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Perennial flower strips increase pollinator and natural enemy abundance but have limited effects on pest control in adjacent crops

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ABSTRACT

Flower strips are a valuable agri-environmental measure to foster ecological intensification by providing floral and nesting resources to beneficial organisms. Nevertheless, few flower strip studies integrate assessments of multiple ecosystem services and their providers (simultaneous promotion of pollinators and natural enemies) or consider trade-offs (unintended promotion of pests in adjacent crops). This gap is further exacerbated if below-ground functions are considered. We sampled pollinators, natural enemies, and herbivores using visual observations, yellow sticky traps, pitfall traps, and tiller counts in ten pairs of perennial flower strips and control field margins, and their adjacent cereal fields in Scania, Sweden, in 2021. In addition, we estimated predation and below-ground decomposition rates with sentinel prey cards and bait lamina strips. Flower strips increased floral availability, pollinator, natural enemy and herbivore abundances, relative to control field margins. Natural enemy and herbivore responses to the implemented strips were taxon-specific. The positive effects of flower strips extended beyond the strips themselves, as spillover effects were evident for several natural enemy groups, with increased abundances in adjacent crop fields. A trade-off was also observed: pest thrips were more abundant in crop tillers near flower strips than near controls. No effect of flower strips on aphid predation rates was observed. Decomposition rates were as high in flower strips as in controls, despite flower strips only being established for two years. These findings emphasize flower strips' potential to support multiple ecosystem service providers, while underscoring the importance of context-specific design and management to maximize benefits and avoid unintended trade-offs.

1. Introduction

In intensively farmed landscapes, biodiversity loss is closely linked to declines in essential ecosystem services, such as pollination and natural pest control, both of which are critical for maintaining crop productivity (Tilman et al., 2014; Dainese et al., 2019). To sustain these services, it is essential to promote environmentally friendly practices that mitigate or reverse the negative impacts of agricultural intensification on biodiversity (Bommarco et al., 2013). In the European Union (EU) and other regions, agri-environmental schemes have emerged as a key strategy to reach these goals. These schemes focus on restoring, maintaining, or creating habitats that provide functional diversity of beneficial arthropods along with essential resources and protection from agricultural disturbances (Ekroos et al., 2014; Batáry et al., 2015). In this context, flower strips, areas sown with flowering herbaceous species along field edges, are commonly implemented as an agri-environmental

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measure to support biodiversity and ecosystem services (IPBES, 2016; Albrecht et al., 2020).

Flower strips are particularly valued for their ability to increase the local abundance and diversity of pollinators and natural enemies (Landis et al., 2000; Wratten et al., 2012; Snyder, 2019). These habitats provide shelter, oviposition sites, overwintering habitats, and food resources (Landis et al., 2000). While extensive research highlights their role in supporting beneficial arthropods, their effects on ecosystem service delivery in adjacent crops remain less well-studied and the results have shown more variable outcomes (Albrecht et al., 2020; Lowe et al., 2021; Rodenwald et al., 2023; Jachowicz and Sigsgaard, 2025). This variability creates uncertainty, which acts as a significant barrier to their adoption by farmers (Kleijn et al., 2019). In fact, according to Kleijn et al. (2019) flower strips remain one of the less preferred agri-environmental practices in the EU, despite being eligible for subsidy support.

Studies indicate that farmers are more likely to implement agri-environmental schemes when they are well-informed and can be confident in the benefits of the schemes (Vanslembrouck et al., 2002; Uyttenbroeck et al., 2016). Hence, improving the design and multifunctionality of flower strips can play a key role in improving farmer perception and adoption, particularly by addressing concerns about their cost-effectiveness and broader ecosystem service delivery (Snyder, 2019). However, research on multifunctional habitats supporting diverse beneficial organisms remains underdeveloped (Boetzl et al., 2021, 2023; Lundin et al., 2023; Favarin et al., 2024). Most studies have focused on single functional groups, such as pollinators or natural enemies, with limited efforts to integrate resources for both pollination and pest control (Lundin et al., 2019; Rowe et al., 2021). Consequently, it remains unclear whether flower strips designed for pollinators can simultaneously enhance multiple functional groups (i.e. pollinators, natural enemies, herbivores and decomposers) or their services, such as pollination and pest control.

Beyond pollination and pest control, research on other ecosystem services and potential disservices associated with flower strips is limited. For instance, while these habitats can enhance resources for beneficial arthropods, they may also inadvertently support herbivorous insects that act as pests in specific crop contexts (Lavandero et al., 2006; Lundin et al., 2023). Understanding the interactions between floral resources, natural enemies and herbivores is crucial for minimizing trade-offs and maximizing benefits of flower strips. In this regard, flower strip type is also important, where perennial flower strips can offer long-term regrowth and flowering over several years, providing structural resources and undisturbed habitats that increase opportunities for beneficial organisms to find nesting and overwintering sites (Albrecht et al., 2020; Hatt et al., 2020). Emerging research also highlights the potential of perennial flower strips to positively affect belowground biodiversity and ecosystem functions, such as enhancing earthworm and microbial diversity, decomposition rates, and carbon sequestration (Bednar et al., 2023; Harbo et al., 2023; Pelosi et al., 2024; Vaupel et al., 2024). These findings underscore the need for comprehensive evaluations of perennial flower strip impacts across multiple ecosystem services.

This study addresses these gaps by evaluating the multifunctional effects of flower strips and their spillover to adjacent crops. Specifically, we quantify the effects of a perennial flower strip mixture designed for pollinators on (1) pollinator abundance within field margins, (2) natural enemy and herbivore abundance within field margins and their spillover into adjacent cereal fields, (3) biological pest control in adjacent fields, and (4) soil detritivore activity within field margins and in adjacent fields. By doing so, we assess the multifunctionality of flower strips and identify potential trade-offs between ecosystem services and disservices. We hypothesize that (a) perennial flower strips enhance the abundance of pollinators, natural enemies, herbivores and soil detritivore activity within the margins, but (b) these groups will not spillover, (c) leading to a lack of benefits for pest control or soil detritivore activity in adjacent crops. Through this multifaceted approach, this study seeks to provide actionable insights into the ecological and agricultural benefits of flower strips, contributing to the development of sustainable farming systems.

2. Materials and methods

2.1. Study design

We conducted the study during the spring-summer of 2021 in the region of Scania in southernmost Sweden. We studied 10 pairs of sown perennial flower strips and spontaneous vegetation controls located along crop field margins and their adjacent fields. The distance between each flower strip and its paired control ranged from 100 m to 500 m, while the minimum distance between pairs was 1 km to ensure spatial independence. In all but one case, the flower strips and their controls were located within the same crop field; the exception involved a nearby field with the same crop managed by the same farmer. We calculated the proportion of cropland within a 1 km radius of each flower strip or control by analyzing the land uses obtained from the digitalized map layer 'Terrängkartan'(Lantmäteriet, 2018) in ArcMap 10.8.2 (Esri, 2020). The landscapes were dominated by arable land, and the proportions of land use types were comparable between flower strip and control sites (Table S1).

The selected perennial flower strips had been established along the edge of crop fields as part of a Swedish initiative, 'Sweden Blossom', encouraging farmers to dedicate small field areas to promote pollinators (Hushållningssällskapet, 2024). These strips were sown with a perennial seed mixture designed to attract pollinators, consisting of a blend of annual and perennial forbs: *Carum carvi* L. (Apiaceae) (0.05 kg ha^{-1}), *Fagopyrum esculentum* Moench. (Polygonaceae) (0.4 kg ha^{-1}), *Lotus corniculatus* L. (Fabaceae) (0.1 kg ha^{-1}), *Melilotus officinalis* Lam. (Fabaceae) (0.05 kg ha^{-1}), *Phacelia tanacetifolia* Benth. (Hydrophyllaceae) (0.2 kg ha^{-1}), *Trifolium pratense* L. (Fabaceae) (0.1 kg ha^{-1}), and *Trifolium repens* L. (Fabaceae) (0.1 kg ha^{-1}). The established flower strip can remain in the field for at least three years before needing resowing. To minimize heterogeneity, we only surveyed strips in their second year of establishment. The selected strips were on average 485 m long (range: 210 – 730 m) and 1.26 m wide (range: 1 – 1.5 m). We selected the control margins to match as closely as possible with their paired flower strips. Control margins were on average 236 m long (range: 100 – 455 m) and 1.23 m wide (range: 1 – 2 m). Control margins were permanent habitats between two fields, or between fields and road verges, dominated by spontaneously growing grasses and forbs. They were typically managed through mowing, which resulted in lower vegetation height compared to the flower strips. In each field margin type (i.e. flower strip or control) we selected a 100 m long and 1 m wide transect to conduct the surveys.

In the adjacent fields, we set up two parallel 100 m transects, each positioned 10 m from the field margin. Six of the adjacent fields were cultivated with winter wheat (*Triticum aestivum* L.) and four with spring barley (*Hordeum vulgare* L.) (Table S1). All fields were conventionally managed, but an unsprayed buffer, where no foliar applications of insecticides were performed, was maintained along the entire length of the transects. This buffer comprised the 10 m from the field margin to the transect, the transect itself, an additional 10 m into the crop beyond the transect, and 10 m beyond the start and end of the transect. This resulted in a total untreated area which was 20 m wide from the field margin into the crop and 120 m long.

2.2. Vegetation and floral area

To characterize both field margin types, we collected data on vegetation cover and floral resource availability in all of the field margins two times during the main blooming period of the flower mixture, once in June 2021 (9th to 17th) and once in July 2021 (6th to 17th). Vegetation cover and floral area were recorded in eight 0.6×0.6 m quadrats evenly distributed along the 100 m transect. In each quadrat, we estimated the percentage of vegetation cover and counted the number of floral units of each species. For most species, a floral unit was equal to an individual flower, but for Asteraceae and clovers (*Trifolium* spp.) each inflorescence was counted as one unit. To estimate the floral area, we measured the diameter (for actinomorphic or composite flowers) or length and width (for zygomorphic flowers) of three floral units per target species. We then calculated the average floral area per unit for each species and multiplied this by the number of open floral units in each quadrat.

2.3. Pollinators

We observed pollinators in all field margins two times during the main blooming period of the flower mixture, once in June 2021 (9th to 17th) and once in July 2021 (6th to 13th). At each field margin, we observed all flower visitors for 10 min along the 100 m long and 1 m wide transect. We did not perform in-field surveys of pollinators, since our focus crops are neither dependent on, nor providing resources for, pollinators. Each flower visit was recorded as a new visit, regardless of whether it was by the same, or a different, individual. Flower visitors were counted and categorized as honey bees, hoverflies, bumblebees, solitary bees or butterflies (Table S2). Unknown flower visitors were collected with a hand net and frozen for later identification in the laboratory. Observation time was paused for handling of the collected specimens. All surveys were conducted between 9:00 and 17:00, when temperatures were at least 15°C, wind speeds were low (5 m s^{-1} or less), and the sky was at least partly sunny or brightly overcast. To control for potential daily variations, each pair of sown perennial flower strips and spontaneous vegetation controls were surveyed on the same date. The pollinator surveys were always conducted on the same day as the vegetation characterization of the field margins.

2.4. Natural enemies and pests

We sampled natural enemies and pests in all field margins and inside all adjacent fields two times during the main blooming period of the flower mixture, once in June 2021 (8th to 15th) and once in July 2021 (5th to 14th). Leaf-dwelling natural enemies and herbivores were sampled using yellow sticky traps (20 cm×12.6 cm; Silvandersson Sweden AB; Sweden), while ground-dwelling natural enemies were sampled using pitfall traps made from polypropylene beakers (12 cm diameter) with 200 mL of soapy water. We placed four traps of each type along the 100 m transect in the field margins and another four in the adjacent crop area, at 10 m from the margins, for a total of 16 traps per site. Traps were spaced 20 m apart within each transect and remained in the field for seven days. Yellow sticky traps were stored in the freezer and pitfall trap samples were preserved in 70 % ethanol until processing. The taxonomic level and life stages considered for each taxon in both types of traps are specified in Table S3. Due to the large number of samples, we limited the analyses to three randomly selected traps of each type per transect.

We also surveyed the arthropod community present on the crop tillers twice during the main blooming period of the flower mixture, once in June 2021 (10th to 18th) and once in July 2021 (7th to 14th). We counted and identified all arthropods found on four groups of five tillers located along each adjacent crop transect, spaced every 20 m, resulting in 80 crop tillers per site.

2.5. Pest control

We assessed pest control services in adjacent crop fields by estimating aphid predation rates with sentinel prey cards (Boetzl et al., 2020). Live bird cherry-oat aphids, *Rhopalosiphum padi* L. (Hemiptera: Aphididae), were collected from the field in spring and reared on barley plants in the greenhouse. The largest available aphids were then glued alive with egg white onto 2 × 8 cm sandpaper cards (BOSCH 2608606820, grain 120) using a brush. Eight aphids were affixed to each card, leaving 1.5 cm from the lateral edges and 0.5 cm between each aphid and from the front and hind edges. After preparation, the aphid cards were immediately frozen at −20°C and stored for a maximum of 24 h prior to use. In the field, sentinel prey cards were set up at two heights targeting different natural enemy groups: ground level for ground-dwellers and approximately 70 cm height for leaf-dwellers. Ground-level cards were secured with a pin through each of the lateral edges, while leaf-level cards were stapled to crop leaves. Four groups of two cards at ground level and two cards at vegetation level were set up along each adjacent crop transect, spaced every 20 m, resulting in 32 cards per site. This setup followed the same spatial arrangement as the other surveys. Sentinel prey cards were exposed simultaneously during the first sampling interval of the tiller counts in mid-June 2021 (10th to 17th), coinciding with the emergence of inflorescences in spring barley and winter wheat in the region. After 24 h of exposure, the sentinel prey cards were collected, and the remaining aphids were counted.

2.6. Decomposition rate

We estimated the feeding activity of soil detritivores using the bait lamina test (Von Törne, 1990), which provides an indication of decomposition activity by soil organisms such as collembolans, earthworms, enchytraeids and microorganisms. The bait lamina strips consisted of 160 mm × 6 mm × 1.5 mm plastic strips, with 16 holes of 2 mm diameter arranged at 5 mm intervals (terra protecta GmbH, Germany). These holes were filled with a standardized bait mixture of cellulose, wheat bran and activated carbon (ISO 18311–2016). The strips were inserted in the soil with the uppermost hole positioned just beneath the soil surface. Four groups of five bait lamina strips were placed along each 100 m transect, with groups spaced every 20 m, resulting in 80 strips per site. Within each group, strips were spaced 20 cm apart. The bait lamina strips were buried in the ground for 15 days, coinciding with

Table 1
Accumulated counts (N) or averages (A), along with statistical test results for the responses in the field margin habitats. W = Wilcoxon W-statistic value; χ2 = chi-square value from GLMM; p = p-value; * indicates 0.01 < p ≤ 0.05; ** indicates 0.001 < p ≤ 0.01; *** indicates p ≤ 0.001.

	Field margin		Treatment		
Response	Flower strip	Control	Test statistics	p	
Margin characterization					
Proportion of vegetation cover	A = 0.962	A = 0.974	χ2 = 6.16	0.013	*
Total floral area (cm^2 m^{-2})	N = 9226	N = 1120	χ2 = 112.00	**< 0.001**	***
Pollinators					
Bumblebees	N = 197	N = 20	χ2 = 15.54	**< 0.001**	***
Butterflies	N = 22	N = 3			
Honey bees	N = 366	N = 0	W = 95	**< 0.001**	***
Hoverflies	N = 235	N = 102	χ2 = 9.45	0.006	**
Solitary bees	N = 50	N = 28	χ2 = 2.52	0.112	

the end of the surveys (5th to 23th of July 2021). After this exposure period, they were removed, wrapped in aluminium foil, and transported to the laboratory. There, we recorded the number of pierced holes per lamina strip as a measure of soil detritivore feeding activity. This feeding activity was expressed as a decomposition rate by dividing the number of pierced holes by the total number of bait-filled holes.

2.7. Statistical analysis

For all analyses, data were aggregated across all within-transect replicates and sampling rounds, separately for each field margin habitat and its adjacent crop area, to reduce excessive zeros and improve model convergence. Vegetation cover and floral area were averaged, insect counts from sticky traps, pitfall traps, and tiller counts were summed, and predation and decomposition rates were calculated as proportions based on aggregated totals. Arthropod taxonomic groups with fewer than 50 individuals in total and similar ecological roles were pooled into larger taxonomic categories where possible (see Table S3 for details). Butterflies recorded during pollinator observations (Table 1), cereal leaf beetles in the tiller counts (Table 3) and five herbivore groups captured in the yellow sticky traps (Table S3) were excluded from the analysis due to too few occurrences. To characterize field margin habitats and assess the effect of field margin habitat types on pollinator abundance, we fitted generalized linear mixed models (GLMMs). Fixed effects included 'field margin habitat type' (perennial flower strip or spontaneous vegetation control), with field as a random intercept. Response variables included the proportion of vegetation cover (%), total floral area ($cm^2\ m^{-2}$) and the abundance of hoverflies, honey bees, bumblebees, and solitary bees (Table 1). Similar GLMMs were used to evaluate the effects of field margin habitat types and adjacent in-crop areas on arthropod abundance (from yellow sticky and pitfall traps) and decomposition rates (from bait lamina strips). Fixed effects included 'field margin habitat type', 'location' (field margin or adjacent crop area), and 'crop type' (winter wheat or spring barley), along with their two- and three-way interactions. Field was included as a random intercept. Response variables were the abundances of leaf-dwelling spiders, predatory beetles, predatory bugs, lacewings, predatory thrips, hoverflies, parasitic wasps, aphids, thrips, other herbivores, ground-dwelling spiders, carabid beetles, rove beetles, and decomposition rates (Table 2). GLMMs were also used to examine the effects of the field margin habitat type on arthropod groups collected from tiller counts and aphid predation rates from sentinel prey cards. Fixed effects included 'field margin habitat type', 'crop type' and their interaction, with field as a random intercept. Response variables were natural enemies, aphids, thrips, and aphid predation rates by leaf-dwelling and ground-dwelling predators (Table 3). Negative binomial distributions were used for most models. Exceptions included models assessing proportion vegetation cover, decomposition rates and aphid predation rates (leaf- and ground-dwelling), which used a beta-binomial distribution. A shrink transformation was applied to variables bounded between 0 and 1. For vegetation cover, values of exactly 1 were rescaled to 0.999999. For aphid predation rates, we used the transformation $y^*(n-1) + 0.5)/n$ where n is the sample size, following Smithson and Verkuilen (2006). For aphid predation and decomposition, the transformation was applied to handle zero inflation; in the case of proportion of vegetation cover, the transformation ensured that all values fell within the interval required by the beta distribution (larger than zero and lower than one). For honey bees, a non-parametric Wilcoxon signed-rank test was used because the GLMM did not fulfill model assumptions even after applying a shrink transformation due to a large number of zeros. Model validation for distribution appropriateness, overdispersion, underdispersion, and zero inflation was performed using the 'DHARMa' package (version 0.4.7, Hartig, 2025). GLMMs were fitted with the 'glmmTMB' package (version 1.1.10, Brooks et al., 2017). Statistical significance was assessed through Type III Wald χ^2 tests using the 'Anova' function from the 'car' package (version 3.1–3), with marginal contrasts adjusted following

Table 2
Accumulated counts (N) or averages (A), along with test results for the responses in the field margin habitats and corresponding adjacent crop. χ2 = chi-square value; p = p-value; (*) indicates $0.05 < p \le 0.1$; * indicates $0.01 < p \le 0.05$; ** indicates $0.001 < p \le 0.01$; *** indicates $p \le 0.001$. For significant interactions with crop, see the supplementary material (Figure S1 & Figure S2).

	Field margin		Adjacent crop area		Treatment		Crop		Location		Treatment: Crop		Treatment: Location		Crop: Location		Treatment: Crop: Location	
Response	Flower strip	Control	Flower strip	Control	χ2	p	χ2	p	χ2	p	χ2	p	χ2	p	χ2	p	χ2	p
Yellow sticky traps																		
Leaf-dwelling spiders	N = 63	N = 67	N = 81	N = 70	0.53	0.467	3.18	0.074 (*)	0.00	0.955	0.20	0.658	0.72	0.397	2.24	0.134	0.30	0.585
Predatory beetles	N = 215	N = 69	N = 99	N = 76	11.18	**0.001** ***	0.00	0.945	3.01	0.083 (*)	0.12	0.729	2.78	0.095 (*)	0.68	0.411	1.99	0.158
Predatory bugs	N = 106	N = 44	N = 66	N = 45	5.12	**0.024** *	2.37	0.124	0.83	0.362	3.31	0.069 (*)	0.66	0.415	0.10	0.747	0.18	0.668
Lacewings	N = 19	N = 11	N = 13	N = 8	1.53	0.216	2.64	0.104	0.70	0.404	0.03	0.853	0.00	1.000	0.05	0.826	0.38	0.539
Predatory trips	N = 112	N = 69	N = 73	N = 108	0.00	0.973	1.23	0.267	0.01	0.936	0.57	0.450	1.82	0.177	0.16	0.685	0.12	0.730
Hoverflies	N = 1096	N = 1730	N = 2584	N = 2151	0.21	0.646	1.45	0.228	4.43	**0.035** *	0.05	0.824	1.42	0.234	0.02	0.900	1.38	0.240
Parasitic wasps	N = 4403	N = 2475	N = 2189	N = 1813	27.06	**< 0.001** ***	4.92	**0.026** *	33.42	**< 0.001** ***	1.31	0.253	8.46	**0.004** **	5.00	**0.025** *	0.41	0.524
Aphids	N = 565	N = 388	N = 608	N = 544	5.09	**0.024** *	14.58	**< 0.001** ***	1.40	0.237	0.24	0.622	0.56	0.454	1.70	0.193	0.05	0.819
Leafhoppers	N = 67	N = 31	N = 66	N = 31	15.13	**< 0.001** ***	0.17	0.676	0.05	0.817	0.53	0.467	0.21	0.647	0.17	0.679	2.37	0.124
Seed bugs	N = 132	N = 53	N = 109	N = 108	3.07	0.08 (*)	0.14	0.708	0.01	0.94	1.98	0.16	2.02	0.155	4.66	**0.031** *	0.14	0.707
Sap beetles	N = 1112	N = 235	N = 584	N = 710	15.15	**< 0.001** ***	4.57	**0.033** *	0	0.946	0.1	0.751	16.83	**< 0.001** ***	1.08	0.299	0.2	0.658
Psyllids	N = 73	N = 122	N = 11	N = 29	0.45	0.501	4	**0.045** *	7.94	**0.005** **	7.41	**0.006** **	0.33	0.563	0.03	0.861	0.05	0.823
Thrips	N = 15127	N = 6144	N = 14123	N = 10506	17.12	**< 0.001** ***	0.24	0.627	2.39	0.122	2.07	0.150	4.27	**0.039** *	0.01	0.923	0.00	0.961
Pitfall traps																		
Ground-dwelling spiders	N = 1205	N = 685	N = 1022	N = 821	7.30	**0.007** **	0.43	0.513	0.04	0.833	7.75	**0.005** **	1.15	0.283	0.86	0.353	3.65	0.056 (*)
Carabid beetles	N = 1580	N = 574	N = 1008	N = 684	10.01	**0.002** **	0.17	0.683	0.04	0.851	0.05	0.826	1.67	0.197	0.01	0.913	0.97	0.324
Rove beetles	N = 476	N = 205	N = 582	N = 233	13.39	**< 0.001** ***	0.06	0.812	2.35	0.125	0.24	0.623	0.23	0.629	7.48	**0.006** **	2.46	0.117
Bait lamina test																		
Decomposition rate	A = 0.467	A = 0.545	A = 0.433	A = 0.311	0.47	0.492	1.01	0.314	8.95	**0.003** **	0.69	0.407	3.47	0.062 (*)	0.88	0.348	0.2	0.652

Table 3
Accumulated counts (N) or averages (A), along with statistical test results for the responses in adjacent crop. χ2 = chi-square value; p = p-value; (*) indicates 0.05 < p ≤ 0.1; * indicates 0.01 < p ≤ 0.05; ** indicates 0.001 < p ≤ 0.01; *** indicates p ≤ 0.001. For significant interactions with crop, see the supplementary material (Figure S3).

Model	Adjacent crop area		Treatment			Crop			Treatment: Crop		
	Flower strip	Control	χ2	p		χ2	p		χ2	p	
Tiller counts											
Natural enemies	N = 32	N = 26	0.17	0.679		0.34	0.560		0.17	0.679	
Aphids	N = 122	N = 115	2.72	0.099	(*)	5.14	**0.023**	*	31.22	**< 0.001**	***
Cereal leaf beetles	N = 19	N = 28									
Thrips	N = 285	N = 208	11.68	**0.001**	***	0.04	0.844		0.05	0.821	
Sentinel prey cards											
Aphid predation rates by leaf-dwellers	A = 0.096	A = 0.094	0.33	0.568		9.78	**0.002**	**	2.87	0.090	(*)
Aphid predation rates by ground-dwellers	A = 0.139	A = 0.256	2.46	0.117		4.73	**0.030**	*	1.26	0.263	

Al-Sarraj (2023). Post-hoc tests were performed to evaluate significant interactions between fixed effects (package *emmeans*, Lenth, 2025), with pairwise comparisons adjusted for multiple testing using Tukey's method. All analyses were conducted in R 4.4.2 (R Development Core Team, 2024).

3. Results

3.1. Vegetation and floral area

The proportion of vegetation cover was slightly lower in the flower strips than in the spontaneous vegetation controls (flower strip: 0.95, 95 % confidence interval (CI): 0.91 – 0.98; control: 0.98, 95 % CI: 0.96 – 0.99), while the average floral area per m^2 was approximately 8 times higher in the flower strips than in the controls (flower strip: 863 cm^2 m^{-2}, 95 % CI: 614 – 1212; control: 109 cm^2 m^{-2}, 95 % CI: 77 – 152) (Fig. 1, Table 1). Most of the floral area in the flower strips was provided by *P. tanacetifolia* and *Tripleurospermum inodorum* (L.) Sch. Bip (Asteraceae), while in the controls most of the floral area was provided by *Anthriscus sylvestris* (L.) Hoffm. (Apiaceae) and *Achillea millefolium* L. (Asteraceae) (Table S4).

3.2. Pollinators

The pollinator community was dominated by honey bees (36 %) and hoverflies (33 %), followed by bumblebees (21 %), solitary bees (8 %) and butterflies (2 %). All of the analysed pollinator groups, except solitary bees (flower strip: 3.18 individuals per 200 m^2, 95 % CI: 1.03 – 9.483; control: 1.28 individuals, 95 % CI: 0.37 – 4.43), were significantly more abundant in the flower strips compared to the spontaneous vegetation controls (Fig. 1, Table 1). The abundance of hoverflies was 2.8 times higher in the flower strips compared to the controls (flower strip: 23.30 individuals per 200 m^2, 95 % CI: 13.79 – 39.17; control: 8.17, 95 % CI: 4.40 – 15.17) and almost 10 times higher for bumblebees (flower strip: 20.39 individuals per 200 m^2, 95 % CI: 10.60 – 39.22; control: 1.70, 95 % CI: 0.62 – 4.64) (Fig. 1, Table 1). In the flower strips, 366 honeybees were observed while none were observed in the spontaneous vegetation controls (Fig. 1, Table 1).

3.3. Natural enemies and pests

Specimens identified on yellow sticky traps were dominated by thrips (64 %), followed by parasitic wasps (15 %), hoverflies (11 %), sap beetles (4 %) and aphids (3 %). Leaf-dwelling predatory spiders, predatory beetles, predatory bugs, lacewings and predatory thrips were the least abundant, contributing to 2 % of the captures. Leafhoppers, seeds bugs and psyllids contributed to the remaining 1 % (Table 2).

Among natural enemies on yellow sticky traps, abundances of leaf-dwelling predatory beetles (Fig. 2B) and predatory bugs (Fig. 2C) were approximately 2 times higher in the perennial flower strip areas, both in the field margin and in the adjacent crop, than in the control areas. Hoverflies (Fig. 2F) were 1.48 times more abundant within the

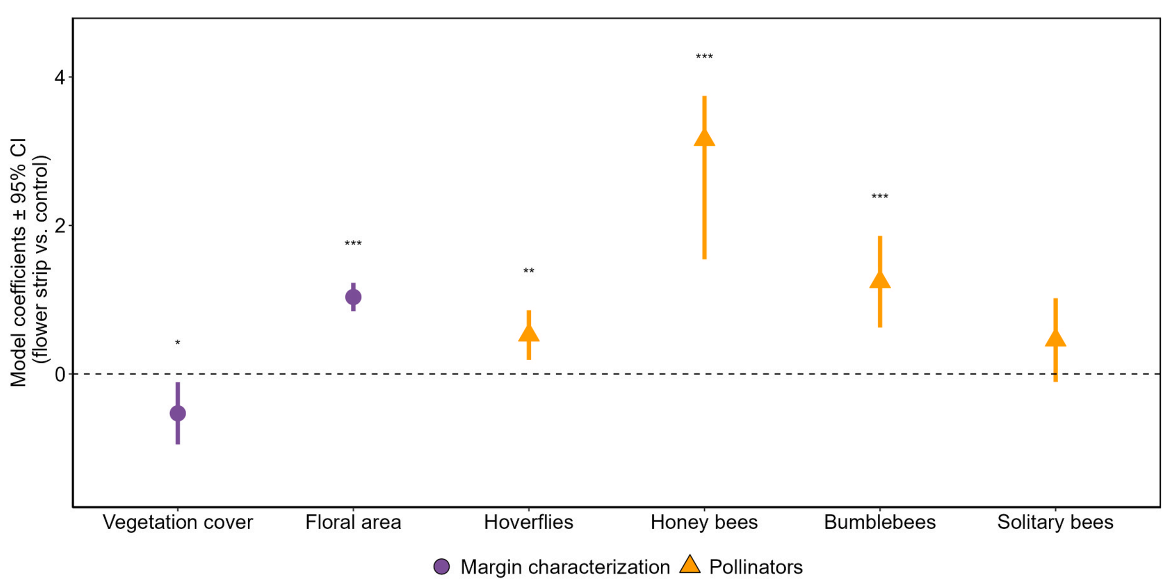

Fig. 1. Model coefficients (±95 % confidence intervals) comparing the flower strip with the control field margin (positive values indicate the response is higher in the flower strip than in the control field margin) for margin characterization and pollinator responses. * indicates 0.01 < p ≤ 0.05; ** indicates 0.001 < p ≤ 0.01; *** indicates p ≤ 0.001. Colors and symbols indicate different methods (see legend). For statistics, see Table 1.

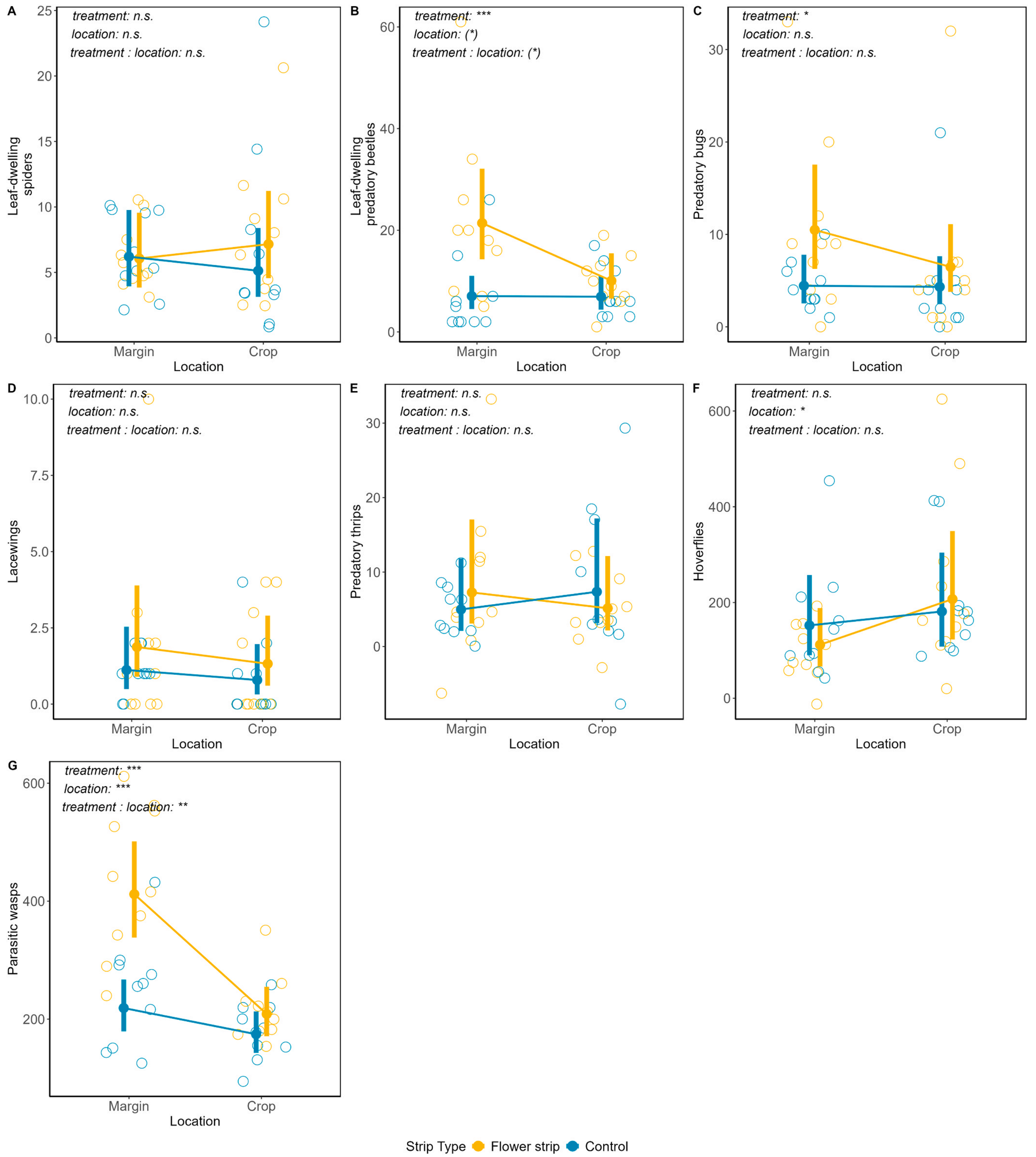

Fig. 2. Predicted densities of arthropod natural enemy groups in margins (flower strip and control field margins) and crop fields (10 m); (A) leaf-dwelling spiders, (B) leaf-dwelling predatory beetles, (C) predatory bugs, (D) lacewings, (E) predatory thrips, (F) hoverflies, and (G) parasitic wasps captured in the yellow sticky traps. Estimates are individuals per 6 sticky traps and are based on estimated marginal means with 95 % confidence intervals. Open symbols represent partial residuals. Colors indicate adjacent margin treatments (yellow: flower strip; blue: control margin; see legend). n.s. indicates $p > 0.1$; (*) indicates $0.05 < p \leq 0.1$; * indicates $0.01 < p \leq 0.05$; ** indicates $0.001 < p \leq 0.01$; *** indicates $p \leq 0.001$. For statistics, see Table 2.

adjacent fields compared to the margins, regardless of the treatment. Parasitic wasps (Fig. 2G) were about 1.88 times more abundant in the flower strip margins relative to the spontaneous vegetation control margins; however, for this group, no significant differences were observed between treatments at 10 m within the crop field. Leaf-dwelling spiders, lacewings, and predatory thrips were not affected by either flower strip treatment, location (margin or crop field) or its interaction (Fig. 2A, D, E).

Among herbivores on yellow sticky traps, aphids and leafhoppers were 1.32 and 2 times more abundant in the perennial flower strip areas,

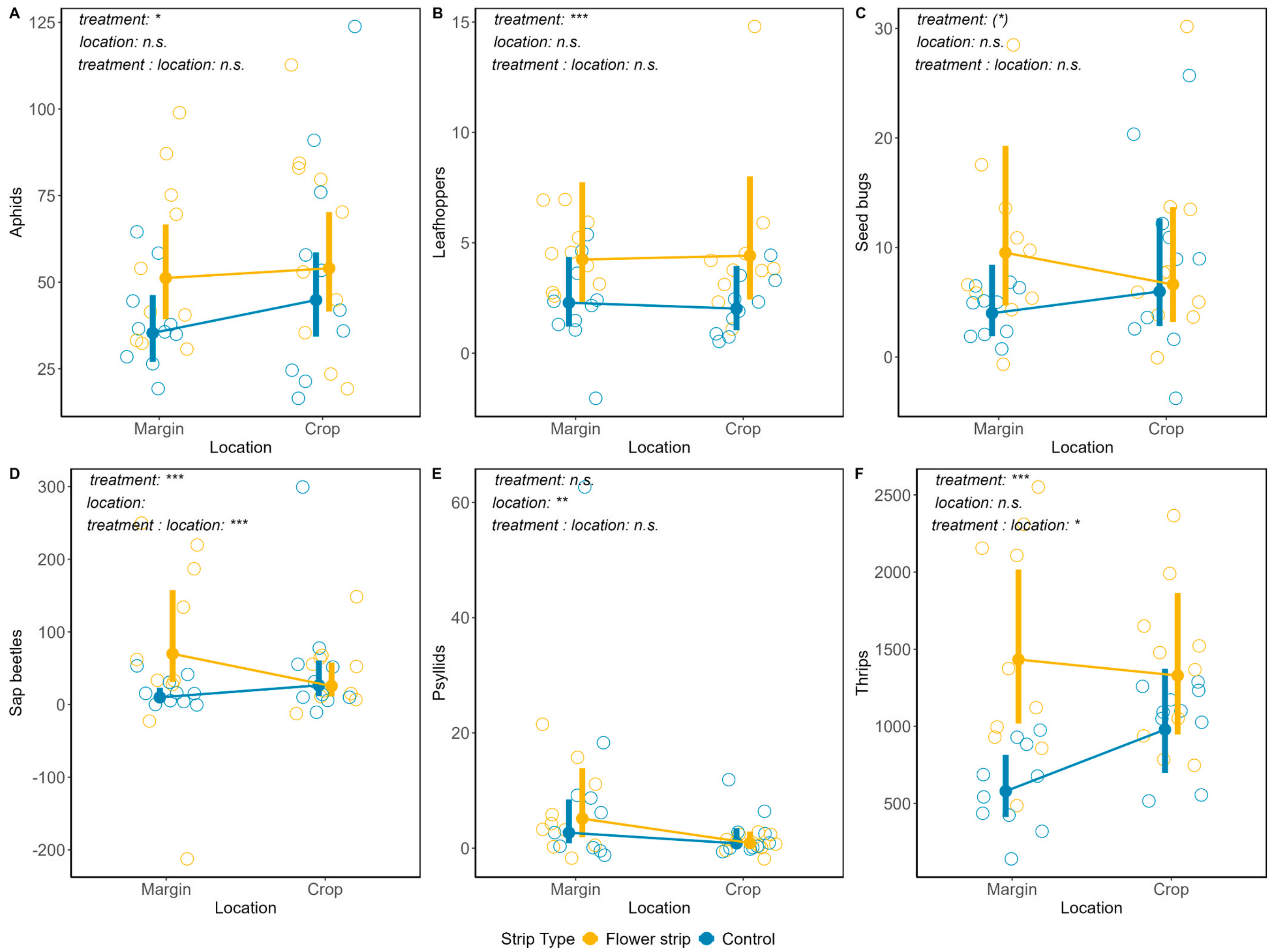

Fig. 3. Predicted densities of arthropod herbivore groups in margins (flower strip and control field margins) and crop fields (10 m); (A) aphids, (B) leafhoppers, (C) seed bugs, (D) sap beetles, (E) psyllids, and (F) thrips, captured in the yellow sticky traps. Estimates are individuals per 6 sticky traps and are based on estimated marginal means with 95 % confidence intervals. Open symbols represent partial residuals. Colors indicate adjacent margin treatments (yellow: flower strip; blue: control margin; see legend). n.s. indicates $p > 0.1$; (*) indicates $0.05 < p \leq 0.1$; * indicates $0.01 < p \leq 0.05$; ** indicates $0.001 < p \leq 0.01$; *** indicates $p \leq 0.001$. For statistics, see Table 2.

both in the field margin and in the adjacent crop, compared to the control areas, respectively (Fig. 3A, B). Seed bugs were not affected by either flower strip treatment, location or its interaction (Fig. 3C). Sap beetles were 7 times more abundant in the flower strip margins than in the controls, but there were no significant differences in the adjacent crop areas (Fig. 3D). Psyllids were 4.21 times more abundant in the margins than in the adjacent crop areas regardless of treatment (Fig. 3E). The interaction between flower strip treatment and crop type was significant for psyllids, where the number of psyllids was higher in winter wheat than in spring barley but only in the control areas, including both margin and adjacent crop (Figure S1A; Table 2). Thrips were 2.47 times more abundant in the perennial flower strip margins compared to the controls, but there were no significant differences in the adjacent crop areas (Fig. 3F).

Ground-dwelling natural enemy predators in pitfall traps were dominated by carabid beetles (42 %) and spiders (41 %) followed by rove beetles (16 %) (Table 2). All three ground-dwelling natural enemy groups were more abundant in the flower strip area compared to the control areas, with 1.38 more ground-dwelling spiders (Fig. 4A) and approximately 2 times as many carabid beetles (Fig. 4B) and rove beetles in the flower strip areas, including both the field margin and adjacent crop (Fig. 4C). The interaction between flower strip treatment and crop type was significant for ground-dwelling spiders, where the number of spiders was 1.92 times higher in the flower strip area than in the control area for winter wheat, but there were non-significant differences in spring barley (Figure S1B; Table 2).

Tiller count observations were dominated by thrips (59 %), followed by aphids (28 %), natural enemies (7 %) and cereal leaf beetles (6 %) (Table 3). The natural enemies observed included parasitic wasps, hoverflies, spiders, mirids, staphylinids, lacewings, predatory thrips, and coccinellids. No statistically significant differences were observed for natural enemies (flower strip: 3.03 individuals per 80 tillers, 95 % CI: 1.79–5.12; control: 2.58, 95 % CI: 1.50–4.43) or aphids (flower strip: 7.37 individuals per 80 tillers, 95 % CI: 3.74 – 14.51; control: 5.81, 95 % CI: 2.92 – 11.58). However, the interaction between flower strip treatment and crop type was significant for aphids (Table 3), where the number of aphids was higher in the flower strip area than in the control area for winter wheat but lower in the flower strip area than in the control area for spring barley (Figure S2). Thrips were 1.37 times more abundant on tillers in the field adjacent to flower strips than to spontaneous vegetation controls (flower strips: 27.43 individuals per 80 tillers, 95 % CI: 22.02–34.17; control: 19.94, 95 % CI: 15.82 – 25.14) (Fig. 5, Table 3).

Significant effects of 'crop type' (winter wheat or spring barley) and the interaction between crop type and 'location' (field margin or adjacent crop area), are shown in Table S5 and Figure S3, respectively.

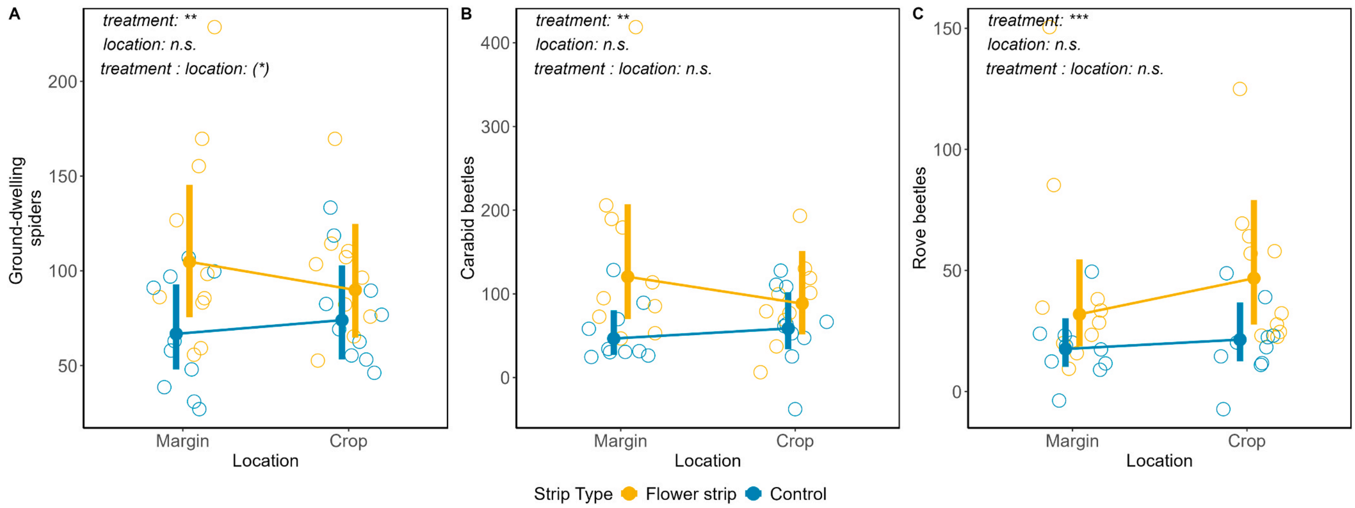

Fig. 4. Predicted densities of natural enemy arthropod groups in margins (flower strip and control field margins) and crop fields (10 m); (A) ground-dwelling spiders, (B) carabid beetles, and (C) rove beetles captured in the pitfall traps. Estimates are individuals per 6 pitfall traps and are based on estimated marginal means with 95 % confidence intervals. Open symbols represent partial residuals. Colors indicate adjacent margin treatments (yellow: flower strip; blue: control margin; see legend. n.s. indicates $p > 0.1$; (*) indicates $0.05 < p \leq 0.1$; * indicates $0.01 < p \leq 0.05$; ** indicates $0.001 < p \leq 0.01$; *** indicates $p \leq 0.001$. For statistics, see Table 2.

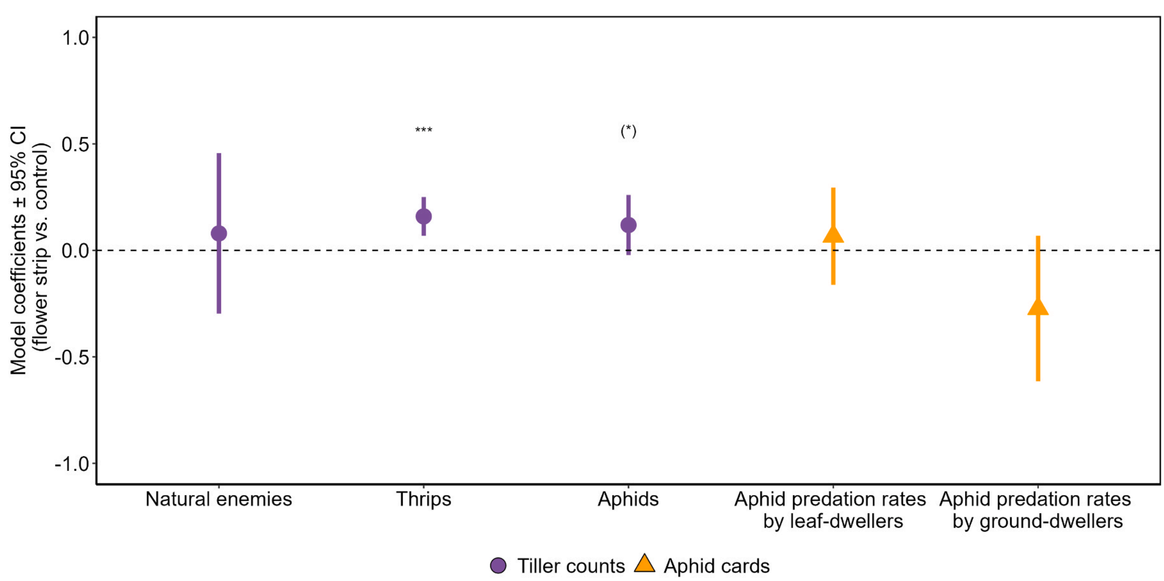

Fig. 5. Model coefficients (±95 % confidence intervals) for the flower strip compared with control field margin (positive values indicate the response is higher in the flower strip than in the control field margin) for tiller counts and aphid cards responses. (*) indicates $0.05 < p \leq 0.1$; *** indicates $p \leq 0.001$. Colors and symbols indicate different methods (see legend). For statistics, see Table 3.

3.4. Pest control

The average percentage of aphids predated did not differ between treatments on leaf cards (flower strip: 8.06 % aphids predated, 95 % CI: 4.80–13.23; control: 6.64 % aphids predated; 95 % CI: 3.73–11.55) or ground cards (flower strip: 13.19 % aphids predated, 95 % CI: 8.1 % - 20.76; control: 20.93 % aphids predated, 95 % CI: 13.92–30.24) (Fig. 5, Table 3).

3.5. Decomposition rate

The decomposition rate was approximately 1.39 times higher in the field margins compared to the area at 10 m within the field, but was similar between the perennial flower strip and the control areas (Fig. 6, Table 2).

4. Discussion

Our multifaceted approach showed that there is potential to affect multiple ecosystem service providers by implementing flower strips in agroecosystems. Perennial flower strips designed to attract pollinators in agroecosystems do enhance pollinator abundances within the strips relative to control field edges with spontaneous vegetation. Though the effects were taxon-specific, many groups of natural enemies had higher abundance in the perennial flower strips relative to the controls. Although most natural enemy groups that benefitted from the perennial flower strips also spilled over into and had higher abundances in the crop fields adjacent to the flower strips, this did not translate into increased pest control as measured as pest counts on tillers and sentinel pest cards. Additionally, we noted an undesirable trade-off, as herbivorous thrips were 1.37 times more abundant on crop tillers near the

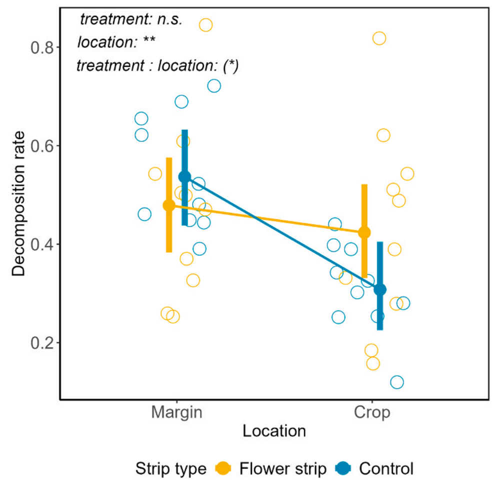

Fig. 6. Predicted average decomposition rate per 20 bait lamina strips in margins (flower strip and control field margins) and crop fields (10 m from the margins) obtained by the bait lamina test. Estimates are based on estimated marginal means with 95 % confidence intervals. Open symbols represent partial residuals. Colors indicate adjacent margin treatments (yellow: flower strip; blue: control margin; see legend). n.s. indicates $p > 0.1$; (*) indicates $0.05 < p \leq 0.1$; ** indicates $0.001 < p \leq 0.01$. For statistics, see Table 2.

flower strips. Further, decomposition rates were enhanced relative to the adjacent crop and reached levels similar to the permanent field edges within only a year from establishment.

Pollinators, including hoverflies, honey bees and bumblebees were consistently more abundant in the perennial flower strips than in the spontaneous vegetation controls. A similar, but non-significant, trend was also observed for solitary bees. This increase is likely due to the additional floral and nesting resources provided by the perennial flower strips, which have been shown to support pollinator populations and offer long-term conservation benefits (Jönsson et al., 2015; Bommarco et al., 2021). Flower plantings generally have strong positive effects on pollinator abundance and richness within the plantings themselves (Haaland et al., 2011; Uyttenbroeck et al., 2016; Albrecht et al., 2020; Zamorano et al., 2020). Specifically, the substantial increase in overall flower availability in our study —approximately 8 times more in flower strips compared to control margins— may have contributed to greater floral resource provisioning. These results highlight the role of perennial flower strips in supporting pollinators in agricultural landscapes, emphasizing the need for their strategic design to maximize ecological benefits.

Leaf- and ground-dwelling natural enemies captured in yellow sticky and pitfall traps responded in a taxon-specific manner, with all natural enemy taxa either being equal to or more abundant in perennial flower strips compared to spontaneous vegetation controls. While leaf-dwelling predatory beetles, predatory bugs, parasitic wasps and ground-dwelling spiders, carabid beetles, and rove beetles were more abundant in flower strip margins, the presence of flower strips had no effect on the abundances of leaf-dwelling spiders, lacewings, predatory thrips, or hoverflies. The variation in taxon responses might be driven by factors such as floral resource availability, alternative prey availability, or the temporal continuity of habitat provision, including overwintering opportunities (Blümel et al., 2024). Many natural enemies rely on floral resources, such as nectar and pollen, to complete their life cycle or to sustain themselves during prey shortages. For instance, most adult parasitic wasps require floral resources to enhance their longevity and reproductive success, while lady beetles (Coccinellidae) and flower bugs (Anthocoridae) benefit from supplementary floral feeding (Wäckers and van Rijn, 2012). The taxon-specific responses observed in our study align with previous research on flower strip effects, which has similarly found that different functional groups respond in distinct ways to habitat manipulations (Boetzl et al., 2021; Lundin et al., 2023; Blümel et al., 2024). These findings underscore the importance of considering species-specific ecological requirements when designing flower strips to maximize natural enemy benefits in agroecosystems.

Spillover effects were evident; all natural enemy taxa, except parasitic wasps, which showed increased abundances in the perennial flower strip margins also exhibited higher abundances 10 m into the adjacent crops. While evidence shows that flower plantings enhance natural enemies within the margin habitats, evidence of natural enemy or biological control spillover is more variable (Albrecht et al., 2020; Jachowicz and Sigsgaard, 2025). This variability might be partly explained by the fact that spillover effects tend to weaken with increasing distance from the field margin, and vary depending on arthropod functional traits such as mobility, resource dependence, or habitat preferences (Martin et al., 2019). Nevertheless, it is noteworthy that natural enemy abundances were not lower in the crop areas adjacent to the flower strips, suggesting that the strips did not deplete natural enemies from the crop by aggregating them at the floral margins (Tscharntke et al., 2016). Despite being conducted only a year after the establishment of the flower strips, our study aligns with previous findings that indicate robust short-term effects of flower strips on pollinators and natural enemies (Albrecht et al., 2020; Lowe et al., 2021; Jachowicz and Sigsgaard, 2025). However, longer-term monitoring is essential to discern interannual variability in environmental conditions and insect population dynamics and hence properly evaluate potential temporal trade-offs and long-term ecological benefits. A further consideration is the relatively limited sample size of ten fields, which may have constrained our ability to detect effects of the perennial flower strip in certain groups, particularly solitary bees and less abundant natural enemy taxa.

Herbivores, including aphids and thrips, captured in yellow sticky traps were more abundant in the flower strips than in the controls. Taxon-specific responses were also noted, with aphids showing higher abundances in traps placed in crop areas adjacent to flower strips, whereas thrips levels remained similar in the crop regardless of treatment. Similar to natural enemies, herbivores likely benefited from the additional resources in the flower strips, such as floral rewards or alternative host plants. Consistent with this, other studies have reported increased herbivore abundances in flower strips (e.g. Lavandero et al., 2006, Lundin et al., 2023; but see Jachowicz and Sigsgaard, 2025), although this is not always translated into increased pest pressure in the adjacent crops. In this regard, the increased aphid captures in both flower strips and adjacent fields, are likely due to a greater diversity of aphid species, that are supported by the established plant species but not necessarily pests of the adjacent crop, such as the pea aphid (*Acyrthosiphon pisum* Harris) feeding on red and white clover. Species identifications of aphids would be needed to corroborate this hypothesis, but that was beyond the scope of our study and represents a limitation in interpreting the observed increase in aphids as a potential trade-off. Without taxonomic resolution, it remains uncertain whether the captured aphids were crop pests or non-pest species. Hence, complete and precise taxonomic identification and context-specific categorization of organisms as beneficial or detrimental is highly relevant to effectively avoid unintended consequences of implementation of flower strips.

The effect of the strip treatment on arthropod abundances was generally consistent across spring barley and winter wheat, with a few exceptions. Ground-dwelling spiders in the pitfall traps were more abundant in the flower strips areas only next to winter wheat. This is likely due to differences in spider recolonization of arable fields, which is family-specific and influenced by habitat structure (Öberg et al., 2008). As a result, different spider communities were present in spring barley and winter wheat. Thus, the increased resources and habitat complexity provided by the flower strip (Mei et al., 2021) facilitated spider population buildup in winter wheat, while the existing spider community in spring barley was less responsive. In contrast, aphids were less abundant on spring barley tillers adjacent to flower strips, but more abundant on winter wheat. The flower strip in spring barley provided additional overwintering and food sources for natural enemies (Landis et al., 2000), contributing to reduced aphid numbers. However, winter wheat's earlier establishment might have already provided similar resources, including overwintering habitats for natural enemies (Bannwart et al., 2025) and alternative prey such as the English grain aphid (*Sitobion avenae* Fabricius), a significant pest of cereals. As a result, the flower strip might have been temporarily competing with the crop in winter wheat by providing for example more preferred prey for natural enemies than the crop (Tscharntke et al., 2016), hence potentially leading to increased aphid numbers. These differences emphasize the complexity of promoting biological control and underscore the importance of context-specific strategies.

Pest control did not increase in the crop areas adjacent to the perennial flower strips, as indicated by pest counts on crop tillers and aphid predation rates on sentinel prey cards. The lack of increased pest control in our study suggests that the spillover of natural enemies from the flower strips into adjacent crops was insufficient to enhance pest suppression. An important limitation in our study is the sentinel prey method used, which in our case consisted of dead aphids: assessing alive prey (Boetzl et al., 2020), or alternative prey species (Eubanks and Denno, 2000) could have resulted in different outcomes. Outcomes regarding the enhancement of pest control by flower strips in cereal crops are highly variable and strongly context dependent. Some studies have reported a significant reduction in cereal leaf beetle (*Oulema* sp.) densities in fields with flower strips compared with control fields (Tschumi et al., 2015, 2016), while others have not found such an effect (Rodenwald et al., 2023). Similarly, aphid control has been observed to improve closer to flower strips, as indicated by higher aphid mummy densities within wheat plots at 5 m distance from the strips (Magagnoli et al., 2024). However, other research has reported no significant effect of flower strips on predation rates of aphids (Mansion-Vaquié et al., 2017; Pollier et al., 2018; Rodenwald et al., 2023), plasticine caterpillars (Mansion-Vaquié et al., 2017) or parasitism on sentinel stink bug eggs (Lundin et al., 2023). This variability likely arises from differences in factors such as flower strip composition, crop identity, pest targeted or surrounding habitat composition.

Notably, we observed increased numbers of thrips in crop tillers close to the sown flower strips, suggesting that flower strips may not only fail to enhance pest control but could also introduce unintended trade-offs. The added floral resources likely facilitated this increase, providing resources not only to beneficial arthropods, but also to flower-dwelling thrips present in our study. These thrips often feed on pollen and nectar and use flowers as reproductive sites, which could explain their increased abundance near the flower strips (Mound, 2009). Furthermore, some of these flower-feeding thrips are major crop pests, like many species in the genera *Thrips* and *Frankliniella* (Mound, 2009). In line with this, on crop tillers in our study we identified *Frankliniella tenuicornis* (Uzel) together with *Limothrips denticornis* (Haliday) and *Limothrips cerealium* (Haliday), suggesting that the floral resources may have facilitated their presence. For instance, previous studies have documented preferences of other *Frankliniella* species for flowers of *T. pratense* (Northfield et al., 2008; Canovas et al., 2023), one of the species included in the perennial flower mixture, where its total floral area was over 160 times greater compared to the controls. To our knowledge, there are no previous reports specifically investigating the control of thrips in cereal crops using flower strips. However, the role of floral resources in thrips management has been explored in other crops, such as blueberry (Walton and Isaacs, 2011), strawberry (Canovas et al., 2023), onion (Gagnon et al., 2024), or fruit orchards (Denis et al., 2021). While common thrips predators include lady beetles, predatory bugs, lacewings, hoverflies, and predatory thrips, and the abundance of some of these groups increased both within the flower strip and in the adjacent crop, this did not appear to be sufficient to suppress their populations. Understanding the interactions between pests, such as thrips, their natural enemies and preferred flora is crucial for improving biological control strategies and optimizing the ecological functions of flower strips in agroecosystems, ensuring they provide maximum benefits while minimizing potential drawbacks. Additionally, although thrips abundances were higher in crop areas adjacent to flower strips, the observed densities (approximately 0.34 individuals per tiller in flower strips and 0.25 in controls) remained below the established economic thresholds of 0.5–1 individuals per tiller in barley or 1–2 individuals in wheat (Swedish Board of Agriculture, 2025). Despite the observed increase in the number of thrips the likelihood of actual crop damage remains low, and our findings not only warrant further monitoring but also demonstrate that while biodiversity-based measures can provide multiple benefits, they may also create pest-related trade-offs that must be carefully managed in specific contexts.

Decomposition rates were higher in the field margins than in the adjacent field areas, regardless of the treatment. Avoiding tillage is well-known to benefit several groups of soil organisms, including arbuscular mycorrhizal fungi, earthworms, microarthropods and soil microbial biomass (Bender et al., 2016). Thus, the higher decomposition rates in the spontaneous field margins compared to the adjacent tilled fields can be explained by the absence of soil disturbance, allowing decomposer communities to establish and persist over time. Notably, decomposition rates in the flower strip margins were comparable to those in the spontaneous vegetation margins, despite the fact that the flower strips were tilled one year prior for their establishment. This suggests that the composition of the flower strips facilitated the rapid recovery of soil fauna, including earthworms and microbial communities, leading to decomposition rates similar to that of permanent field margins. Grassy field margins, annual flower strips, and perennial flower strips harbour distinct earthworm and soil microbial communities, contributing to differences in decomposition dynamics (Bednar et al., 2023). Perennial flower strips, in particular, have been found to strongly promote earthworm populations and serve as refuge for decomposers (Bednar et al., 2023; Vaupel et al., 2024), contributing to improved soil structure, nutrient cycling and overall soil health compared to croplands (Vaupel et al., 2024). This underscores the role of perennial strips in enhancing ecosystem functioning in agricultural landscapes and the importance of incorporating below-ground components into the assessment of ecosystem services provided by flower strips to gain a more comprehensive understanding of their ecological benefits.

5. Conclusions

Our findings show that perennial flower strips support both pollinators and natural enemies, with spillover effects extending into adjacent crops. However, their effects were highly taxon-specific and counterbalanced by unexpected trade-offs, including increased abundance of thrips on the cereal tillers (however, levels still remained below the economic threshold) and a lack of measurable enhancement of pest control. Decomposition rates were similar in flower strips and spontaneous vegetation field margins and higher compared to in the adjacent crop field, despite recent flower strip establishment, suggesting a positive contribution of the strips to soil functioning. These findings underscore the multifunctionality potential of flower strips in agroecosystems while also highlighting the need for careful design and management to maximize their services and mitigate unintended drawbacks, emphasizing the context-dependent nature of agroecological interventions. Future research should explore how plant species composition, landscape complexity, and habitat management influence the balance between pollination, pest regulation, and soil functioning services provided by flower strips.

CRediT authorship contribution statement

Johan A. Stenberg: Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Elodie Chapurlat:** Writing – review & editing, Methodology, Investigation. **Maria Viketoft:** Writing

– review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Neus Rodríguez-Gasol:** Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ola Lundin:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Mattias Jonsson:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

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.2025.110025.

Data availability

Data are publicly available from the Swedish National Data Service (Svensk nationell datatjänst): https://doi.org/10.5878/38na-y098.

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