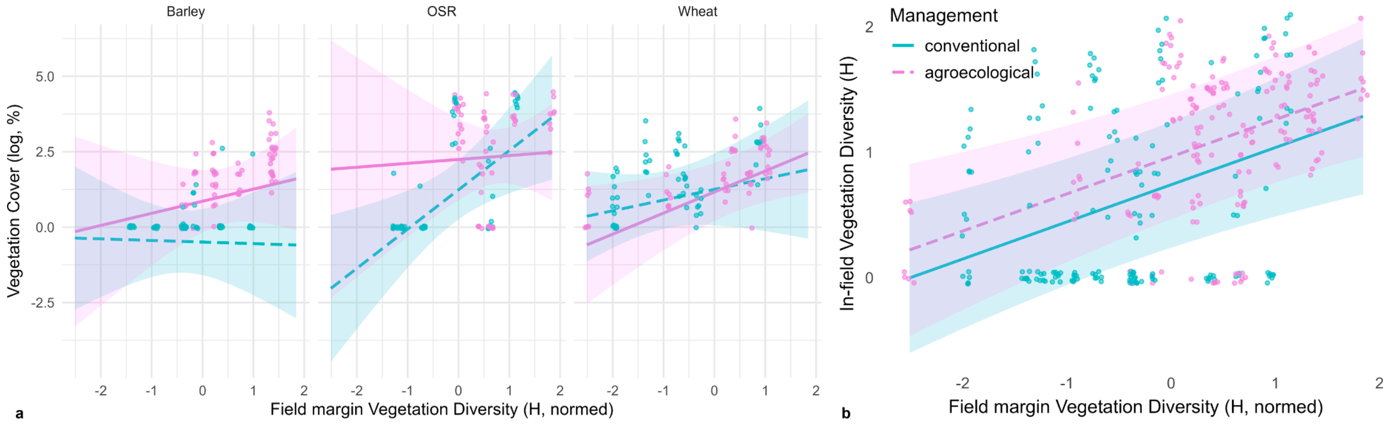

Fig. 2. In-field weedy a) vegetation cover and, b) diversity depending on the diversity (Shannon Index, H, normed) of the field margin vegetation (i.e. control strip or wildflower strips (WFS)). Every point corresponds to a vegetation sampling quadrant within the field. Field margin vegetation has been averaged across sampling quadrants and normed.

weedy vegetation in 2023 than in 2022 ($p < 0.01$).

3.2. *Field margin vegetation diversity (along with environmental and management factors) drives in-field plant diversity*

Our analysis confirms that in-field vegetation diversity linearly depends on field margin vegetation diversity, although conventional sites mostly had no weedy in-field vegetation (Fig. 2b). Specifically, in-field vegetation diversity increases with increasing field margin vegetation diversity ($p < 0.005$). In line with this, vegetation diversity is higher in agroecological fields compared to conventional fields, although not significantly so ($p > 0.05$). Moreover, there was no significant interactive effect of field margin diversity and management, and the interaction was therefore excluded from the model fit.

3.3. *Environmental heterogeneity is more effectively contributing to increased predator abundances than agroecological management and increased local vegetation*

3.3.1. *Abundance of ground-dwelling predators (Staphylinids, Carabids, Spiders, sampled by PFT)*

Contrary to our expectations, - in the full model, that integrated the effects of the environment and management (see *2.8. Data Analysis*) - the increase in abundances of ground-dwelling predators (staphylinids, carabids, spiders) in agroecological fields was not significant compared to conventional fields ($p > 0.1$). Among the predator groups, staphylinids were the least abundant ($p < 0.0001$), followed by spiders ($p < 0.005$), while carabids were the most abundant overall.

Increased in-field vegetation diversity did not have a consistent positive effect on predator abundances ($p > 0.05$). However, the response of spiders to in-field vegetation diversity was weaker compared to staphylinids and carabids ($p < 0.05$). The interaction between vegetation diversity and predator groups revealed significant differences in responses, particularly for staphylinids in OSR fields ($p < 0.0001$) and a positive association between in-field vegetation diversity and spider abundance in OSR ($p < 0.05$).

Furthermore, OSR fields had significantly lower predator abundances overall compared to cereals ($p < 0.0001$), with spiders being notably less abundant in OSR than in wheat and barley. Landscape patchiness also showed a marginally positive effect on overall predator abundances ($p > 0.05$), suggesting that certain landscape features might influence predator distribution.

To further interpret these results, we conducted an additional pairwise comparison of predator abundances between conventional and agroecological fields, analyzing beetles (carabids and staphylinids) and spiders separately within each crop type. In these models, which did not include environmental variables as covariates, agroecological management significantly increased carabid and staphylinid abundances ($p < 0.005$) but had no significant effect on spiders (see Supplementary Figure 2a and b, and Supplementary Table 5).

3.3.2. *Abundance of spiders occurring in the vegetation*

In-field vegetation diversity had no significant effect on spider abundances in either sampling method (sweepnetting or vacuum, $p > 0.05$). Furthermore, there was no significant difference in spider abundance between agroecological and conventional fields ($p > 0.05$), regardless of the sampling method (see Fig. 3b).

Spider abundance in cereals was significantly lower in wheat fields when sampled using vacuum suction ($p < 0.005$), but not with sweepnetting ($p > 0.1$). In contrast, PFT sampling revealed significantly higher spider abundances in wheat fields compared to other crops. Likewise, in the simplified model that allows direct comparison of spider abundances in conventional vs agroecological fields, as well as across methods, we did not observe a consistent positive effect of agroecological management on spider abundances ($p > 0.05$, Supplementary Figure 2b and Supplementary Table 5).

Landscape heterogeneity appeared to positively influence spider abundance, but this effect varied by sampling method. For sweepnetting, landscape patchiness had a positive effect on spider abundance ($p < 0.05$), while environmental diversity had a significant positive effect on spider abundance when sampled by vacuum suction ($p < 0.005$).

Ultimately, spider abundances were significantly lower in 2023 compared to 2022, particularly when assessed through vacuum suction ($p < 0.005$), but this decline was also noted with sweepnetting ($p < 0.05$).

3.3.3. *Parasitoid abundance and parasitism rate*

There was no effect of agroecological management on parasitoid abundance across crops (cereals: $p > 0.1$; OSR: $p > 0.1$). In cereals (Fig. 4a), there were significantly more parasitoids in wheat than in barley ($p = 0.005$), but parasitoid abundance was not affected by in-field vegetation diversity in both cereals ($p < 0.5$) and OSR ($p > 0.1$). Parasitoid abundances differed significantly across sampling methods, with tillermonitoring showing lower ($p < 0.005$), and sweepnetting ($p < 0.05$) higher abundances compared to pan trapping. In OSR, abundances were markedly lower in 2023 compared to 2022 ($p < 0.0005$). Additionally, landscape diversity negatively influenced parasitoid abundances in OSR ($p < 0.05$).

The parasitism ratio was 13 % for CLB larvae (37 larvae tested positive for parasitoid DNA out of 296), with 20 of these larvae collected in agroecological fields and 17 in conventional fields. Only one out of 180 CSFB larva tested positive for parasitoid DNA.

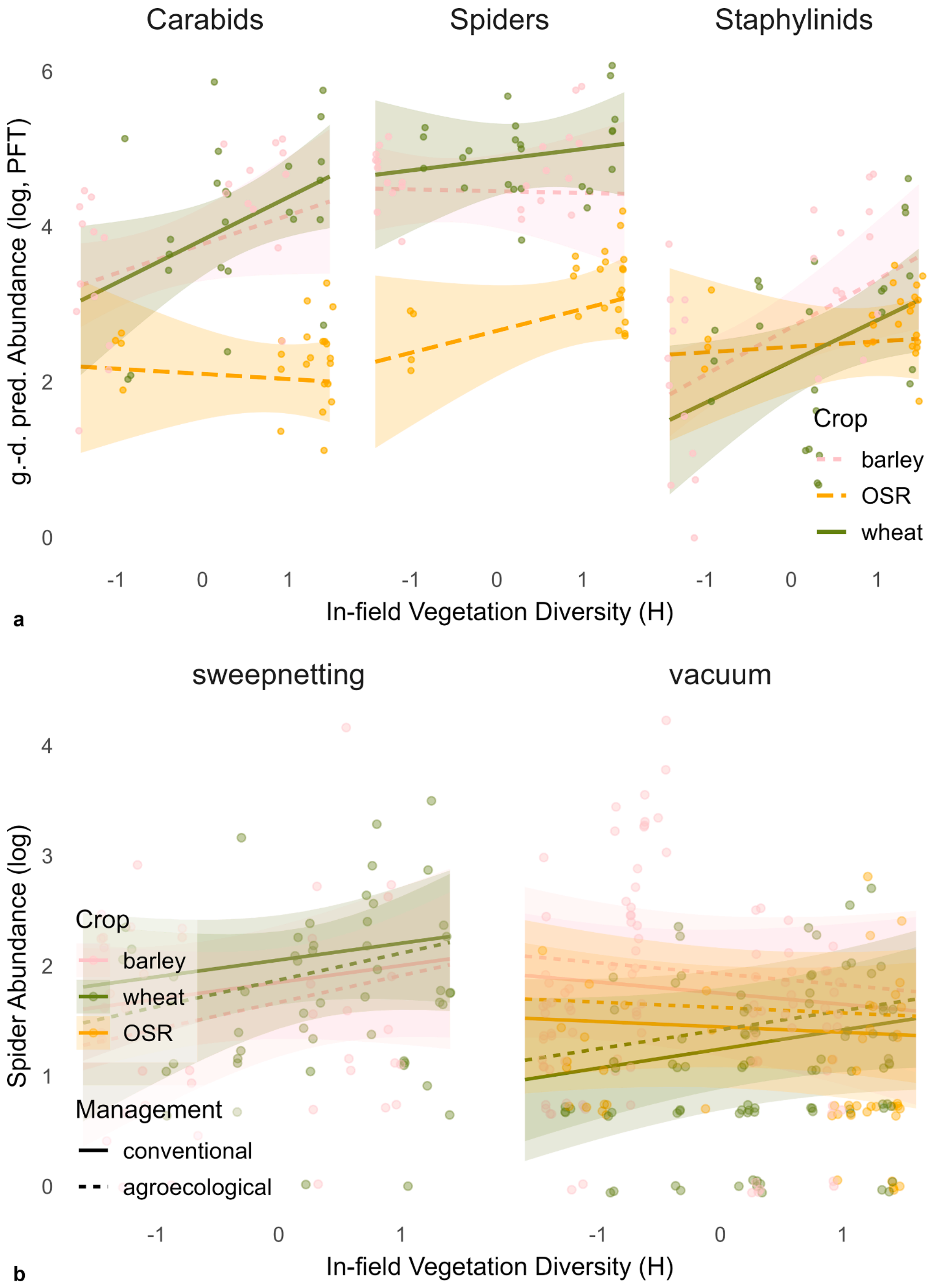

Fig. 3. Different predator communities in response to in-field vegetation diversity. a) Effect of in-field vegetation diversity (Shannon) on ground-dwelling predator (g.-d. pred.) abundances (pitfall traps (PFT)). The level of replication (i.e. datapoint) for arthropod abundances is the sampling round. b) Effect of in-field vegetation diversity (Shannon) on spiders living in the vegetation (sweepnetting), and spiders sampled by vacuum suctioning. Each point corresponds to a sampling cylinder in the case of vacuum suctioning. In both methods, there were multiple rounds, but there was only one sweepnetting transect.

None of the environmental variables affected parasitism rates, and as for parasitoid abundances, there was no significant difference in parasitism ratios between conventional and agroecological fields $p < 0.5$)). Parasitism was also not affected by high CLB abundance ($p > 0.5$).

3.4. *Pest abundances are shaped by other factors than management, environmental heterogeneity, or predator abundances*

3.4.1. *Drivers of CLB abundances in wheat and barley*

CLB abundance was not significantly higher in agroecological than in conventional fields ($p > 0.5$), but significantly higher in wheat than in barley ($p = 0.001$). This effect was most pronounced for eggs ($p < 0.0001$). Higher vegetation diversity within fields had no overall significant effect on CLB abundance (Fig. 5a). CLB abundance was not significantly influenced by any of the environmental heterogeneity variables (neither landscape diversity, mean patch size, nor percent edge SNH). Similarly, there was no effect of adjacent forests ($p > 0.5$).

The potentially repressive effect of predator abundances was not significant on CLB abundances ($p > 0.5$, tested in a separate model), as shown in Fig. 5b.

3.4.2. *Drivers of CSFB infestation in OSR*

To identify the drivers of CSFB infestation in OSR, we related environmental variables and predator abundances to adult CSFB counts from

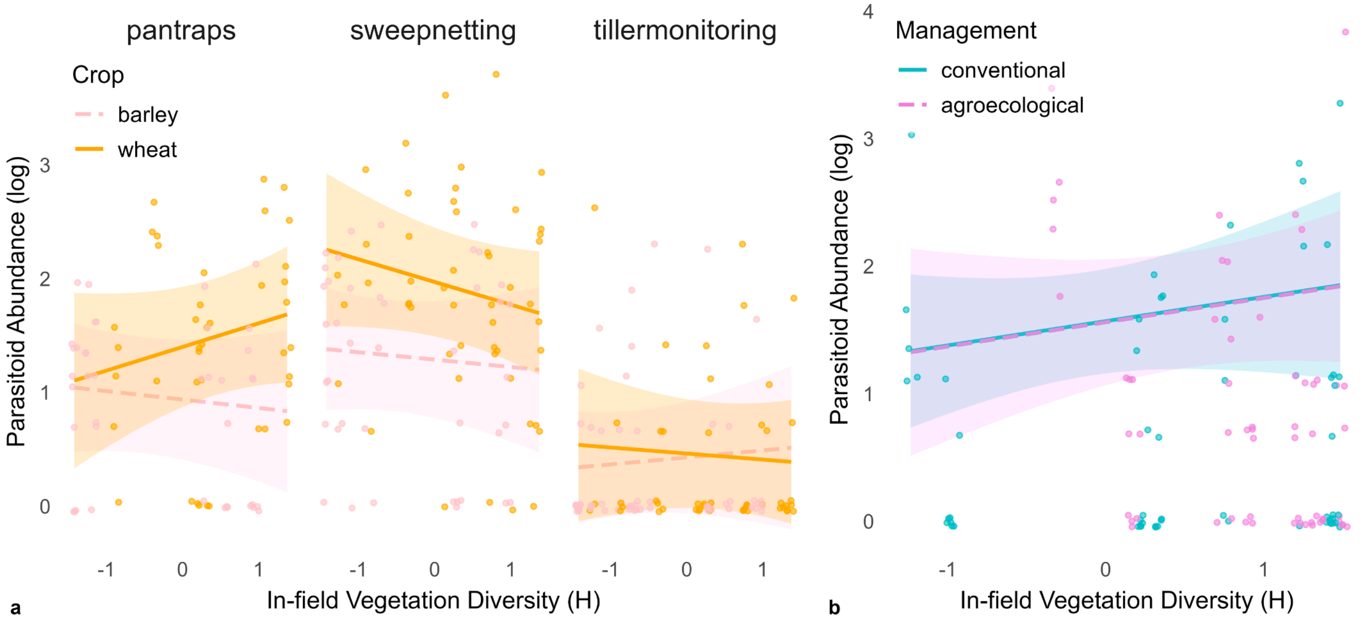

Fig. 4. Effect of vegetation diversity (Shannon Index, H) on parasitoid abundance depending on the management, sampling method, and culture across sampling rounds (i.e. each point corresponds to a sampling round). a) Effect in cereals per sampling method, b) effect on parasitoid abundance monitored using pantraps in oil seed rape (OSR).

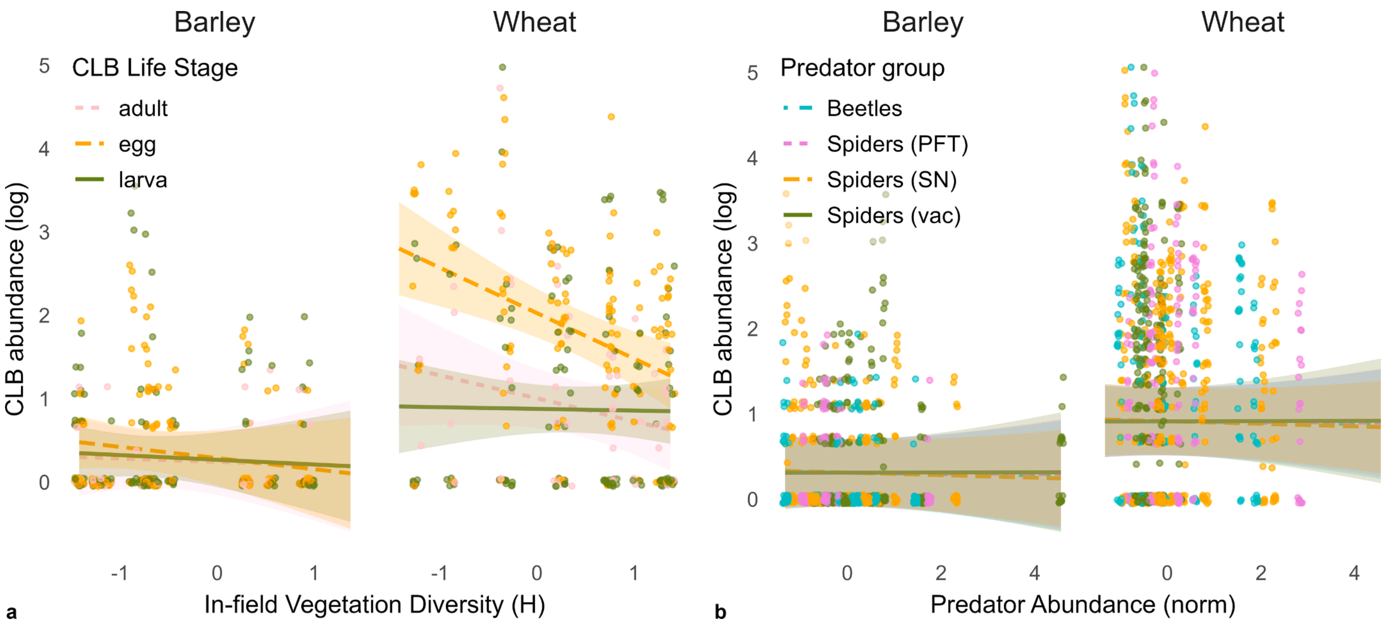

Fig. 5. Drivers of CLB abundance. a) The effect of increased vegetation diversity in the field on CLB abundance in wheat and barley depending on the treatment. Every point corresponds to a pest sampling occasion (i.e. round per method and transect). b) Effect of predator abundances on CLB abundance. Every point corresponds to predator abundance per field, sampling round and predator group.

pan traps. None of the potential explanatory variables had a significant effect on CSFB counts: Specifically, neither agroecological management ($p < 0.5$, Fig. 6a), nor environmental heterogeneity had an apparent effect. Further, CSFB counts did only slightly react to in-field vegetation diversity yet not significantly ($p < 0.5$).

CSFB counts did not significantly respond to predator abundances (Fig. 6b, $p > 0.5$, tested in a separate model). However, a weak negative trend was observed, suggesting that increasing ground-dwelling predator abundances—particularly spiders—may be associated with lower CSFB counts, though this relationship was not statistically significant.

3.5. *Agroecological management reduces crop yields, but not due to higher weed and pest abundances*

We lastly assess how the effects of management intensity on crop yield are modulated by in-field vegetation and pest abundances. We check if agroecological management reduces crop yields due to higher weed and pest abundances. Indeed, yield was significantly lower in agroecological fields ($p < 0.05$, Fig. 7) regardless of the crop.

The measured differences between agroecological vs conventional fields in percent of all the yield variables assessed are given in Supplementary Table 1 and graphically represented in Supplementary Figures 5 and 6.

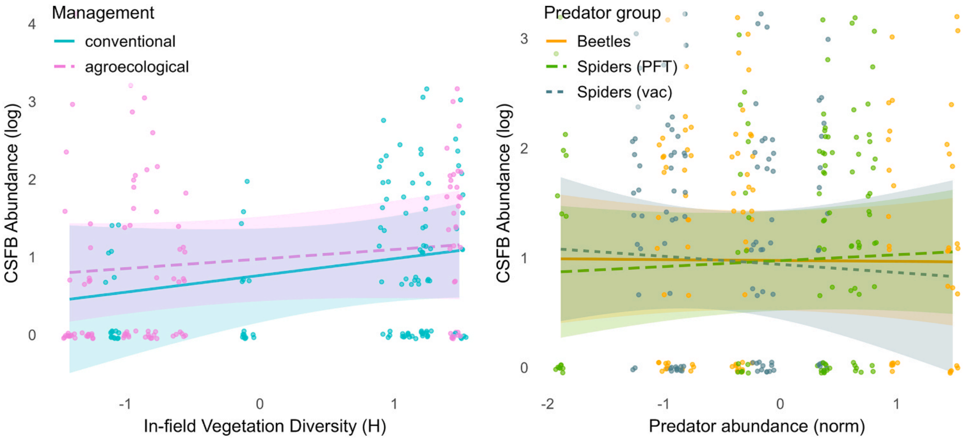

Fig. 6. Effects of in-field vegetation diversity, and predator abundances on CSFB counts (log transformed) monitored using pantraps. a) Effect of in-field vegetation diversity on CSFB counts. Every point corresponds to a pantrap count: there were multiple rounds and multiple monitoring types. b) Effect of predator abundance on CSFB abundance depending on the predator group. Every datapoint corresponds to a CSFB pantrap count per sampling round and field. Predator abundances have been averaged per field.

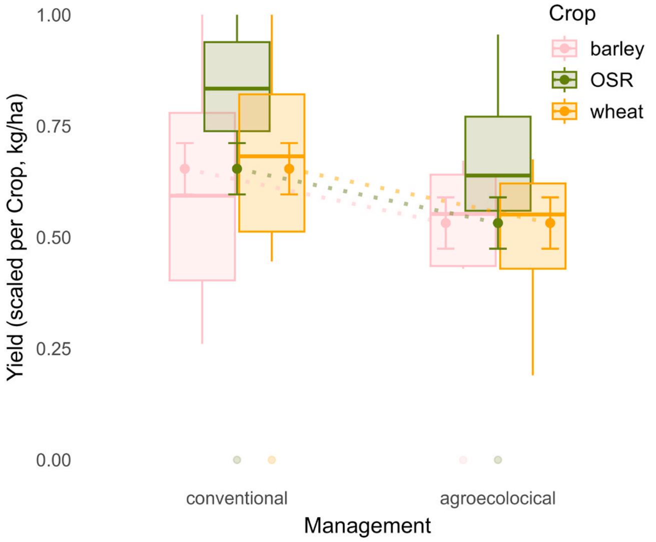

Fig. 7. Pairwise comparison of yield (scaled per culture, kg/ha) per crop and management type.

The yield was 10.6 % higher in barley, 8.1 % higher in wheat, and 18.0 % higher in OSR conventional fields compared to agroecological fields. Protein content was 8.8 % higher in conventional cereal fields (8.75 % in barley, 11.5 % in wheat). Interestingly, however, the seed weight (weight of 1000 seeds (g), TSW) was not affected by agroecological management. The fruiting rate in OSR was 11.7 % higher in agroecological fields, while plant density was 18.9 % lower. Pest abundances and vegetation diversity had no effect on any of the quality measures, with the only exception of high in-field vegetation diversity correlating with lower OSR yields ($p < 0.005$).

We previously showed that the pest abundances are not significantly higher in agroecologically managed fields compared to conventional. Accordingly, pest abundance did not explain yield variability. Similarly, vegetation diversity within fields had no significant effect on yield and was removed from the model based on AIC.

Yield was most strongly positively influenced by TFI ($p < 0.005$), and negatively by the number of weeding operations after seeding ($p > 0.05$), followed by soil management operations before seeding ($p < 0.05$). Nitrogen and ploughing had no significant effect on yield.

To further examine the main differences in management between conventional and agroecological fields, we performed a PCA (Fig. 8a). The first principal component (Dim1) accounted for 39 % of the variance, while the second principal component (Dim2) explains 27 %. Notably, TFI differentiated conventional fields, whereas weeding and soil management practices were predominant in distinguishing agroecological fields. Separate PCAs for each crop revealed consistent patterns with the greatest divergence in management types observed for OSR. Since TFI in conventional fields and weeding intensity in agroecological fields were the most distinguishing management factors and had the strongest effects on yield, we introduced the variable 'practice' to directly compare their impact across both systems. In conventional fields, 'practice' corresponds to pesticide use (TFI), while in agroecological fields, it represents the number of weeding operations. Both 'practice' and yield were scaled between 0 and 1 per crop, allowing for a unified model across different crops and management types. Pest pressure was also summarized into a single scaled variable.

Fig. 8b demonstrates the highly significant impact of 'practice' on yield ($p < 0.0005$), contingent on the management type ($p < 0.0001$). In conventional fields, where 'practice' represents pesticide use (TFI), the effect on yield was positive. Conversely, in agroecological fields, where 'practice' signifies the number of weeding passages, the effect on yield is markedly negative ($p < 0.0005$). The negative effect of weeding on yield was strongest in OSR ($p > 0.05$), and weakest in barley. The same, but slightly less pronounced response had been observed for the number of soil management operations before seeding (see Supplementary Table 5).

To further assess which types of pesticides contributed most to yield differences in conventional fields, we examined their individual effects. Due to the nature of TFI, which relates the applied dose to the allowed dose, total pesticide usage was comparable across crops. We again confirmed he positive association between TFI and yield ($p < 0.005$). Among pesticide types, the strongest yield effects were observed for fungicides and plant growth regulators ($p > 0.05$), whereas herbicide applications had the weakest effect ($p < 0.9$). However, the differences between pesticide types were not statistically significant (Fig. 8c).

4. Discussion

4.1. Drivers of in-field vegetation and arthropod density

Our study confirmed that agroecological field margins (WFS) supported higher vegetation diversity compared to conventional field edges (see also Supplementary Figure 1), but this increased diversity in field margins did not translate into higher in-field vegetation cover.

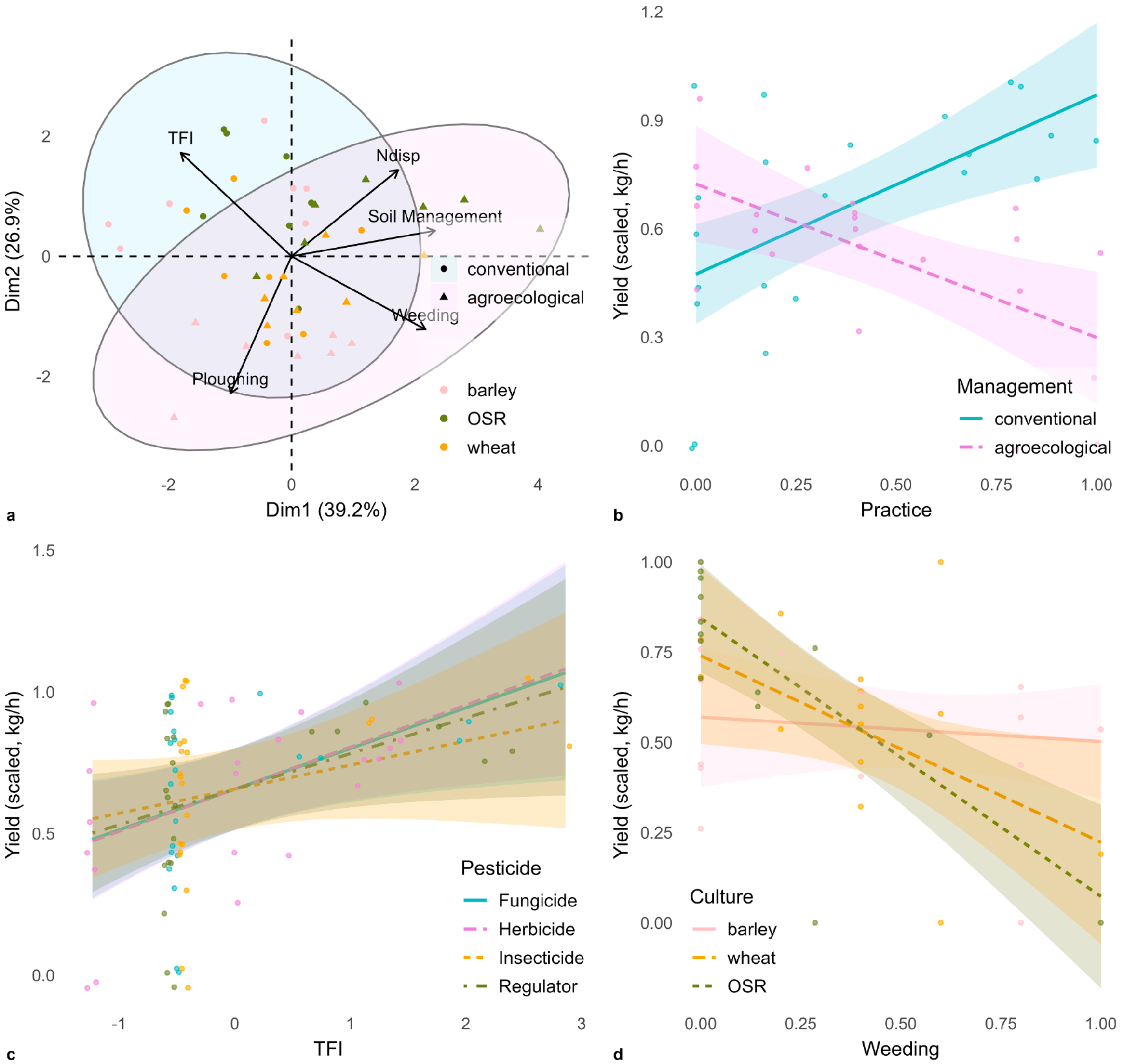

Fig. 8. Effects of management on yield. a) PCA depicting the primary distinctions in terms of the management practices across agroecological and conventional fields. b) Relating yield to the proxy variable "practice", i.e. the management variable that explains most of the variability per management type. In conventional field, "practice" corresponds to the amount of pesticide applied (TFI), while in agroecological fields, "practice" corresponds to the number of weeding passages. c) Effect of different pesticides on yield in conventional fields (where TFI > 0). d) Relating the number of weeding passages to the yield per crop in agroecological fields.

Nevertheless, in agroecological fields, seed dispersal from field margins likely contributed to higher in-field vegetation diversity, facilitated by the absence of herbicide treatments.

While increased vegetation complexity is expected to support arthropod diversity (Tschumi et al., 2016b, 2015), we did not observe a consistent positive effect of in-field vegetation diversity on arthropod abundance. Ground-dwelling beetles (carabids and staphylinids) were more abundant in agroecological fields, but this was not observed for spiders, revealing different responses across predator taxa to local vegetation structure.

Landscape heterogeneity—measured as a combination of patchiness and habitat diversity— also had taxon-specific effects on arthropod abundance. Spiders sampled by sweep netting responded positively to landscape patchiness, whereas spiders sampled by vacuum suction were more strongly influenced by landscape diversity. In contrast, no significant landscape effect was observed for ground-dwelling predators (PFT samples which included carabids, staphylinids, and spiders). These results confirm that simplification at landscape scales reduces local arthropod species richness (Dainese et al., 2019), and that different predator groups interact with landscape features in distinct ways, likely due to variation in habitat use and movement patterns (e.g. Hendrickx et al., 2007; Rusch et al., 2016; Tscharntke et al., 2012).

Studies have found that WFS enhance natural enemy abundance (Tschumi et al., 2015), but this is often shaped by the proportion of semi-natural habitats in the landscape (Hendrickx et al., 2007; Weibull et al., 2003). In particular, adjacent forest habitat has been shown to increase arthropod abundance, albeit with variation across taxa depending on their ecological traits (Birkhofer et al., 2014; Boetzl et al., 2020; Krimmer et al., 2019). In our study, however, we found no significant effect of locally adjacent forests on plant or arthropod diversity. The Swiss agricultural landscape is characterized by relatively small fields and a high degree of habitat interspersion, and this comparatively small-scale landscape heterogeneity might obscure local site-specific effects of forests. Swiss agricultural landscape heterogeneity therefore may buffer some of the negative effects of landscape simplification that are often observed in intensively farmed regions elsewhere.

Another explanation for the lack of an effect of forests and other field margin semi-natural habitats on in-field arthropod abundances is that our sampling was conducted at 20 m distance into the field, and any effect on arthropods might be limited to the edges of the field. We chose 20 m as we wanted to evaluate the effect on crop production, and limiting our sampling to field edges would therefore have been largely unrepresentative of the impacts of pest control services on yield (see Methods Section 2.3). Results from other studies are variable in this respect, with some reporting increased densities of carabid beetles and spiders either close to field edges (Pollier et al., 2019) or to cereal field centers (Anjum-Zubair et al., 2010; Birkhofer et al., 2014; Boetzl et al., 2020).

Overall, determining a consistent effect of habitat simplification on in-field predatory arthropod abundance distribution remains challenging, as shown by our results, and by the contrasting results from other studies. Some studies give more emphasis to WFS and grassy margins (Boetzl et al., 2019), while others highlight broader environmental heterogeneity as a stronger predictor of arthropod communities (Concepción et al., 2008; González et al., 2022; Hendrickx et al., 2007). Moreover, our study also revealed differences in both arthropod abundance and vegetation diversity across the two years (2022 and 2023) which may be linked to weather conditions (Agrometeo, 2023), although there were no obvious differences between precipitation and temperature between the two years (data not shown). Long-term studies will be necessary to account for multi-year trends and how they affect predatory arthropod, pest, and yield fluctuations.

4.2. *Limits of predators for pest regulation and knowledge gaps on parasitoids*

We did not observe an effect of predators on pest abundance. The biological control potential of predators might be too weak compared to the effects of chemical pesticides, while adjacent habitats that support biotic pest control agents might also support pest populations (Landis et al., 2000; Tscharntke et al., 2005). While some studies suggest that higher predator species richness enhances biological control (Griffin et al., 2013), others emphasize that functional diversity—rather than species richness alone—is a stronger predictor of pest suppression (Jonsson et al., 2017). Moreover, pesticides most likely not only reduce pests but also natural enemy populations (Rusch et al., 2017; Thies and Tscharntke, 1999). In our study, the lack of a clear relationship between predator abundance and pest suppression suggests that increased predator presence alone is not sufficient to control pests effectively.

Parasitoid abundances in cereals were not influenced by environmental heterogeneity, agroecological management, or in-field vegetation diversity. Parasitism ratios (mean value of 13 %) were not especially responsive to changing abundance of CLB in this study. Therefore, while parasitoids account for some CLB mortality, this is unlikely to be sufficient to control the population for agricultural purposes. Without a clear understanding of the factors that affect parasitoid abundances or parasitism ratios it is difficult to proscribe management guidelines to encourage parasitoids. In general, there is a paucity of information on parasitoids, particularly in agricultural settings, or on their responses to field and landscape conditions, and their effects on pests (Geiger et al., 2016; Miller et al., 2021; Morinière et al., 2019).

While controlled experiments show that natural enemies can reduce pest populations (Thies et al., 2011), our results suggest that, under real-world agricultural conditions, predator and parasitoid effects are weak. Enhancing functional biodiversity alongside agronomic strategies will be essential to improving pest control in low-input systems.

4.3. *Yield trade-offs and management implications in agroecological fields*

Yield in agroecological fields was lower than in conventional fields (-11.7 % in 2022 and −10.6 % in 2023, across all crops) (Fig. 7), indicating that balancing reduced inputs with sustainable yields is challenging but feasible. Regardless of the crop, seed weight remained unaffected by the agroecological management. The fruiting rate in OSR was 11.7 % higher in agroecological fields, but this was not reflected by an overall yield increase due to an 18.9 % lower plant density in agroecological fields. Higher fruiting rates could be due to observed increased pollinator activity in agroecological fields (data not shown), though lower intraspecific competition for resources in lower density crops might also have contributed. This trade-off between fewer plants but higher reproductive success per plant warrants further investigation, as it may influence yield stability under reduced-input management. On the other hand, cereal protein content was significantly lower in agroecological fields, highlighting a potential limitation for grain quality under this management system.

Our results indicate that agroecological management approaches reduce crop yields, but this was not attributable to pest pressure or increased weedy plants in the field. Duflot et al. (2022) also found that the benefits of agrobiodiversity (such as natural pest control) were often overshadowed by the more immediate and significant yield benefits of pesticide use, highlighting a trade-off between chemical inputs and biodiversity benefits. Colbach et al. (2020) discuss inconsistencies in assessing the relationship between weeds, herbicide use, and crop yield, noting that many studies fail to account for all the factors influencing these relationships, emphasizing the need for more comprehensive weed monitoring throughout the growing season.

In attempting to further elucidate factors affecting the yield gap between agroecological and conventional treatments, we evaluated within-treatment variation in management practices. In doing so, we indeed found a negative effect of the number of pre-sowing soil management operations as well as weeding after seeding on crop yield, especially in OSR. We conjecture that in agroecological fields (where synthetic inputs are precluded) farmers might try to compensate for problems (e.g., increased density of weeds or high pest or fungal pressures) by increased soil management and weeding, both of which involve mechanical interventions in the field. Farmers noted that the outcome and success of mechanical intervention was often uncertain, and in the event of high weed pressure, mechanical weeding must be repeated several times.

In summary, agroecological systems offer potential sustainability benefits, including biodiversity conservation, reduced pesticide exposure, and pest control (Destoumieux-Garzón et al., 2018), but there are complex trade-offs with crop yields.

4.4. *Limitations and strengths*

While our study provides valuable insights into the effects of agroecological management on plant and arthropod communities, several limitations should be considered. First, the lack of a consistent multi-year time series limits our ability to assess long-term trends and fluctuations in arthropods, plants, and yields. Inconsistencies in the sampling protocol between years, and in how farmers implemented agroecological measures, may have introduced variability into the dataset.

The strength of our study is in its pairwise experimental design, where each farmer managed two fields under different treatments for multiple years, allowed for direct comparisons within farms, reducing variability due to farm-specific management. The close collaboration and co-design of the study with farmers ensured that they followed the same crop rotation, and provided detailed agronomic data for all trial years, including yield, inputs, and management operations. The relatively similar environmental conditions across the canton of Solothurn further enhance the comparability of results.

4.5. *Conclusion*

Our study highlights the trade-offs between biodiversity conservation and yield stability in agroecological farming. While agroecological field margins increased vegetation diversity, this did not consistently enhance arthropod abundance or pest suppression. Pest populations were not significantly higher in agroecological fields, yet natural enemies did not sufficiently compensate for reduced pesticide use.

Despite these challenges, agroecological management remains a viable alternative if integrated with complementary strategies for biological control and disease management. However, the stability of natural pest control services remains difficult to predict, emphasizing the need for long-term research and adaptive management approaches

Future research should explore how to optimize trade-offs between biodiversity conservation and crop productivity, including assessing the long-term effects of agroecological practices on soil health, pest regulation, and ecosystem resilience. In view of the complex responses among different arthropod communities to field and landscape conditions further investigation will be needed to specify targeted agroecological interventions—such as optimized WFS placement, diversified crop rotations, or alternative disease management strategies. Beyond predator-based pest control, parasitoids represent a promising yet underutilized tool for biological pest suppression in agroecosystems. While they are widely used in controlled environments (e.g., greenhouses), their application in open-field agriculture remains limited. This limitation is due in part to knowledge gaps in host–parasitoid interactions and regulatory restrictions (Miller et al., 2021). Addressing these limitations—through improved taxonomic resources, DNA barcoding, and regulatory adjustments—could help unlock their potential for integrated pest management in agroecological systems.

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CRediT authorship contribution statement

Jaboury Ghazoul: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Maura Ganz:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Philippe Jeanneret:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used OpenAI (2024) ChatGPT (4o version) [Large language model] to improve language conciseness, style and detect redundancies. During data analysis, it had been used to assist the code formulation. Data analysis had never been conducted in the ChatGPT interface itself. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109771.

Data availability

The dataset is publicly accessible on Dryad via this link:

DryadArthropod and plant abundances, crop yield, field management, and environmental structures

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