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Distance-associated responses of arthropod communities to flower strips in contrasting agroecosystems

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Flower strips have been proposed as a strategy to enhance biodiversity and support beneficial arthropods in intensive farming systems; however, evidence of their effectiveness under Mexican conditions remains scarce. We evaluated the effects of flower strips on arthropod diversity at field margin and adjacent crop areas in two contrasting agroecosystems in Mexico: El Batán (maize) and CENEB (wheat), each comprising a single field. A flower strip was established along one field margin, and arthropods were sampled over three years using malaise traps placed within the flower strip and at site-specific distances into the adjacent crop fields, reflecting differences in field width. Arthropods abundance and richness of taxonomic and functional groups at each distance were analyzed using generalized linear mixed models, with contrast comparation against the farthest in-field distance at each site (112 m in El Batán and 200 m in CENEB). Arthropod responses differed strongly between sites, with non-linear distance patterns at El Batán and predominantly linear declines at CENEB. Across both sites, more than 980,000 arthropods representing over 170 taxonomic groups were collected. Total arthropod abundance and richness were significantly higher in the flower strip. At El Batán, 35% of total captures were recorded in the flower strips, with most of taxonomic groups showing significant increases. At CENEB, 28% of catches were recorded in the flower strips, with fewer taxonomic groups showing substantial increases. Functional groups, including both biological control agents and potential pest species, increased within the flower strip at both sites, although only a short-range spillover into crop fields detected at El Batán, varying seasonally. Overall, flower strips enhanced arthropod diversity at field margins while effects within crops were generally localized and context-dependent, emphasizing the importance of strategic design and placement to maximize ecological benefits in intensively managed agroecosystems.

KEYWORDS
diversity, field margins, functional groups, malaise traps, spillover

1 Introduction

Worldwide, more than 700 million hectares are allocated to cereal crop production, with maize and wheat being the most extensively cultivated, comprising approximately 14 and 15%, respectively, of the total cultivated area (FAO, 2024). These crops are typically grown in large-scale monocultures, characterized by intensive tillage and the application of chemical crop protection and synthetic fertilizers. While these farming practices effectively maximize yields (Woodcock et al., 2025) they have been linked to a decline in arthropod diversity, which in turn compromises critical ecosystem services essential for sustaining agricultural productivity, such as pollination, pest control, and nutrient cycling (Altieri et al., 2024; Gurr et al., 2017; Peris-Felipo et al., 2025). In recent decades, increasing concern has arisen over biodiversity decline, with landscape simplification recognized as a key driver of insect decline and pest outbreaks (Altieri et al., 2024; Nichols et al., 2022; Ziesche et al., 2024).

Efforts to restore plant diversity at various spatial scales have been a cornerstone strategy for mitigating the loss of ecological service-providing organisms, such as beneficial insects and soil biota (Altieri et al., 2024; Brittain et al., 2022; Gurr et al., 2017; Jaworski et al., 2023). These efforts often involve practices such as crop rotations, planting flower strips, establishing hedgerows, and managing field margins. However, implementing such diversity-promoting practices typically requires additional investment in labor, seeds, targeted crop protection measures and may reduce the area of productive cropland, thereby creating barriers to voluntary adoption (Jaworski et al., 2023; Woodcock et al., 2025).

To overcome these limitations, some proposals include designating low-yield areas for biodiversity conservation without significant yield losses or improving existing biodiversity reservoirs (Knapp et al., 2023; Rodenwald et al., 2023; Woodcock et al., 2025). Field margins have been used to demarcate land ownership or as fences and frequently host a diverse array of plant species and their associated fauna (Jachowicz and Sigsgaard, 2025; Rodenwald et al., 2023). Many species inhabiting these margins disperse into adjacent crop fields through a process known as spillover (Boetzl et al., 2020; Rodenwald et al., 2023). Diversity-promoting practicescould be designed to harness this effect to enhance ecosystem services in intensively cropped areas (Jachowicz and Sigsgaard, 2025; Lundin et al., 2023; Rodenwald et al., 2023).

In this sense, regions with high biological richness stand to benefit the most from biodiversity-friendly agricultural practices, whose effectiveness is often shaped by the surrounding landscape context (Albrecht et al., 2020; Boetzl et al., 2020; Haenke et al., 2009; Hussain et al., 2023). Mexico is globally recognized as a megadiverse country, harboring high species richness and endemism across several taxa, although biodiversity is unevenly distributed among two regions (Morrone and Márquez, 2008). This regional heterogeneity highlights the need for context-specific evaluations of biodiversity-promoting practices within agricultural systems. However, aside from some studies demonstrating biodiversity's role in biological pest control, the potential benefits of improved biodiversity remain poorly understood in Mexico, especially in annual crops (Aluja et al., 2014; Cortez-Madrigal and Gutiérrez-Cárdenas, 2023).

This study aimed to evaluate the effects of establishing a flower strip along a single field margin on arthropod diversity and its spatial attenuation into adjacent maize and wheat fields in two contrasting agroecological regions of Mexico. We hypothesized that increased floral resources would enhance arthropod diversity at flower strip margins and potentially into nearby crop areas, with responses varying among functional groups.

2 Materials and methods

2.1 Areas of study

Two experiments were conducted in contrasting agro-ecological regions of Mexico, using similar methodologies and objectives. One experiment was established at CIMMYT experimental station El Batán, in Central Mexico with maize, while the other was conducted at the CENEB Experimental station in northwestern Mexico with wheat (Supplementary Figure S1). At each site, the experiment was conducted in a single experimental field adjacent to a flower strip. The field size was approximately 1.3 ha at El Batán and 2.9 ha at CENEB. In both cases, the cereal crop was planted adjacent to a flower strip, and the abundance and richness of arthropod were quantified at increasing distances from the flower strip.

2.1.1 El Batán experimental site

The experiment was conducted from May 2021 to December 2023 at El Batán experimental station in Texcoco, State of Mexico, Mexico (19°31 N, 98° 50 W, elevation 2,240 m). The average annual temperature is 15.6 °C, and the average annual rainfall is 614 mm. The most precipitation falls in summer, whereas winters are dry with occasional frost. On the experimental station, maize and wheat are the dominant crops, with some fields cultivated with sunflower, alfalfa, or rapeseed. The surrounding landscape consists of urban areas, interspersed with small-scale farms and remnants of pine-oak or pure pine forests (Hernández-Villa et al., 2020).

The flower strip was planted or renovated each year in early May and consisted of four beds, each 0.75 m wide (total width = 3 m) and 105 m long, in a single field margin. Plant species were grouped into perennials or annuals and then arranged according to growth height, with shorter species placed adjacent to the crop row. Perennial species were planted in a single row, whereas annual species occupied the remaining rows; within each row, species were interspersed (Table 1; Figure 1). In 2021, all species were established by transplanting individuals spaced 30 cm apart. In 2022 and 2023, the strip was reestablished from seed, except for the perennial species that had survived since 2021. In 2022, a seed mix totaling 450 grams was sown across three beds. In 2023, individual species were planted at rates of 2–3 grams per species, distributed evenly along a bed. A weekly irrigation was applied until consistent rainfall began in early June. Manual weeding was conducted in May to support the establishment of the sown species.

An irrigated maize crop was planted next to the flower strip in early June. The seed rate was 75,000 ha^{-1}, and the fertilization rate was 150 kg N ha^{-1} as urea and 40 kg ha^{-1} P_2O_5 as calcium triple superphosphate. In 2023, 67 kg ha^{-1} of KCl was added. Weeds were managed by applying the pre-emergent herbicide Primagram Gold® (Atrazine 33.7%, S-Metolaclor 26.1%) at a rate of 4 L ha^{-1} and post-emergent application of 0.1 L ha^{-1} of Convey® (Topramezone, 29.7%) plus 1 kg ha^{-1} of Gesaprim® Calibre 90 (Atrazine, 90%). Insecticides were not applied, except for commercial seed treatments with Thiamethoxam in 2021 and 2023, because pest monitoring indicated no need for application.

10.3389/fsufs.2026.1841061

2.1.2 CENEB experimental site

The experiment was conducted from November 2021 to June 2024 at the CENEB experimental station (Norman E. Borlaug Experimental Field), located in Ciudad Obregón, in the Yaqui Valley in southern Sonora, Mexico (27°33′N, 109°09′W, 38 m asl). The Yaqui Valley is one of the most important agricultural production regions in the country, and the station is situated in an area surrounded by irrigated wheat fields. The regional climate is arid, with a mean annual precipitation of 290 mm and a mean annual temperature of 24 °C. Rainfall is concentrated between June and November, while the wheat growing season typically extends from early November to late May.

The flower strip was planted in mid-November each year. It consisted of four beds, each 0.8 m wide (total width = 3.2 m) and 222 m long, in a single field margin. The species were categorized as perennials or annuals and arranged by growth height. All species were planted from seed. In 2021 and 2022, a mix of small seeds was sown, while larger seeds, such as runner beans and faba beans, were planted separately. In 2023, 2–3 grams of seed per species were sown in multiple plots per species distributed along the flower strip. Each plot measured 3.2 m in width (covering four beds) and 2 m in length

TABLE 1 Plant species established in the flower strip during the three-year duration of the experiment at both experimental sites.

Plant species	Life cycle	Year of growing	
		El Batán	CENEB
Basil (*Ocimum basilicum* L.)	Annual	2021	-
Salvia (*Salvia officinalis*)	Perennial	2021	-
Ore (*Ruta* sp.)	Perennial	2021	-
Rosemary (*Salvia rosmarinus* Spenn)	Perennial	2021, 2022, 2023	-
Lavender (*Lavandula spica* L.)	Perennial	2021, 2022, 2023	-
Runner beans (*Phaseolus coccineus* L.)	Perennial	2021, 2022, 2023	2021, 2022, 2023
Dill (*Anethum graveolens* L.)	Annual	2021, 2022, 2023	2021, 2022, 2023
Mustard (*Sinapis alba* L.)	Annual	2021, 2022, 2023	2021, 2022, 2023
Alyssum (*Lobularia marítima* L.)	Annual	2021, 2022, 2023	2021, 2022, 2023
Chia (*Salvia hispanica* L.)	Annual	2022, 2023	2023
Coriander (*Coriandrum sativum* L.)	Annual	2022, 2023	2021, 2022, 2023
Common vetch (*Vicia sativa* L.)	Annual	2022, 2023	-
Faba bean (*Vicia faba* L.)	Annual	2023	2023
Arugula (*Eruca vesicaria* L.)	Annual	2023	2021, 2022, 2023
Cosmos (*Cosmos bipinnatus* Cav.)	Annual	2023	2021, 2022, 2023

FIGURE 1
Flower strip and wheat in the early growing season at the El Batán experimental site, in August 2022.

FIGURE 2
Flower strip and wheat in the early growing season at the CENEB experimental site, in March 2022.

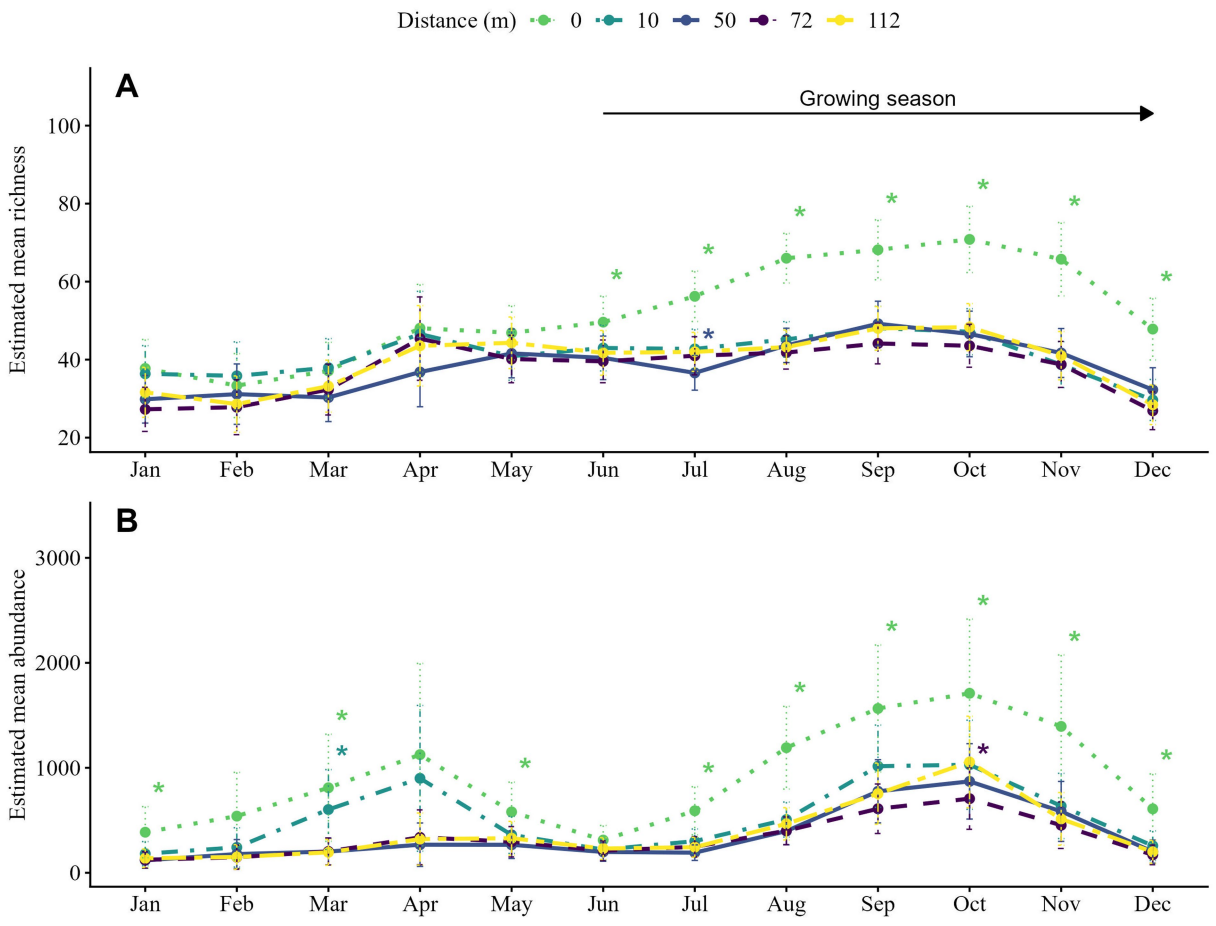

FIGURE 3
Model-estimated arthropod richness **(A)** and abundance **(B)** at each distance within each month at the El Batán site, derived from GLMMs including a Distance × Month interaction. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m) within the same month. The growing season runs from June to December.

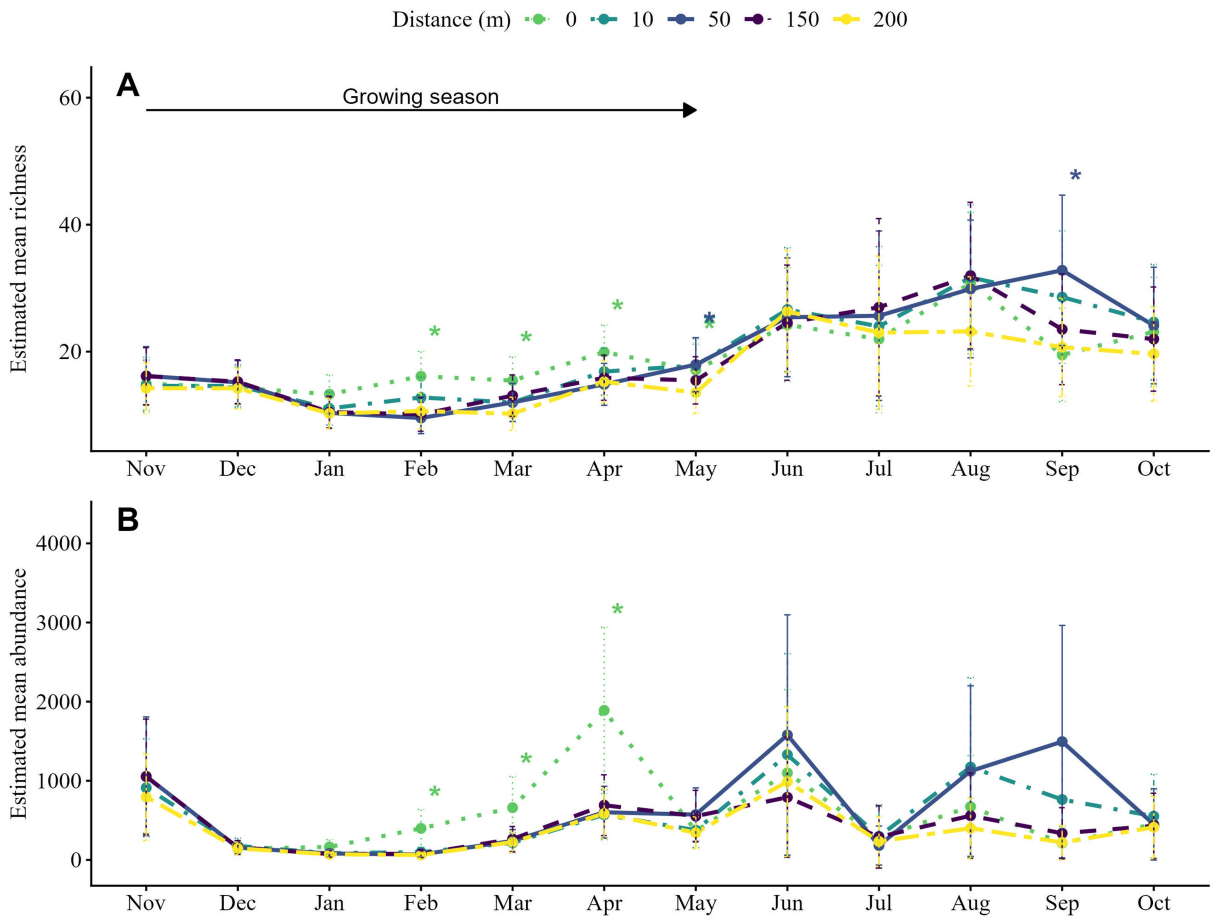

FIGURE 4
Model-estimated arthropod richness **(A)** and abundance **(B)** at each distance within each month at the CENEB site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m) within the same month. The growing season runs from November to May.

TABLE 2 Model-based estimated mean of richness and abundance at each distance from the flower strip for each functional group and the overall community, at both sites, averaged across all sampling events.

Variable	Group	Distance from the flower strip (m)									
		El Batán					CENEB				
		0	10	50	72	112	0	10	50	150	200
Richness	Herbivores	20.9*	14.8	14.2	13.7	14.3	5.7*	5.3	5.3	5.2	4.8
	Predators	9.1*	6.7	6.4	6.2	6.8	3.6*	3.4	3.3	3.3	3.0
	Parasitoids	13.7*	10.1	9.6	9.1	9.7	2.1	1.8	1.7	1.8	1.6
	Decomposers	11.2*	9.5	9.1	9.0	9.5	5.4*	5.4*	5.3*	5	4.6
	Nectivores	0.4*	0.1	0.06	0.05	0.06	1.2	1.2	1.0	1.2	1.6
	Hematophagous	0.5	0.4	0.5	0.4	0.4	1.0	1.0	1.0	1.0	1.0
	All functional groups	56.4 *	42.1	40.1	38.8*	41.2	17.1*	16.1*	15.6*	15.4*	14.0
Abundance	Herbivores	313.8*	135.7*	111.8*	108*	118.8	155.9*	69.9	70.9	70.5	62.5
	Predators	47.9*	25.7*	21.3*	21.5*	23.9	25.8	12.9	12.8	11.4	10.7
	Parasitoids	141.5*	69.2*	53.4*	45.5*	61	25.9*	9.1	9.2	9.6	8.6
	Decomposers	252.3*	195.7*	133.0*	119.1*	141.5	149.8*	127.8*	133.8*	104.8*	88.1
	Nectivores	0.6*	0.1	0.04	0.05	0.05	4.1	2.0*	2.3*	1.0*	5.9
	Hematophagous	1.2*	0.7	0.7	0.6*	0.8	13.4*	11.2	10.7	10.2	9.2
	All functional groups	875 *	477*	343*	331*	380	515*	305	322*	295	245

Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m at El Batán and 200 m at CENEB). Differences reflect either higher or lower values compared to the reference distance.

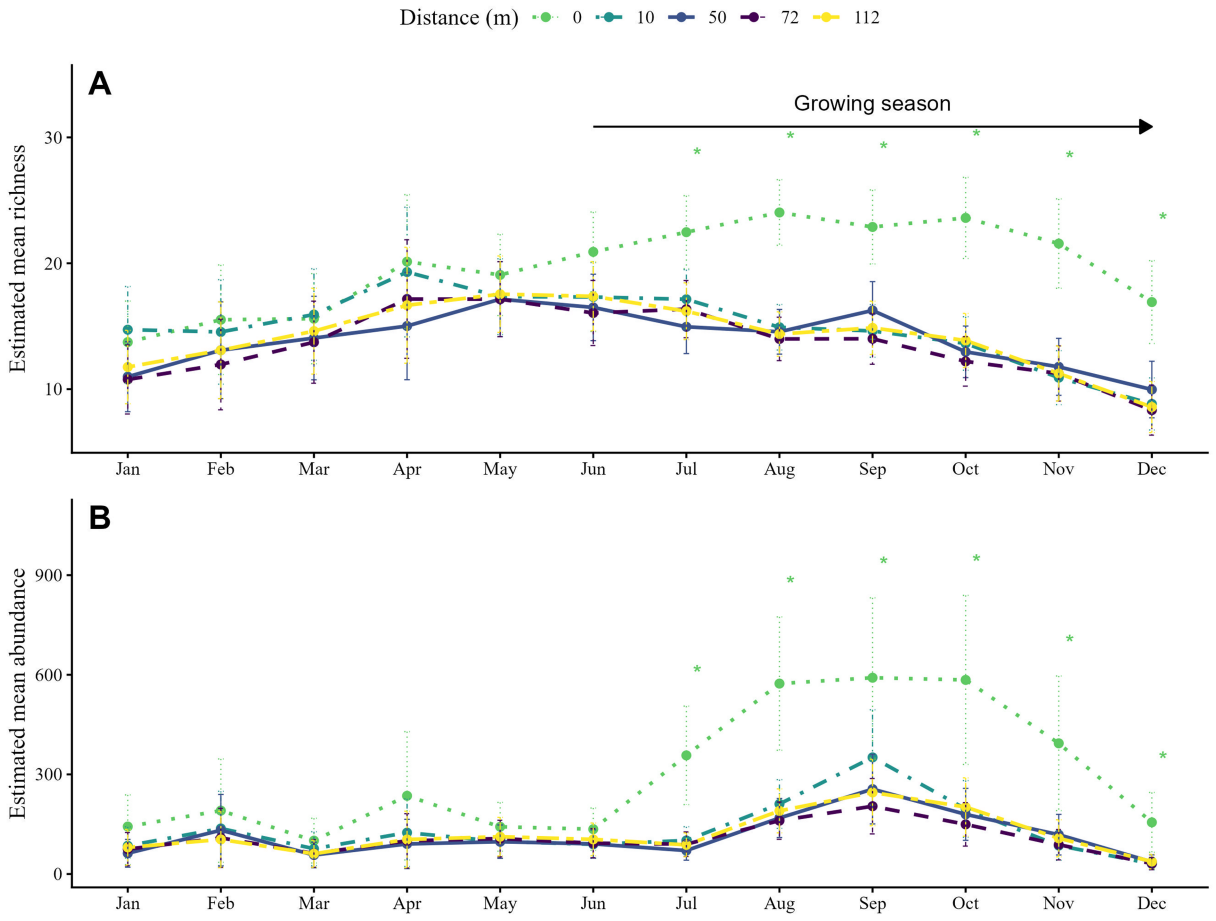

FIGURE 5
Model-estimated arthropod richness **(A)** and abundance **(B)** of herbivores at each distance within each month at the El Batán site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m) within the same month. The growing season runs from June to December.

(Table 1; Figure 2). Irrigation was applied once before planting and four times during the growing season. Weeds were removed manually throughout the season.

The field was conditioned in each cycle, which consisted of raking, chiseling, harrowing, and finally bed formation. During the three cropping cycles, durum wheat of the Don Lupe variety was sown in early December. The seeding density was 120 kg ha^{-1}. For each season, pre-planting fertilization consisted of 59 kg N ha^{-1} as urea and 52 kg ha^{-1} P_2O_5 as triple superphosphate. The second fertilization, applied before the first complementary irrigation, consisted of 175 kg N ha^{-1} as urea. Weed control was carried out manually with a hand hoe. Toretto® (21.8% Sulfoxaflor) was applied at a rate of 0.5 L ha^{-1} at the onset of aphid infestation. Irrigation and weed management were carried out as described for the flower strip.

2.2 Arthropod sampling

To characterize the arthropod community, Townes-style Malaise traps with a white roof (Uhler et al., 2022) were arranged along three transects perpendicular to the flower strip at 10, 50, 72, and 112 m at El Batán, and 0, 10, 50, 100, 150, and 200 m at CENEB. Differences in sampling distances between sites were due to variation in field width, with the farthest distances corresponding to 10 and 50 m from the field edge without a flower strip (Supplementary Figures S2, S3). Sampling was conducted weekly during the crop season and once per month during the fallow period (when no crops were present in the field), with each sampling event lasting between three to seven days.

The individuals collected were identified to the family level using a Nikon SMZ1500 stereoscopic microscope, except for certain groups (e.g., microlepidopterans or arachnids), which were identified to the lowest taxonomic level possible. Due to time constraints, some samples from the El Batán site were not examined, but at least two samples per month were analyzed. All identified arthropod taxa were assigned to one of six functional groups: hematophagous, decomposers (including detritivore, fungivore, saproxylic, and xylophage), herbivores, nectivores, predators, and parasitoids. Functional groups were defined as ecological categories, and each taxonomic group was assigned to a single functional group based on its dominant trophic role in agroecosystems following functional guild approaches commonly used in studies assessing arthropod responses to flower strips and field margins (Boetzl et al., 2020; Haaland et al., 2011; Hatt et al., 2017). Although some taxa may exhibit multiple ecological roles depending on life status or context, groups were classified according to their most prevalent function to ensure mutually exclusive categories for analysis.

2.3 Data analysis

Total abundance and diversity, as well as the abundance and diversity of each functional group, were analyzed separately for each site. Arthropod assemblages were analyzed at three

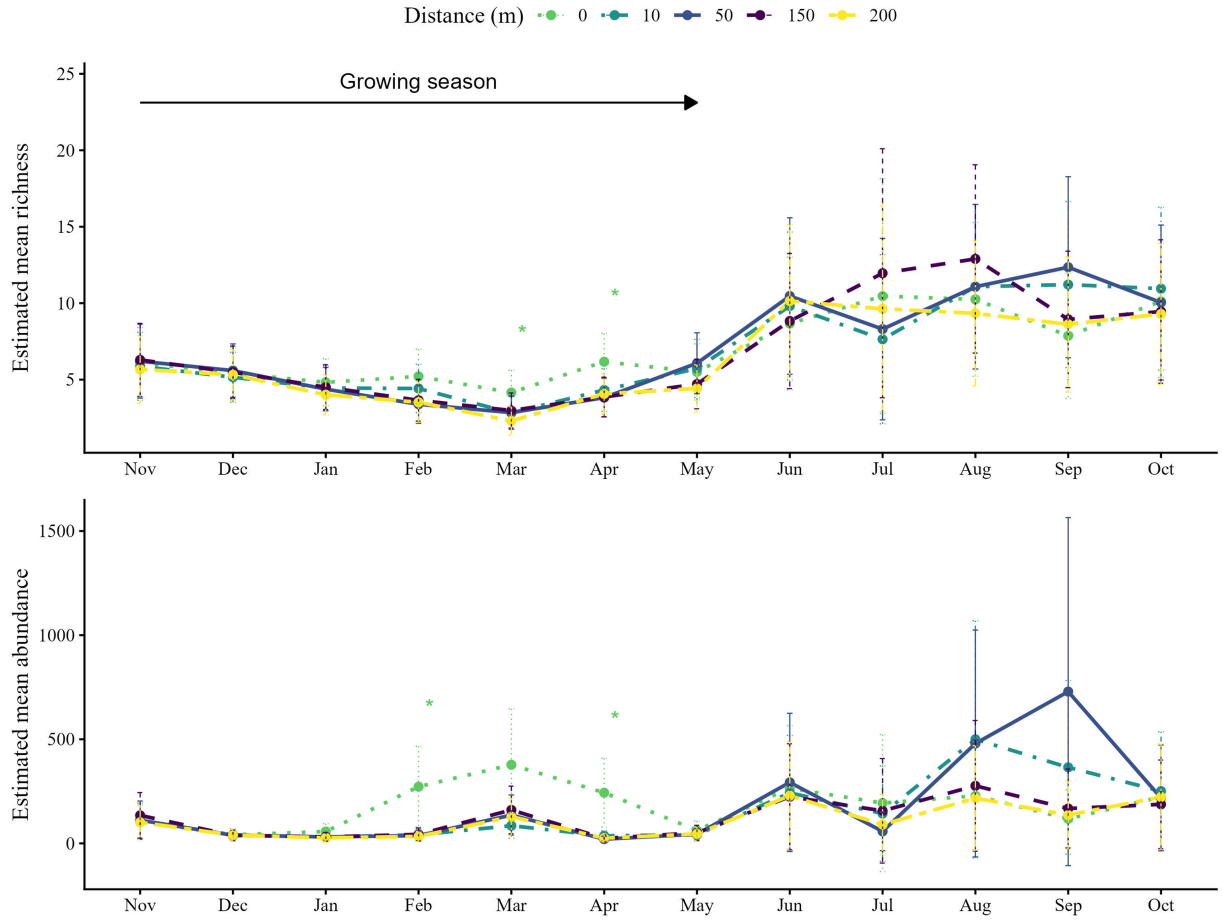

FIGURE 6
Model-estimated arthropod richness **(A)** and abundance **(B)** of herbivores at each distance within each month at the CENEB site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m) within the same month. The growing season runs from November to May.

hierarchical levels: community, functional groups, and taxonomic groups. To account for seasonal variation, monthly averages across all years were used to calculate statistics at each sampling distance. Taxonomic richness was defined as the number of distinct taxonomic groups, while abundance was defined as the number of individuals captured per trap on each sampling date. In addition, data from all sampling events were pooled to examine overall trends.

Generalized linear mixed models (GLMMs) were fitted using the glmmTMB package in R (version 4.5.2) (Brooks et al., 2017). Distance from the flower strip was evaluated using two complementary approaches. First, distance was treated as a continuous predictor to assess the overall form of arthropod responses across the field. Subsequently, distance was treated as a categorical variable corresponding to the discrete sampling distances, facilitating the assessment of localized spillover effects. For community-level analyses and for each functional group, abundance and richness were modeled as a function of Distance, with sampling date included as a random effect to account for the repeated-measures design. Additionally, models including Distance, Month, and their interaction (Distance × Month) were fitted to evaluate temporal variation in distance effects. For taxon-specific analyses, abundance was modeled separately for each taxonomical group, with Distance included as a fixed effect and sampling date as a random effect. Taxonomic groups with insufficient data leading to model non-convergence were excluded, resulting in the exclusion of 42 taxonomic groups at El Batán and 33 at CENEB (Supplementary Table S1).

Models were fitted using a log link function with a negative binomial error distribution. Model diagnostics were assessed using the DHARMa package, including formal tests for dispersion, zero inflation, and outliers, as well as visual inspection of scaled residuals. Dispersion values were generally close to unity and tests for zero inflation were non-significant, indicating that model assumptions were adequately met (Supplementary Table S2). Estimated marginal means were computed using the emmeans package and back-transformed to the response scale for presentation. For figures showing monthly patterns, model-estimated marginal means were extracted for distance within each month.

Each distance was compared to a site-specific reference distance (112 m at El Batán and 200 m at CENEB) using linear contrasts of estimated marginal means and resulting *p*-values were adjusted for multiple testing using the Bonferroni–Holm procedure (Lenth, 2016). The reference distance corresponded to 10 m from the opposite field edge lacking a flower strip, enabling direct comparison with the 10 m sampling distance adjacent to flower strips. Sampling sufficiency was evaluated separately for each site and distance using sample-based species accumulation curves generated from random permutations of sampling units (100 permutations) based on presence–absence data, as implemented in the vegan package.

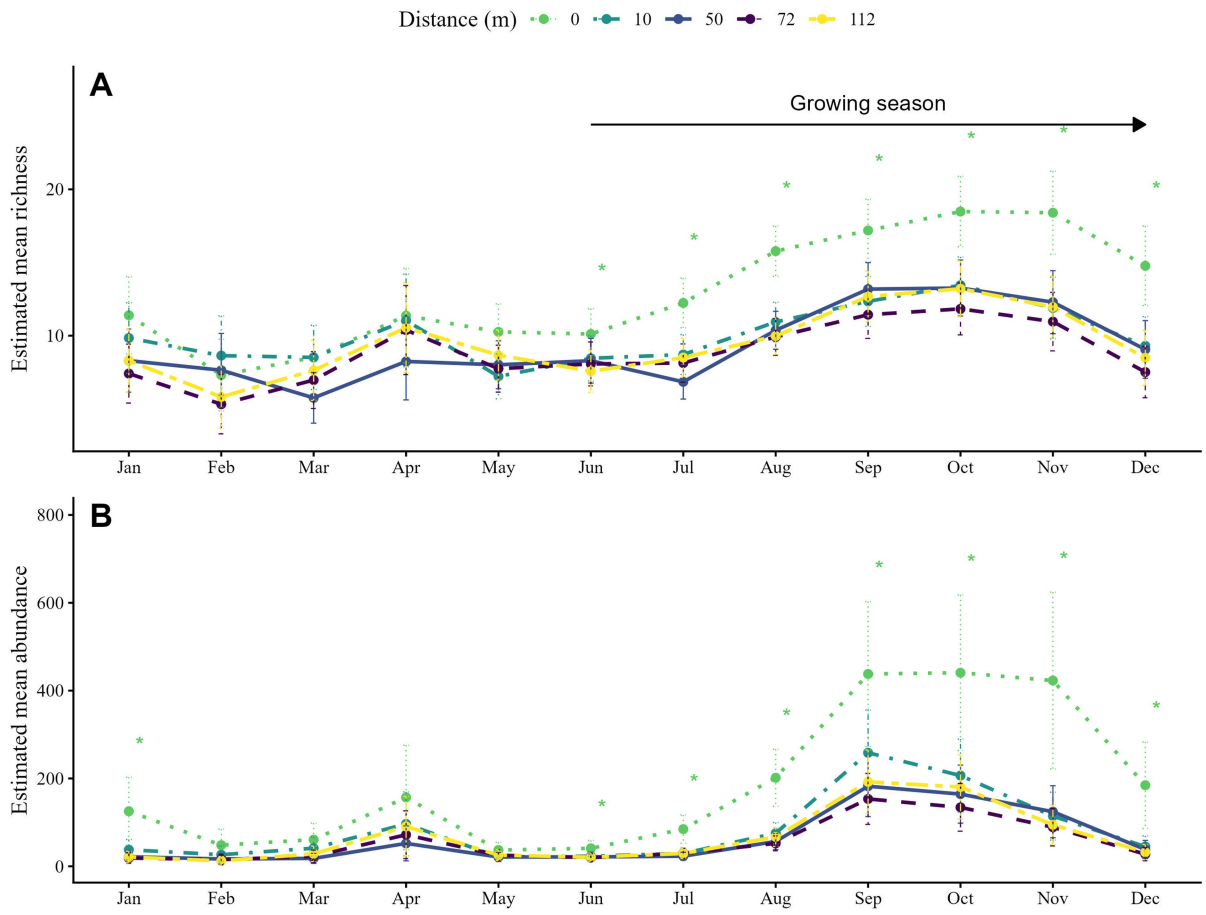

FIGURE 7
Model-estimated arthropod richness **(A)** and abundance **(B)** of parasitoids at each distance within each month at the El Batán site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m) within the same month. The growing season runs from June to December.

3 Results

Species accumulation curves were used as a diagnostic assessment of sampling effort and suggested adequate sampling coverage at both El Batán and CENEB, as taxonomic richness increased consistently with sampling effort across distances (Supplementary Figure S3).

Mixed effects models treating distance as a continuous predictor revealed contrasting spatial responses between sites. At El Batán, arthropod richness and abundance exhibited a strongly non-linear spatial response. Both variables were highest adjacent to the flower strip, declined sharply at intermediate distances within the field, and partially recovered toward the opposite field margin. This spatial pattern indicates the concomitant influence of multiple edge effects rather than a single monotonic gradient (Supplementary Figure S4). In contrast, CENEB showed a strong and consistent negative spatial gradient. Community-level richness declined linearly with increasing distance from the flower strip ($\beta = -0.050 \pm 0.010$ SE), corresponding to an approximate 5% reduction in richness per unit increase in distance. The effect was even stronger for abundance ($\beta = -0.155 \pm 0.027$ SE), indicating an average decrease of approximately 14% per unit of distance. No indication of recovery toward the opposite field margin was detected across the sampled range, consistent with a single, monotonic edge effect extending into the crop interior (Supplementary Figure S5).

Because distance responses differed in both form and interpretability between sites, subsequent analyses focused on categorical distance contrasts to quantify effect sizes at the sampled distances and facilitate comparisons between sites.

3.1 Arthropod diversity

At El Batán, a total of 593,150 individuals representing 203 taxonomic groups were collected, where Collembola, Cecidomyiidae (Diptera), Mymaridae (Hymenoptera), Chloropidae (Diptera), and Mycetophilidae (Diptera) accounted for 45% of all individuals captured (Supplementary Table S3). On average, 35% of total catches originated from the flower strip, being significantly higher than at the reference distance. An additional 20% of catches were recorded at 10 m from the flower strip, whereas proportions at the remaining distances ranged between 14 and 16%, indicating a strong spatial concentration of arthropods near the flower strip when averaged across sampling events.

Temporal dynamics revealed pronounced seasonal variation in both arthropod abundance and richness (Figure 3). The highest values were recorded between September and October, coinciding with the peak blooming period of most flower strip species. In 2021, this peak occurred earlier, in August, as transplanted plants flowered earlier than in 2022 and 2023, when direct seeding resulted in a later onset of flowering. Large numbers of Collembola were collected during the fallow season.

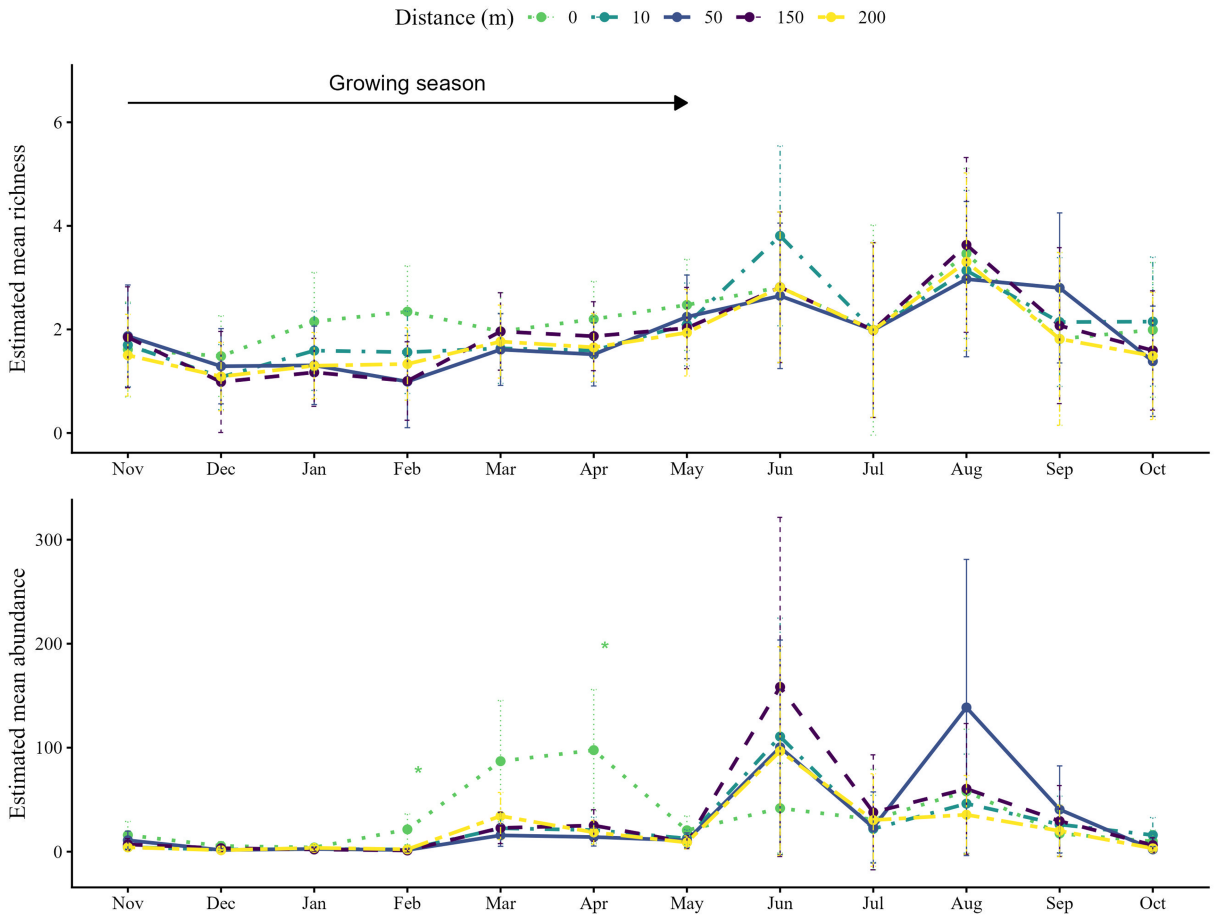

FIGURE 8
Model-estimated arthropod richness **(A)** and abundance **(B)** of parasitoids at each distance within each month at the CENEB site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m) within the same month. The growing season runs from November to May.

At the CENEB site, a total of 390,867 individuals representing 171 taxonomic groups were collected during the experiment. Entomobryidae (Collembola), Chironomidae (Diptera), Aphididae (Hemiptera), Isotomidae (Collembola), Ceratopogonidae (Diptera), and Culicidae (Diptera) accounted for 64% of all individuals captured (Supplementary Table S2). When averaged across all sampling events, 28% of the total catches originated from the flower strip followed by 18% at 10 m, 22% at 50 m, 18% at 150 m, and 14% at 200 m, reflecting the gradual decrease in arthropod captures with increasing distance from the flower strip. Temporal dynamics showed strong seasonal variation in arthropod abundance and richness (Figure 4). Abundance peaked between April and June, toward the end of the growing season, dominated by Ceratopogonidae flies, which were caught in large swarms. In contrast, arthropod richness peaked during the rainy season between June and October.

3.2 Functional groups

Decomposers and herbivores were the dominant groups at both sites, together accounting for more than 70% of total arthropod catches. Model fitted to data pooled across all sampling events revealed clear differences in arthropod richness and abundance among distances for most functional groups at both sites (Table 2).

3.2.1 Herbivores

When averaged across all sampling events, herbivore richness at El Batán was highest at the flower strip, with an estimated mean of 20.9 taxa per sampling event at the flower strip, compared to 14.3 taxa at the reference distance (Table 2), indicating an increase of 46%. Estimated Mean abundance was also higher at the flower strip, reaching 313.8 individuals per sampling event, which was 2.6 times higher than at the reference distance. A consistent and significant effect of distance on both abundance and richness was detected at 0 m from July to December (Figure 5).

At CENEB, herbivore richness at the flower strip was slightly higher than at the reference distance, with an estimated mean of 5.7 taxa per sampling event and a modest but significant increase (Table 2). In contrast, herbivore abundance exhibited a stronger response, estimated mean abundance at the flower strip was approximately twice that observed at the reference distance. These spatial differences were temporally restricted, with significant differences between the flower strip and the reference distance detected between February and April (Figure 6).

Overall, herbivores exhibited higher richness and abundance at the flower, with a strong and consistent response across the growing season at El Batán, and a weaker and temporally restricted response at CENEB.

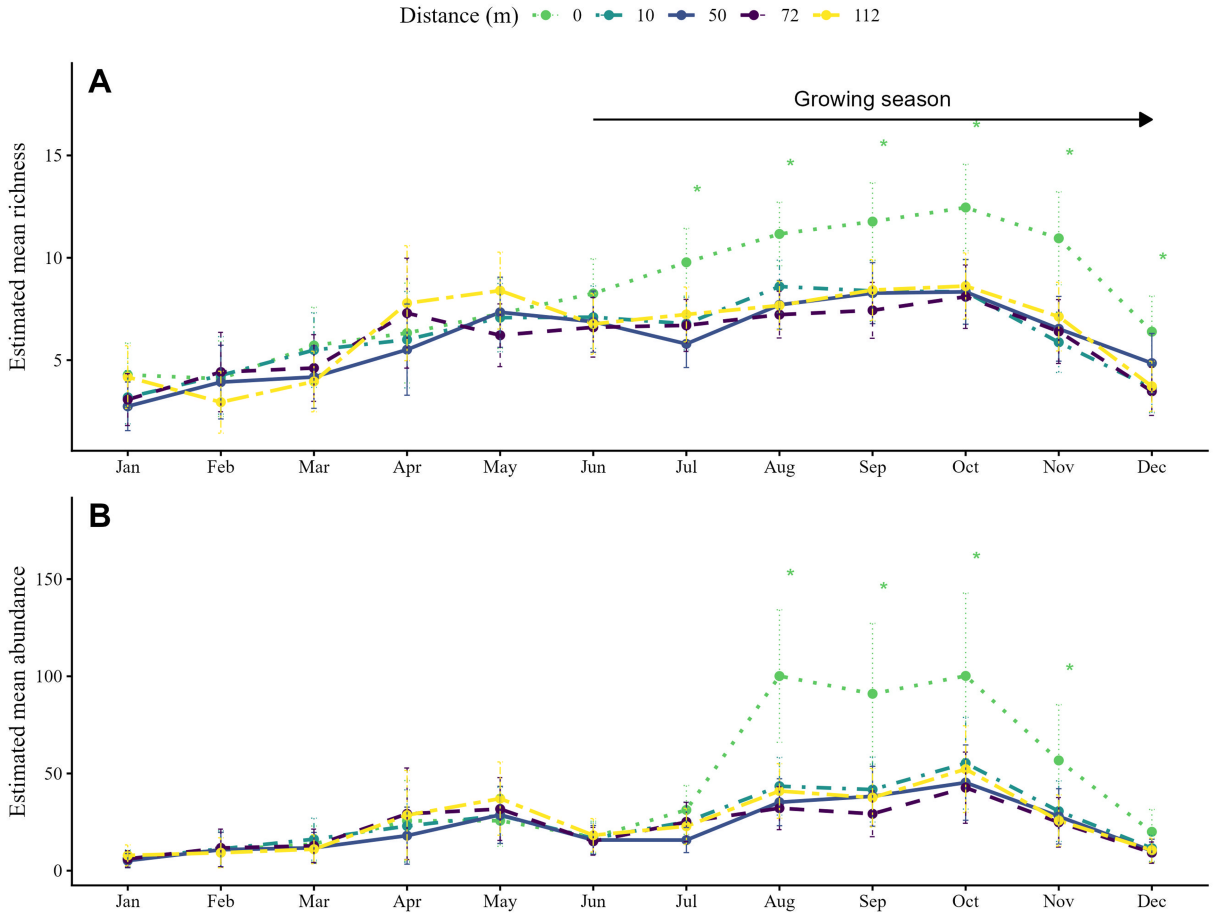

FIGURE 9
Model-estimated arthropod richness **(A)** and abundance **(B)** of predators at each distance within each month at El Batán site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m) within the same month. The growing season runs from June to December.

3.2.2 Parasitoids

When averaged across all sampling events, parasitoids richness at El Batán, was significantly higher at the flower strip with an estimated mean of 13.7 taxa per sampling event, compared to 9.7 at the reference distance, indicating an approximately 41% increase in parasitoid richness (Table 2). The response in abundance was even stronger, estimated mean parasitoid abundance at the flower strip reached 141.5 individuals per sampling event, representing a 2.3-fold increase compared to the reference distance. Abundance at 10 m from the flower strip was also significantly higher than at the reference distance (13% higher), whereas abundance at 72 m was significantly lower (Table 2). Significant differences in both richness and abundance at the flower strip were consistently detected from June to January (Figure 7).

At CENEB, estimated mean parasitoid richness remained low across all distances (2 taxa per sampling event) and did not differ significantly between the flower strip and the reference distance (Table 2). In contrast, estimated mean abundance at the flower strip was 25.9 individuals per sampling event, nearly three times higher than at reference distance. However, this effect was temporally restricted, with significant flower-strip effects detected only in February and April (Figure 8).

In general, parasitoids exhibited markedly higher richness and abundance at the flower strip at El Batán, with strong and persistent effects across multiple months, whereas at CENEB abundance response was limited.

3.2.3 Predators

On average across all sampling events, predator richness at El Batán was highest at the flower strip, with an estimated mean of 9.1 taxa per sampling event, compared to 6.8 taxa at the reference distance (Table 2). This indicates a 34% increase in predator richness. Predator abundance showed a similarly strong response: estimated mean abundance at the flower strip reached 47.9 individuals per sampling event, representing a twofold increase compared to the reference distance. Significant differences at flower strip on both richness were detected from July to December, and from August to November for abundance, covering most of the growing season (Figure 9).

At CENEB, predator richness at the flower strip was slightly higher than at the reference distance, with an estimated mean of 3.6 taxa per sampling event compared to 3.0 taxa at 200 m (Table 2), corresponding to 20% of increase. However, this difference was not consistently detected in monthly analyses. In contrast, estimated mean abundance for predators at the flower strip was 25.8 individuals per sampling event, approximately 2.4 times higher than at the reference distance. Significant differences in predator abundance were detected between February and April (Figure 10).

Overall, predators exhibited higher richness and abundance at the flower strip at El Batán, with strong and sustained effects across the growing season, whereas at CENEB responses were mainly driven by

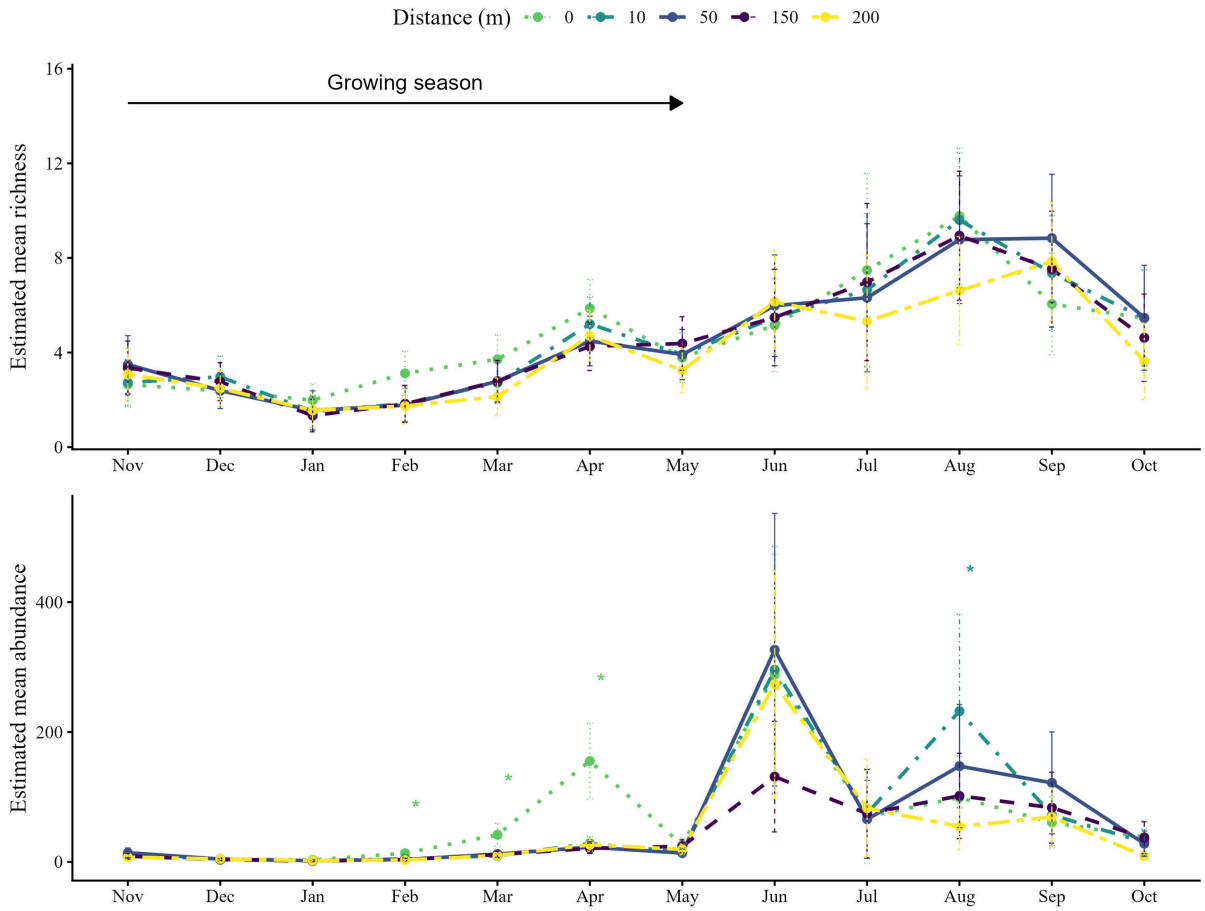

FIGURE 10
Model-estimated arthropod richness **(A)** and abundance **(B)** of predators at each distance within each month at the CENEB site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m) within the same month. The growing season runs from November to May.

increased abundance, were temporally restricted, and showed limited and inconsistent effects on richness.

3.2.4 Decomposers

Decomposer richness at El Batán was significantly higher at the flower strip, with an estimated mean of 11.2 taxa per sampling event compared to 9.5 taxa at the reference distance on average across all sampling events (Table 2). This indicates an approximately 18% increase in decomposer richness at 0 m relative to the reference distance. Decomposer abundance also showed a strong spatial response with an estimated mean abundance at the flower strip reaching 252.3 individuals per sampling event, representing a 1.78-fold increase compared to the reference distance. Abundance at 72 m was likewise significantly lower than at the reference distance (Table 2). Significant positive effects at the flower strip were detected mainly in August and September for both richness and abundance (Figure 11).

At CENEB, the estimated mean richness of decomposers at the flower strip was 5.4 taxa per sampling event and was comparable to values observed at 10 and 50 m, while remaining significantly different from the reference distance (Table 2). Decomposer abundance at the flower strip also differed significantly from the reference distance, and all other sampled distances likewise showed significant differences relative to the reference distance in the pooled analysis (Table 2). However, there were no significant differences between distances for either richness or abundance at any month (Figure 12).

In general, decomposers showed higher richness and abundance at the flower strip than at the reference distance at El Batán, with positive but seasonally restricted effects, whereas at CENEB spatial differences were evident only in the pooled analyses.

3.2.5 Nectivores and hematophagous

At El Batán, nectivores and hematophagous taxa were recorded mainly during the growing season and occurred in much lower numbers than other functional groups. When averaged across all sampling events, nectivore richness and abundance were significantly higher at the flower strip than at the reference distance (Table 2), whereas hematophagous taxa showed only weak responses.

At CENEB, both hematophagous taxa and nectivores were consistently recorded in low numbers throughout the year. In the pooled analysis, hematophagous abundance at the flower strip differed significantly from the reference distance, showing a slight increase, whereas nectivore richness and abundance did not exhibit significant differences (Table 2). Through the year distance effects were similar for either group.

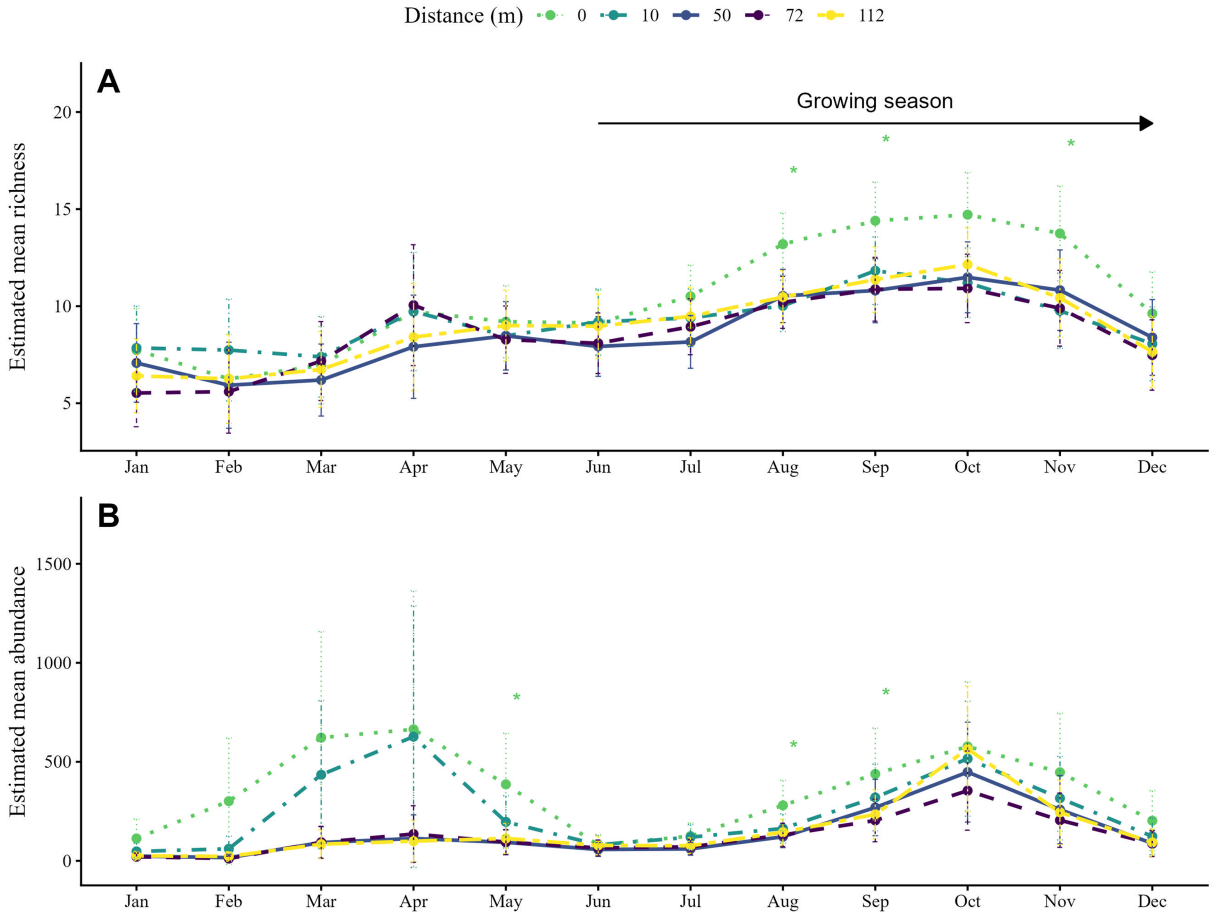

FIGURE 11
Model-estimated arthropod richness **(A)** and abundance **(B)** of decomposers at each distance within each month at the El Batán site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m) distance within the same month. The growing season runs from June to December.

3.2.6 Taxonomic groups

At El Batan, 90 out of 165 taxonomic groups showed a significant increase in abundance at the flower strip, and some also at distances greater than 0 m from it. Of these 90, 36 were herbivores, 23 parasitoids, 15 decomposers, 14 predators, one was nectivore, and one was hematophagous. Notably, Ichneumonidae (Hymenoptera) increased up to 50 m (Figure 13). Elateridae and Arachnida were significantly lower at the flower strip than at reference distance. The remaining 73 groups had no response to the flower strip as they were evenly distributed in the field, of which 31 were herbivores, 18 decomposers, 17 predators, 8 parasitoids, and one nectivore.

At the taxonomic level, 23 out of 141 groups exhibited a significant increase in abundance at the flower strip for the CENEB site. These included seven herbivores, six predators, four parasitoids, six decomposers. Additionally, six taxonomic groups increased significantly at distances greater than 0 m from the flower strip. Among these, one was parasitoid, two were herbivores, and three were decomposers. Notably, Ceratopogonidae (Diptera), Cicadellidae (Hemiptera) and Tetranichidae (Trombidiformes) increased at 50 m (Figure 14). Meloidae (Coleoptera) and Psyllipsocidae (Psocoptera) had lower values at the flower strips compared to the reference. A total of 115 groups had no response to the flower strip, of which 39 were predators, 35 herbivores, 28 decomposers, five parasitoids, five nectivores and three hematophagous.

4 Discussion

Landscape simplification resulting from industrial agriculture is a major driver of biodiversity loss, largely due to the widespread dominance of monocultures that support a limited number of species closely tied to specific crops (Ziesche et al., 2024). However, our findings indicate that even small-scale enhancements in plant diversity, such as the implementation of flower strips, can contribute to mitigating these effects by providing habitat for arthropod biodiversity within these simplified landscapes (Blümel et al., 2024; Haaland et al., 2011; Hatt et al., 2017; Jachowicz and Sigsgaard, 2025; Peris-Felipo et al., 2025). Although flower strips tailored to the main crop may maximize attractiveness for beneficial insects while potentially reducing crop pests (Balzan et al., 2014; Blümel et al., 2024; Hatt et al., 2020; Tschumi et al., 2015), plant species in this study were selected primary for their abundant and prolonged flowering, rather than for their specific suitability to support beneficial arthropods. Even so, the favorable arthropod responses observed provide important evidence, particularly for

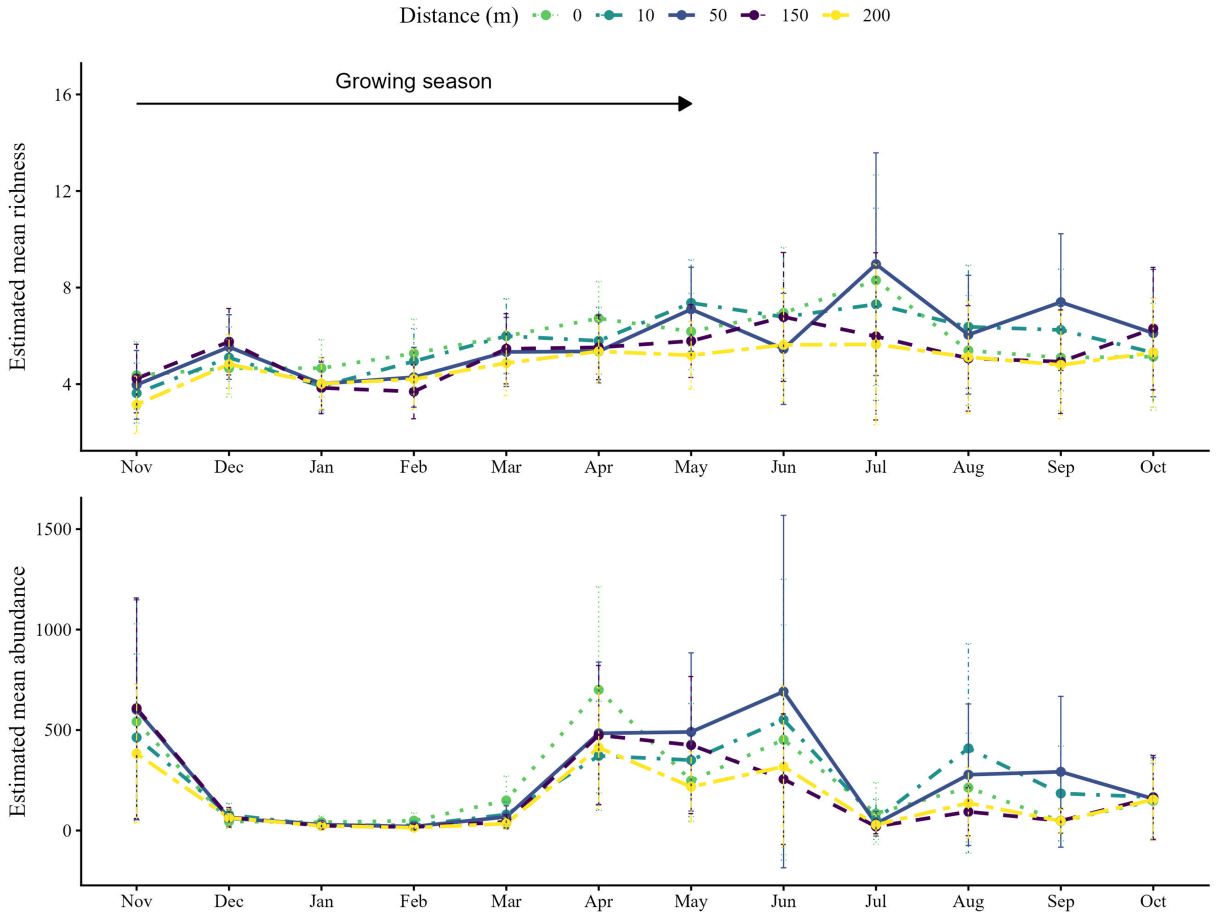

FIGURE 12
Model-estimated arthropod richness **(A)** and abundance **(B)** of decomposers at each distance within each month at the CENEB site. Asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m) within the same month. The growing season runs from November to May.

Mexico, where studies on this topic remain scarce (Cortez-Madrigal and Gutiérrez-Cárdenas, 2023; Vargas et al., 2023).

Differences in arthropod biodiversity and spatial responses were observed between our study sites. At CENEB, located in the less biodiverse Nearctic region (Morrone and Márquez, 2008), responses were predominantly linear with modest increases in arthropod richness. Contributing factors may include higher landscape simplification, the winter planting of wheat and more intensive pesticide use, all of which have been associated with reduced arthropod populations. In contrast, at El Batán, arthropod richness exhibits a non-linear pattern with higher values near the flower strip and in some cases again at the farthest sampled distance suggesting the influence of broader landscape heterogeneity beyond the field margin. This pattern is consistent with the El Batán being embedded in a more heterogeneous landscape including diverse crops, fallow land and remnant forest patches, which likely enhancing flower strip effects by facilitating arthropod dispersal from nearby semi-natural habitats (Albrecht et al., 2020; Boetzl et al., 2020; Gurr et al., 2017; Haenke et al., 2009; Hussain et al., 2023).

Although the use of higher-level taxonomic resolution may underestimate true species richness, several arthropod groups showed clear and contrasting spatial responses. At El Batán, higher abundances near the flower strip were observed for both potential cereal pests and key beneficial taxa, including predators and parasitoids, with effects generally extending up to 10 m into the crop and, in some cases, further. At CENEB, responses were more localized, with increased abundances detected mainly near the flower strip or at intermediate distances for a limited number of taxa. Together, these patterns indicate that flower strips functioned as resource-rich habitats for multiple arthropod guilds, while the spatial extent of their influence varied strongly with landscape context.

Herbivore abundance increased significantly in flower strips, encompassing both generalists and cereal crop pests. This aligns with reports of increased herbivore presence in flower strips (Balzan et al., 2014; Blümel et al., 2024; Lundin et al., 2023). Additionally, a slight increase in generalist herbivores was detected within 10 m of the strip, without evidence of broader infestation. However, the composition of the herbivore community is likely influenced more by the presence of specific plant species than by overall plant diversity (Bröcher et al., 2023), emphasizing the importance when designing and managing flower strip interventions. Alternatively, the concentration of herbivores within non-crop habitats may align with a push–pull mechanism, whereby pests are diverted away from the crop (Altieri et al., 2024; Tschumi et al., 2015), although this interpretation remains speculative as pest damage was not directly quantified.

Decomposer abundance increased consistently at both sites, with particularly strong response at El Batán, where perennial species such as lavender and rosemary contributed to litter accumulation, offering

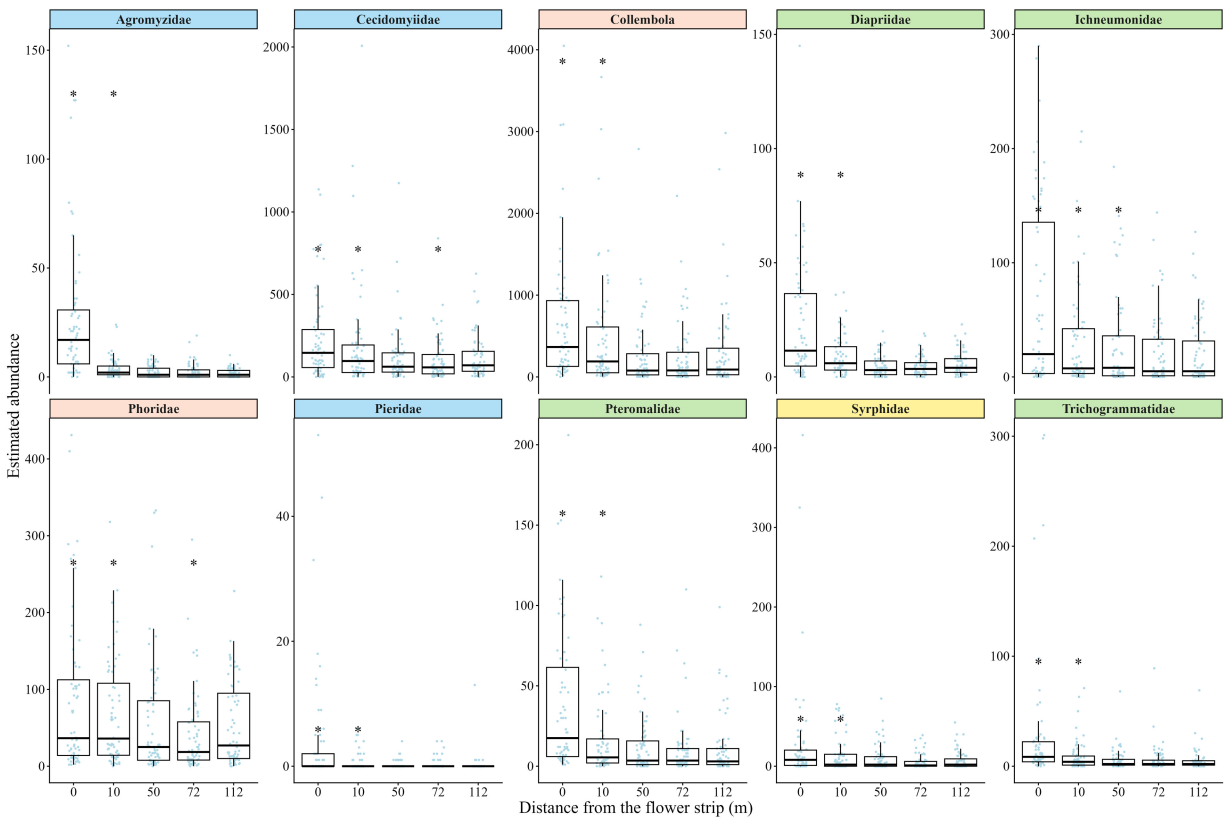

FIGURE 13
Data on the abundance of different taxonomic groups that increased significantly beyond the flower strip throughout the entire study period at the El Batán site. Dots indicate original data points and asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (112 m). Functional group: blue = herbivores, yellow = predators, pink = decomposers, green = parasitoids.

key microhabitats and resources for soil arthropods (Bednar et al., 2023; Smith et al., 2008). The role of undisturbed overwintering habitats appears essential since the response was higher during the fallow season. However, the response of belowground fauna to flower strips remains underexplored and complex, often diverging from aboveground taxa patterns (Hatt et al., 2020; Triquet et al., 2022).

Abundance of predators and parasitoids increase consistently at both sites although their temporal responses varied. At El Batán, parasitoid and predator richness and abundance showed steady increases at the flower strip throughout the growing season, whereas at CENEB this increase was observed at the end of this period. Although the abundance of natural enemies in semi-natural habitats adjacent to crops is often used as an indirect proxy for predicting biological pest control this does not necessarily translate into effective pest suppression in adjacent crops (Blümel et al., 2024; Hatt et al., 2020; Rodenwald et al., 2023; Tschumi et al., 2015). This limitation is partially explained by the rapid decline of flower strips effects with increased distance into the field, consistent with short-range spillover effects observed in this study extending around 10 meters (Albrecht et al., 2020; Rodenwald et al., 2023; Tschumi et al., 2015).

Arthropod spillovers into the crop field are at least partly influenced by dispersal capacity, with winged predators and parasitoids—capable of dispersing over larger distances—benefitting more from flower strips than species such as spiders and carabid beetles generally considered ground-dwelling arthropods with limited dispersal capacities (Hatt et al., 2017; Li et al., 2024; Rodenwald et al., 2023). These patterns suggest that responses of natural enemies are shaped by multiple factors, including prey abundance, plant diversity, and seasonal dynamics (Blümel et al., 2024). Since limited spillovers seem prevalent in isolated flower strips, irrespective of their width (Haenke et al., 2009), such habitats may contribute to arthropod movement by functioning as corridors that connect isolated habitats with surrounding habitats, rather than simply increasing the area within a single field (Haaland et al., 2011).

A key limitation of this study is the lack more spatial replication with and without flower strips, which prevents a direct assessment of net effects. Although the differences observed within the crop are consistent with restricted spillover, alternative explanations cannot be excluded. Additionally, the sampling resolution may have missed short-term movements of highly mobile taxa, meaning that observed spatial patterns likely reflect net distributions rather than real-time dispersal dynamics. Future research should evaluate tailored flower strips, replicated experimental designs across landscapes and finer taxonomical and temporal resolution to better disentangle movement dynamics and evaluate functional outcomes such as pest suppression.

5 Conclusion

Our results indicate that establishing a single flower strip along one field margin can support biodiversity within agricultural landscapes and provide refuges from agricultural disturbance, reinforcing the role as reservoirs of biodiversity in intensively managed agroecosystems. These effects were context-dependent, highlighting the importance of specific implementation. Spillover of arthropods into adjacent crop areas was

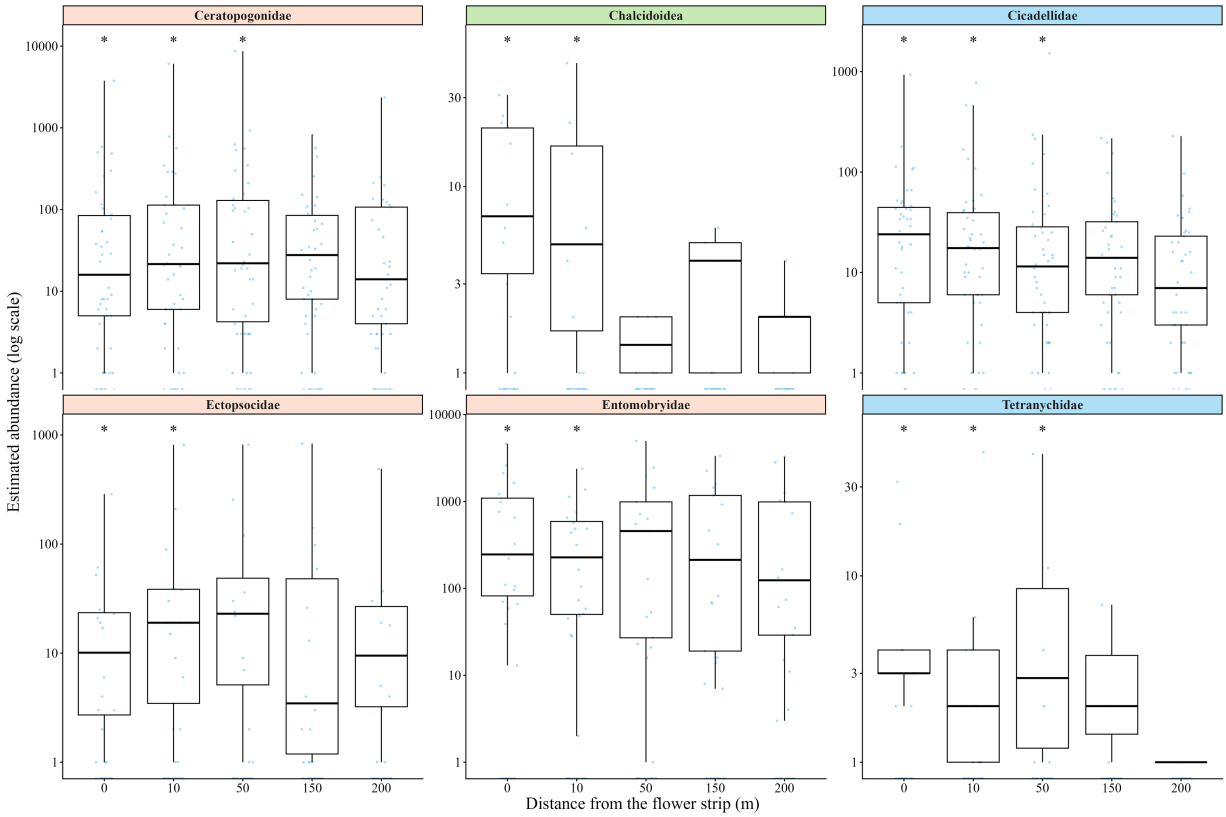

FIGURE 14
Data on the abundance of different taxonomic groups that increased at or beyond the flower strip throughout the entire study period at the CENEB site. Dots indicate original data points and asterisks (*) indicate significant differences ($p < 0.05$) from the reference distance (200 m). Functional group: Blue = herbivores, pink = decomposers, green = parasitoids.

limited and significant only for a small number of taxonomic groups, including both beneficial and potentially harmful taxa. Key limitations of this study, including high taxonomical resolution and limited spatial replication, constrain inference about net effects and causal mechanisms.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://data.cimmyt.org/, persistent Id = doi: https://doi.org/10.71682/10549348.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

AS-T: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. AG-L: Data curation, Investigation, Writing – review & editing. AP-P: Writing – review & editing. FP-F: Conceptualization, Funding acquisition, Writing – review & editing. SF: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

FP-F was employed by Syngenta Crop Protection AG. The author(s) declared that this work received funding from Syngenta Crop Protection AG through the LivinGro®. The funder had the following involvement in the study: design of the study and revision of the manuscript.

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

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