frontiers in Conservation Science

TYPE Original Research
PUBLISHED 08 September 2026
DOI 10.3389/fcosc.2026.1871779

OPEN ACCESS

EDITED BY
Muzafar Riyaz,
Zoological Survey of India, India

REVIEWED BY
Justin Bastow,
Eastern Washington University, United States
Amibeth Thompson,
University of Freiburg, Germany

*CORRESPONDENCE
Jose Vicente Falcó-Garí
J.Vicente.Falco@uv.es
F. Javier Peris-Felipo
peris.felipo@gmail.com

RECEIVED 03 May 2026
REVISED 10 August 2026
ACCEPTED 11 August 2026
PUBLISHED 08 September 2026

CITATION
Falcó-Garí JV, Aguado-Martín O, Gayán-Quijano AL, Hernández de la Fuente I, González-Pérez J, Miranda-Barroso L, Devoto M and Peris-Felipo FJ (2026) Regenerative management enhances pollinator communities in commercial perennial farms across multiple years. *Front. Conserv. Sci.* 7:1871779. doi: 10.3389/fcosc.2026.1871779

Regenerative management enhances pollinator communities in commercial perennial farms across multiple years

Jose Vicente Falcó-Garí[1]*, Oscar Aguado-Martín[2], Ana Lia Gayán-Quijano[3], Isabel Hernández de la Fuente[4], Javier González-Pérez[5], Luis Miranda-Barroso[6], Mariano Devoto[7,8] and F. Javier Peris-Felipo[9]*

[1]Laboratory of Entomology and Pest Control, Institute Cavanilles of Biodiversity and Evolutionary Biology, Paterna, Valencia, Spain, [2]Andrena Iniciativas y Estudios Medioambientales S.L., Valladolid, Spain, [3], Sevilla, Spain, [4], Bottmingen, Switzerland, [5]Institute of Habitat, Territory and Digitalization, University of Malaga, Málaga, Spain, [6]Syngenta España, Madrid, Spain, [7]Cátedra de Botánica General, Facultad de Agronomía, Universidad de Buenos Aires, C. A. de Buenos Aires, Argentina, [8]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina, [9]Basel, Switzerland

Agricultural intensification is one of the primary drivers of global pollinator decline, yet empirical evidence for the effectiveness of biodiversity-oriented management under real commercial farming conditions remains scarce. This study evaluates the effects of a multi-species cover crop mixture, implemented as a regenerative soil management strategy in the inter-row spaces of five commercial perennial farms across Mediterranean Spain, on pollinator abundance, species richness, family richness, alpha diversity, and community composition over three consecutive years (2020–2023). Standardized Malaise trapping yielded a total of 18,483 pollinator individuals comprising 167 species, 97 genera, and 42 families across four orders. Regenerative management consistently enhanced all pollinator metrics relative to conventional bare-soil management. Abundance increased more than threefold overall, with a 5.7-fold increase in olive systems and a 2.2-fold increase in stone fruit systems. Species richness more than doubled, family richness increased by 80%, and both Shannon and Simpson diversity were significantly higher under regenerative management. Community composition also differed significantly between management treatments, and indicator species analysis identified 29 significant indicator species, nearly 90% of which were associated with regenerative management across a broad range of pollinator groups. These responses were robust across contrasting crop types and remained ecologically meaningful throughout the study period, despite a decline in pollinator abundance during the final sampling year. The magnitude of the management effect was particularly pronounced in structurally simplified superintensive olive orchards, where baseline pollinator communities were most impoverished under conventional tillage. Collectively, these results indicate that florally diverse, multi-species cover crop mixtures can produce substantial and consistent increases in pollinator abundance, diversity and community composition under commercial farming conditions, supporting evidence-based cover cropping as a practical strategy to help mitigate the effects of agricultural intensification on pollinators.

KEYWORDS

agricultural practices, biodiversity, cover crops, Mediterranean region, olives, regenerative agriculture, stone fruits

1 Introduction

Agricultural intensification has been identified as one of the main drivers of biodiversity loss worldwide, leading to the simplification of agroecosystems and declines in a wide range of taxa, including insects (Foley et al., 2011; Tscharntke et al., 2005). These changes are particularly concerning given the central role of insects in ecosystem functioning and the delivery of key ecosystem services. Among these, pollination is essential for the reproduction of many wild plants and for the production of a large proportion of crops, making pollinators a critical component of agricultural systems (Klein et al., 2007; Potts et al., 2010; IPBES, 2016).

Olive trees (*Olea europaea*) are primarily wind-pollinated, although honeybees frequently visit and forage on olive flowers, moving between inflorescences in a way that may enhance pollen transfer despite the crop's predominantly anemophilous strategy (Giovanetti, 2018). Stone fruit species (*Prunus* spp., including plum, peach and nectarine) show variable self-compatibility, and insect-mediated cross-pollination consistently improves fruit set relative to self-pollination (Klein et al., 2007; Deng et al., 2022). Beyond their direct role in pollination, the floral resources provided by cover crops can also support natural enemies of crop pests and contribute to soil-related ecosystem services (e.g., erosion control, organic matter input), making biodiversity-oriented inter-row management relevant not only for pollinator conservation but also for crop productivity and broader agroecosystem function.

The decline of pollinator populations has been documented across different regions and production systems and is commonly associated with habitat loss, pesticide use and reduced landscape complexity (Potts et al., 2010; Sánchez-Bayo and Wyckhuys, 2019). In response, there has been increasing interest in the development of agricultural practices that enhance biodiversity while maintaining productivity. A growing body of evidence suggests that management practices that increase habitat heterogeneity, such as the incorporation of floral resources, field margins or vegetated strips, can support higher abundance and diversity of pollinators and other beneficial arthropods (Marshall and Moonen, 2002; Scheper et al., 2013; Batáry et al., 2015; Rey et al., 2019; Albrecht et al., 2020; Ploeg et al., 2025). In this regard, studies conducted in intensive agricultural systems of the Iberian Peninsula have shown that the implementation of multifunctional margins, seed mixtures of native species sown in combined strips, can significantly increase both species richness and insect abundance, including pollinators and natural enemies (Miranda-Barroso et al., 2021; Santa et al., 2021). Furthermore, these areas function as reservoirs that contribute to the conservation of rare, threatened and endangered species (Santa et al., 2021). On a broader temporal scale, experimental long-term monitoring of floral margins in intensive vegetable farms has shown a sustained increase in insect abundance over a decade, with a total growth of 403% in the number of individuals, underscoring the value of these measures as a permanent conservation strategy (Peris-Felipo et al., 2025). Regarding the temporal dynamics of margin use, Brittain et al. (2022) analyzed the response of different pollinator groups to floral margins of varying age across 96 farms in Hungary, finding that all groups studied, including honey bees, bumble bees, mining bees, hoverflies and Lepidoptera, showed greater abundance in sown margins compared to controls, although the relationship with margin age varied by taxonomic group, suggesting that periodic re-sowing may be needed to sustain long-term benefits.

However, much of this evidence comes from experimental or semi-natural systems, and there is still limited understanding of how such practices perform under commercial farming conditions. In particular, few studies have quantified the effects of contrasting management strategies on pollinator communities across different crop types and over multiple years. This limits the ability to assess the generality and robustness of biodiversity responses in real-world agricultural systems.

In this study, we evaluate the effects of alternative management practices on pollinator communities in commercial farms. Specifically, we compare pollinator abundance and diversity between management treatments across different crop groups and over multiple years. By analyzing both abundance and taxonomic richness at different levels, this study provides a comprehensive assessment of how management practices influence pollinator communities under operational agricultural conditions.

We hypothesized that (i) regenerative management would increase pollinator abundance, species richness and family richness relative to conventional bare-soil management, owing to greater floral resource availability; (ii) this effect would differ between crop types, being more pronounced in olive orchards, where the crop itself provides negligible floral resources, than in stone fruit orchards, where tree blossom partially buffers the conventional treatment; and (iii) community composition would differ qualitatively between treatments, reflecting a shift toward a richer and more functionally diverse pollinator assemblage under cover crop management.

10.3389/fcosc.2026.1871779

2 Materials and methods

2.1 Areas of study

The study was carried out in five highly productive Spanish perennial tree crops farms located in Alhama de Murcia (Murcia), Almunia de Doña Godina (Zaragoza), Medina de Rioseco (Valladolid), Mula (Murcia), and Pozaldez (Valladolid) (Figure 1).

Alhama de Murcia farm occupies an alluvial terrace within the Guadalentín River Valley, in the province of Murcia (37°44′42.07″ N, 1°20′35.00″W), at approximately 200 m a.s.l. The gently sloping terrain is underlain by calcaric fluvisol and regosol soils. Regarding soil textural composition, the profile is classified as silt loam (sand 11%, silt 79%, and clay 10%). These characteristics are typical of the semi-arid alluvial systems of southeastern Spain, where soil erosion, surface crusting and organic matter decline are well-documented processes (Calatrava et al., 2011). The farm is cultivated with plums. Following the Köppen-Geiger classification (Kottek et al., 2006), the climate is cold semi-arid steppe (BSk), with hot, arid summers and mild, dry winters. Mean annual temperature stands at 16.6 °C, with summer months (June–August) regularly reaching 26 °C while winter values (December–February) drop to around 8 °C. Precipitation is scarce, irregular, and concentrated mainly in autumn and early winter, reflecting the high interannual variability documented across the Guadalentín basin (Calatrava et al., 2011).

Almunia de Doña Godina farm lies within the Ebro River Valley, in the province of Zaragoza (41°29′48.35″N, 1°16′59.21″W), at 388,90 m.a.s.l. The plot is set on a gently undulating surface (5% average slope) developed over limestone crust formations with silty loam soils (sand 28%, silt 62%, clay 10%). This soil texture is consistent with the loamy to silty loam agricultural soils of Central Aragón, where alkaline, carbonate-rich profiles of low organic matter content are characteristic (Sterk et al., 1999). Nectarines represent the main crop at this location. Under the Köppen-Geiger framework (Kottek et al., 2006), the area is classified as continental Mediterranean (Ds), combining hot, dry summers with cold and relatively wet winters. Mean annual precipitation reaches 378.95 mm and mean annual temperature is 16.1 °C; summer averages (June–August) stand at around 25 °C while winter minima (December–February) remain consistently below 10 °C, with maximum rainfall occurring in winter and spring (González-Pérez et al., 2025).

Medina de Rioseco farm is established on the Tierra de Campos plateau, in the province of Valladolid (41°52′35.39″N, 5°1′12.77″W), at 839 m.a.s.l and a 1.25% slope. The plot is characterized by a sandy-loam textural class (sand 59%, silt 32%, clay 9%). The area forms part of the northern Meseta, a broad sedimentary plain dominated by calcareous loamy soils with semi-arid bioclimatic characteristics and low water retention capacity (Ceballos et al., 2002). The farm follows a superintensive olive plantation system. According to the Köppen-Geiger classification (Kottek et al., 2006), this location falls under a warm-temperate Mediterranean climate (Csb), characterized by warm, dry summers and cold winters with precipitation concentrated in autumn and spring. Mean annual temperature is 12.2°C, with July averages near 22°C contrasting with January values of around 4 °C. Total annual rainfall averages 486 mm, substantially higher than at the Murcian sites, though a marked summer drought persists.

Mula farm is located in the interior valley of the Mula River, in the province of Murcia (38°4′37.06″N, 1°27′13.96″W), at roughly 353 m a.s.l and slope of 11.90%. Furthermore, the soil is characterized by a silt-loam texture, composed of (sand 16%, silt 80%, clay

FIGURE 1
Distribution map of the study farms in Spain. The map shows the geographic location of the five farms localities: Alhama de Murcia, Almunia de Doña Godina, Medina de Rioseco, Mula, and Pozaldez. Source: Image from Google Earth, reproduced under Google's Terms of Service.

4%). The hilly terrain hosts calcisol and regosol soils developed on Quaternary sediments and marls where pedological units well documented across the semi-arid landscapes of the Segura River watershed, where low organic matter and fragile soil structure favor erosive processes (López-Bermúdez et al., 1998). Peach trees constitute the primary crop at this site. The climate is classified as BSk under the Köppen-Geiger scheme (Kottek et al., 2006), exhibiting semi-arid continental conditions with hot, dry summers and mild winters punctuated by scarce and erratic rainfall. Annual mean temperature is approximately 20 °C; summer months (June–August) average near 30 °C, while the coldest period (December–February) remains between 8 and 10 °C, with precipitation concentrated in autumn and spring.

Pozaldez farm is situated on the Castilian plateau of the Duero Basin, in the province of Valladolid (41°22′7.57″N, 4°48′31.10″W), at approximately 740 m a.s.l with a slope of 2,70%. The flat topography and sandy-loam soils (sand 60%, silt 38%, clay 2%), of the Meseta, whose hydrological behavior and limited water retention have been characterized in the broader Duero basin (Ceballos et al., 2002), support both viticulture within the Rueda Designation of Origin and, more recently, superintensive olive cultivation. Climatically, the site is classified as hot-summer continental Mediterranean (Csa) under the Köppen-Geiger framework (Kottek et al., 2006), where high summer temperatures are amplified by the inland position and elevation. Mean annual temperature is around 12 °C, with summer peaks (June–August) near 23 °C and winter lows (December–February) approaching 4 °C. Annual precipitation averages approximately 430 mm, distributed predominantly between October and May, with a pronounced dry summer period.

2.2 Experimental design

The study was conducted from 2020 to 2023 in five highly productive perennial farms (Table 1). In each farm, two distinct zones were established within this plot: a control zone, with no cover crop and no spontaneous vegetation, and a sustainable zone, where a cover crop was sown between the tree rows.

Each zone (control and sustainable) was replicated three times within each farm, yielding three independent sampling points per treatment per farm.

Zones ranged between 2 and 5 ha in size. Because both crop systems are woody perennial plantations with the cover crop sown in the inter-row alleys, Malaise traps were positioned within the field itself, in the inter-row area, rather than at the field margin.

The cover crop consisted of an herbaceous seed mixture of *Chrysanthemum* ssp. (3%), *Coriandrum sativum* L. (10%), *Eruca vesicaria* (L.) Cav. (5%), *Melilotus officinalis* (L.) Pall. (8%), *Onobrychis viciaefolia* Scop. (22%), *Salvia pratensis* L. (10%), *Trifolium vesiculosum* Savi (4%), and *Vicia sativa* L. (30%) (Figure 2).

Soil preparation was carried out by flail mower, after which the cover crop mixture was sown manually or by electric drill with air distribution, and the seed was subsequently covered with a drag. The sowing dose was 15 kg/ha. The cover crop was mowed and replanted each autumn.

Throughout the study, all agricultural practices were maintained unchanged, including tillage, sowing, fertilization, and phytosanitary treatments. Any management measures were confined to the crop rows to avoid interference with the multifunctional cover crop.

In control zones, conventional agricultural practices were applied, including regular tillage and pruning; in sustainable zones, tillage was minimized and herbicide application was reduced as a direct consequence of the cover crop suppressing bare-soil weed growth.

2.3 Sampling and insect analysis

Specimens were captured weekly between 2020 and 2023 using one Malaise trap placed in the center of each treatment plot, with a few exceptions due to unforeseeable circumstances. Collection bottles were replaced weekly, and captured insects were preserved in 70% ethanol until final preparation.

Trapping was conducted from early spring to late autumn each year between 2020 and 2023; sampling was suspended during the winter months owing to low ambient temperatures and correspondingly negligible insect activity. The exceptions to the weekly schedule noted above corresponded to occasional trap malfunctions or physical damage, resulting in a small number of missing sampling points (see Supplementary Figure 3).

All specimens were mounted on entomological pins and identified to species level using appropriate entomological literature (Aguado et al., 2016; Amiet et al., 2001, 2007, 2010; Cobos, 1986; Fernández-Rubio, 1991a, 1991b, 2006; Martín-Piera and López-Colón, 2000; Oosterbroek, 2006; Scheuchl, 2000, 2006; Séméria and Berland, 1988; Vives, 2000). Specimens are deposited in the Entomological Collection of the University of Valencia (Valencia, Spain; UVEG).

Insects were classified as pollinators based on established flower-visiting groups, comprising Hymenoptera (Apidae,

TABLE 1 **Characterization of the study farms including the geographic location, crop type, cultivated area, and altitude above sea level for each farm included in the study.**

Farm	Location	Crop	Area (ha)	Altitude (m)
Alhama de Murcia	Murcia	Plum	7.1	208
Almunia de Doña Godina	Zaragoza	Nectarine	4.7	389
Medina de Rioseco	Valladolid	Olive	22.7	839
Mula	Murcia	Peach	3.3	318
Pozaldez	Valladolid	Olive	21.9	769

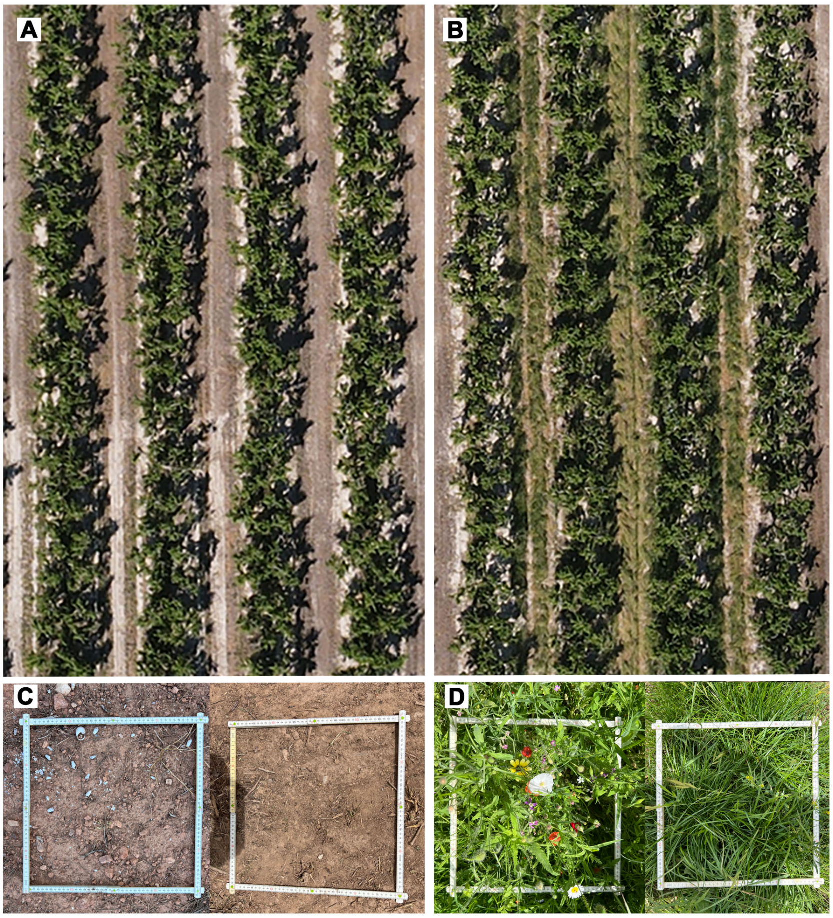

FIGURE 2
Aerial and ground-level views of the two management treatments applied in the inter-row spaces of commercial perennial farms. **(A, B)** Aerial photographs of the conventional treatment **(A)**, characterized by bare soil maintained through tillage, and the regenerative treatment **(B)**, where a multi-species cover crop mixture was established between tree rows. **(C, D)** Ground-level detail of each treatment within a standardized quadrat: the conventional inter-row space **(C)** showing dry, vegetation-free soil surface, and the inter-row **(D)** showing a dense and floristically diverse cover crop community in active growth, with multiple herbaceous species in flower simultaneously.

including the honey bee *Apis mellifera*, together with the wild bee families Megachilidae, Colletidae, Andrenidae and Crabronidae), Diptera (principally Syrphidae), Lepidoptera (Nymphalidae, Pieridae, Lycaenidae and Noctuidae), and Coleoptera (principally Buprestidae, Cerambycidae and flower-visiting Scarabaeoidea), identified using the taxonomic literature listed above. Other arthropods captured in the Malaise traps that do not act as flower visitors (e.g., predatory or parasitoid taxa, including Coccinellidae) were excluded from the dataset and subsequent analyses. A complete list of identified species and their abundances is provided in Supplementary Table 3.

2.4 Statistical analysis

Pollinator abundance, species richness and family richness were analyzed using generalized linear mixed models. Pollinator abundance was modeled with a negative binomial error distribution and a log link function to account for overdispersion. Fixed effects included management treatment (conventional vs. sustainable), crop group (olive vs. stone fruit) and year (e.g. 2020, 2021 and 2022), as well as the interaction between treatment and crop group. Farm was included as a random intercept to account for the hierarchical structure of the data and the non-independence of samples within farms.

Species richness and family richness were analyzed using generalized linear mixed models with a Poisson error distribution and log link function. These models included treatment, crop group and year as fixed effects, and farm as a random intercept. Interaction terms between treatment and crop group were initially evaluated for all response variables. For species richness, the interaction produced only a marginal improvement in model fit relative to the additive model (likelihood-ratio test: $\chi^2 = 3.54$, df = 1, P = 0.060; ΔAIC = 1.6), whereas no improvement was detected for family richness ($\chi^2 = 0.32$, df = 1, P = 0.573; ΔAIC = −1.7). Given the lack of clear statistical support, additive models were retained for both richness metrics.

Estimated marginal means and their 95% confidence intervals were calculated for all models, and results were back-transformed to the response scale for interpretation. For abundance, treatment effects were additionally estimated within each crop group to facilitate interpretation of the interaction term.

Community composition was analyzed using permutational multivariate analysis of variance (PERMANOVA) based on Bray–

Curtis dissimilarities calculated from Hellinger-transformed species abundance data. Management treatment, crop group and sampling year were included as predictors, and permutations were restricted within farms to account for the hierarchical structure of the data. Homogeneity of multivariate dispersion between treatment groups was assessed using the same dissimilarity matrix. To visualize and quantify treatment effects independently within each crop group, principal coordinates analyses (PCoA) and separate PERMANOVAs were conducted for olive and stone fruit systems. Principal coordinates were obtained using a Lingoes correction for negative eigenvalues, permutations were again restricted within farms, and homogeneity of multivariate dispersion was assessed separately for each crop group. Indicator species analysis was performed using the IndVal.g index (Dufrêne and Legendre, 1997) as implemented in the *indicspecies* package. This analysis identifies species that are both frequent and abundant within a given group while being relatively absent from other groups. Indicator values were calculated for the two management treatments, and statistical significance was assessed using 999 permutation tests. Species with $P < 0.05$ were considered significant indicators of a treatment.

All analyses were conducted in R, using the packages *glmmTMB* for model fitting, *emmeans* for *post hoc* estimation of marginal means, and *vegan* for multivariate analyses.

To assess inter-annual climatic variability, daily temperature and precipitation records from the nearest official weather stations to each of the five study farms, obtained from the open-data portal of the Spanish State Meteorological Agency (AEMET, 2026), were used to calculate mean annual temperature and total annual precipitation for each farm in each of the three study years. These annual values were compared between years using paired t-tests, with farm as the pairing unit.

3 Results

A total of 18,483 pollinator individuals were recorded across 339 samples corresponding to 172 site–time combinations distributed across five farms, comprising 167 species, 97 genera and 42 families across four orders. Pollinator communities varied among farms, with the highest species richness recorded in Mula (96 species), followed by Almunia de Doña Godina (70 species), and lower values in Alhama de Murcia (38 species), Pozaldez (31 species) and Medina de Rioseco (27 species).

Across treatments, 99 species and 32 families were recorded under conventional management, compared to 150 species and 40 families under sustainable (regenerative) management, with total abundances of 6,477 and 12,006 individuals, respectively. Differences were also observed between crop groups, with stone fruit systems supporting higher diversity (145 species, 42 families) and abundance (16,025 individuals) than olive systems (41 species, 12 families; 2,458 individuals). Species richness declined across years, from 153 species in year 1 to 100 species in year 3.

Community composition was dominated by a relatively small number of taxa, with the most abundant species including *Apis mellifera*, *Episyrphus balteatus*, and *Pollenia amentaria*. At the family level, Syrphidae was the most abundant group (32.3% of individuals), followed by Apidae (15.2%) and Muscidae (14.7%).

At the sample level, mean pollinator abundance was 9.3 individuals per sample (95% CI: 6.6–13.2) under conventional management and 33.0 (23.5–46.2) under sustainable management. Mean species richness was 3.6 species per sample (2.84–4.56) under conventional management and 8.0 (6.38–10.04) under sustainable management, while mean family richness was 2.49 (1.86–3.34) and 4.48 (3.37–5.95), respectively. Community composition differed significantly between management treatments (PERMANOVA, $F = 74.27$, $R^2 = 0.058$, $P = 0.001$). When additional predictors were included, crop group explained the largest proportion of variation in community composition ($F = 289.11$, $R^2 = 0.224$, $P = 0.001$), followed by management treatment ($F = 74.27$, $R^2 = 0.058$, $P = 0.001$) and crop season ($F = 25.38$, $R^2 = 0.039$, $P = 0.001$), whereas residual variation accounted for 66.0% of the total variance. A test for homogeneity of multivariate dispersion indicated significant differences between treatments ($F = 329.13$, $P = 0.001$). To facilitate visualization of treatment effects independently within each crop group, pollinator communities were further examined using separate principal coordinates analyses (PCoA; Supplementary Figure 4). In olive orchards, management treatment explained 26.6% of the variation in community composition (PERMANOVA: $F = 46.04$, $P = 0.001$), with no evidence of differences in multivariate dispersion between treatments ($F = 1.80$, $P = 0.182$). In contrast, treatment explained a smaller proportion of the variation in stone fruit systems (5.8%; $F = 12.66$, $P = 0.001$), where multivariate dispersion also differed significantly between treatments ($F = 12.35$, $P = 0.001$). Accordingly, separation between conventional and regenerative communities was more pronounced in olive orchards than in stone fruit systems (Supplementary Figure 4).

Indicator species analysis identified 29 significant indicator species associated with management treatment (Supplementary Table 4). Nearly 90% of these species (26 of 29) were significantly associated with regenerative management, whereas only three were indicators of conventional management. Regenerative indicator species comprised a broad range of pollinator groups, including nine bees, six hoverflies, six butterflies or moths, two predatory wasps, two beetles and one bee fly (Supplementary Table 5). The highest indicator values for regenerative management were recorded for *Apis mellifera* (IndVal = 0.877, $P = 0.001$), *Sphaerophoria scripta* (0.838, $P = 0.001$), *Eristalis tenax* (0.803, $P = 0.001$) and *Andrena flavipes* (0.595, $P = 0.001$). In contrast, only three species were significantly associated with conventional management (*Sphaerophoria* sp., *Cerceris arenaria* and *Ceratina dallatorreana*).

Pollinator abundance was significantly affected by management treatment, crop group and year, as well as by the interaction between treatment and crop group (negative binomial GLMM; Supplementary Table 1; Figure 3A). Abundance was substantially higher under regenerative management ($\beta = 1.75 \pm 0.11$ SE, z =

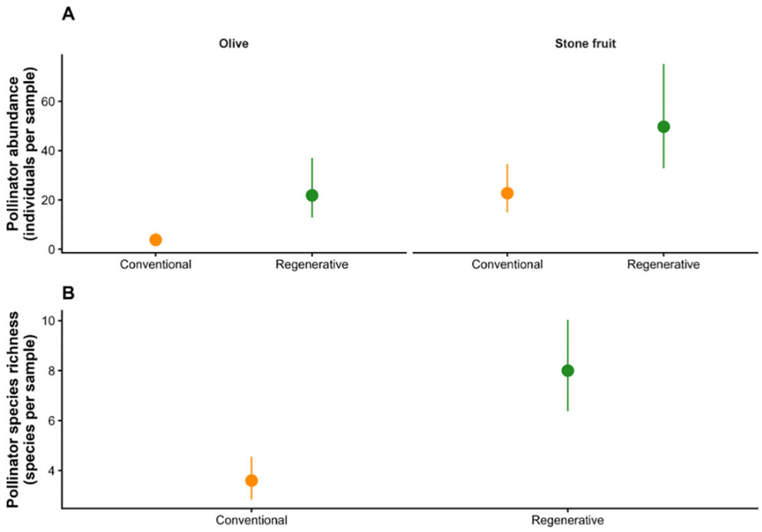

FIGURE 3
Effects of management treatment on pollinator abundance and species richness. **(A)** Pollinator abundance (number of individuals per sample) estimated from a negative binomial generalized linear mixed model including treatment, crop group, year and their interaction (treatment × crop group), with farm as a random effect. Points represent estimated marginal means and error bars indicate 95% confidence intervals, shown separately for each crop group (olive and stone fruit). **(B)** Pollinator species richness (number of species per sample) estimated from a Poisson generalized linear mixed model including treatment, crop group and year, with farm as a random effect. Points represent estimated marginal means and error bars indicate 95% confidence intervals. All estimates are back-transformed to the response scale.

16.24, $P < 2 \times 10^{-16}$), corresponding to strong multiplicative increases in abundance across crop systems (Supplementary Table 2). A significant interaction between treatment and crop group was detected (β = −0.97 ± 0.13, z = −7.17, P < 0.001; Supplementary Table 1; Figure 3A). When stratified by crop group, pollinator abundance in olive systems increased from 3.81 individuals per sample (2.22–6.52) under conventional management to 21.86 (12.90–37.06) under regenerative management, corresponding to a 5.74-fold increase (95% CI: 4.65–7.09, P < 0.001; Supplementary Table 2). In stone fruit systems, abundance increased from 22.73 (14.92–34.62) to 49.70 (32.85–75.19), representing a 2.19-fold increase (1.87–2.56, P < 0.001; Supplementary Table 2). Crop group also had a significant main effect (β = 1.79 ± 0.34, z = 5.23, P < 0.001). Year affected abundance, with lower values in year 3 (β = −0.63 ± 0.18, z = −3.42, P < 0.001), while the effect of year 2 was not significant.

Species richness was significantly affected by treatment, crop group and year (Poisson GLMM; Supplementary Table 1; Figure 3B). Richness was higher under regenerative management (β = 0.80 ± 0.04, z = 19.18, $P < 2 \times 10^{-16}$), corresponding to a 2.22-fold increase relative to conventional systems (95% CI: 2.05–2.41, P < 0.001; Supplementary Table 2). Richness was also higher in stone fruit systems (β = 0.60 ± 0.23, z = 2.63, P = 0.0085) and declined across years (year 2: β = −0.21 ± 0.07, P = 0.0022; year 3: β = −0.26 ± 0.10, P = 0.010).

Shannon diversity was significantly higher under regenerative management (β = 0.676 ± 0.047 SE, z = 14.30, $P < 2 \times 10^{-16}$), decreased across crop seasons, and showed a marginal tendency to be higher in stone fruit systems (P = 0.075). Estimated marginal means were 0.88 (95% CI: 0.65–1.10) under conventional management and 1.55 (1.33–1.77) under regenerative management. Simpson diversity showed the same overall pattern, being higher under regenerative management (β = 0.189 ± 0.021 SE, z = 8.98, $P < 2 \times 10^{-16}$) and decreasing across crop seasons, whereas crop group had no significant effect.

Family richness showed similar patterns (Poisson GLMM; Supplementary Table 1; Supplementary Figure 1). It was higher under regenerative management (β = 0.59 ± 0.05, z = 11.47, $P < 2 \times 10^{-16}$), corresponding to a 1.80-fold increase (95% CI: 1.63–1.99, P < 0.001; Supplementary Table 2), and higher in stone fruit systems (β = 0.83 ± 0.28, z = 2.92, P = 0.0035). Family richness also decreased across years (year 2: β = −0.29 ± 0.07, P < 0.001; year 3: β = −0.47 ± 0.10, P < 0.001). Estimated marginal effects of year on all three metrics are shown in Supplementary Figure 2.

4 Discussion

This study provides evidence that the adoption of sustainable management practices, specifically the incorporation of a multi-species cover crop mixture in the inter-row spaces of commercial perennial farms, is associated with substantial and consistent increases in pollinator abundance, species richness, and family richness across contrasting Mediterranean cropping systems. The magnitude of these responses, combined with their consistency across multiple crop types and three consecutive years, strengthens the case for cover crop-based management as an effective, scalable tool for pollinator conservation in agricultural landscapes, with direct relevance to the global challenge of halting insect pollinator declines (IPBES, 2016; Potts et al., 2010; Sánchez-Bayo and Wyckhuys, 2019).

The composition of the cover crop mixture warrants specific attention as a mechanistic driver of the observed pollinator responses. The mixture combined species with contrasting floral morphologies, phenologies, and reward types. Species such as *Melilotus officinalis* and *Vicia sativa* provide accessible nectar and pollen for a broad range of visitors, whereas *Salvia pratensis* selectively rewards long-tongued bees through its lever-action floral mechanism, and *Coriandrum sativum* and *Chrysanthemum* ssp., with their open floral architecture, favor short-tongued visitors including hoverflies and small solitary bees. This functional diversity in floral traits likely underpins the broad taxonomic range of pollinators recorded under regenerative management, spanning multiple orders and families with markedly different foraging morphologies (Fründ et al., 2013). The temporal staggering of flowering phenologies across component species further extends the period of resource availability throughout the growing season, potentially sustaining pollinator communities beyond the peak flowering period of the tree crops themselves. These characteristics align with growing evidence that florally diverse seed mixtures outperform monoculture or low-diversity sowings in supporting taxonomically and functionally rich pollinator assemblages (Carvell et al., 2007; Kratschmer et al., 2021) and underscore the importance of mixture design as a critical determinant of conservation outcomes in cover crop schemes.

Species richness also responded strongly to regenerative management, increasing more than two-fold relative to conventional plots, and family richness showed a similar pattern. Shannon and Simpson diversity were also higher under regenerative management, indicating that the response was not restricted to the addition of species but also involved a more even distribution of abundances within pollinator communities. Taken together, these multi-level responses suggest that the cover crop not only increased the density of already-present species but also attracted additional taxa from the surrounding landscape while reducing community dominance by a small number of common species (Garibaldi et al., 2013; Dainese et al., 2019). This finding is particularly noteworthy because it was observed in real commercial farms operating under standard agricultural conditions, rather than in experimental or semi-natural systems, thus extending the generalizability of prior evidence (Scheper et al., 2013; Albrecht et al., 2020; Peris-Felipo et al., 2025).

Community composition under regenerative management also differed significantly from that under conventional management, reflecting qualitative as well as quantitative shifts in pollinator assemblages. Indicator species analysis showed that nearly 90% of significant indicator species were associated with regenerative management, spanning a broad range of pollinator groups, including bees, hoverflies, butterflies and moths, predatory wasps, beetles and bee flies. These results indicate that the observed community shift was not driven by the response of only a few dominant taxa, but rather by changes across multiple components of the pollinator assemblage. The particularly strong compositional response detected in olive orchards further suggests that the influence of regenerative management on pollinator communities may depend on crop context. Hoverflies were among the pollinator groups most strongly represented among regenerative indicator species and are well-documented as important pollinators in both agricultural and semi-natural habitats, responding rapidly to increases in floral resource availability (Michener, 2007; Ssymank et al., 2008). Their strong representation among indicator species further highlights the value of cover crops for promoting taxonomically diverse pollinator communities. The effect of sustainable management on pollinator abundance was substantially larger in olive systems than in stone fruit systems. This differential response is likely explained by the very low baseline pollinator abundance in conventional olive plots, which probably reflects the greater structural simplicity and floral poverty of superintensive olive orchards managed under conventional soil tillage relative to peach, plum, and nectarine orchards (Miñarro and Prida, 2013). However, because crop group is confounded with farm location, size, and landscape context, part of this interaction may also reflect landscape differences rather than crop phenology alone. Crop group is also confounded with soil texture: the two olive farms (Medina de Rioseco, Pozaldez) both have sandy-loam soils (59–60% sand), whereas the three stone fruit farms have finer-textured silt-loam to silty-loam soils (62–80% silt). Because soil texture is a known determinant of nest-site suitability for ground-nesting bees (Tschanz et al., 2024), part of the observed difference in management response between crop groups may reflect this pedological contrast rather than crop type per se. In stone fruit systems, the flowering of the trees themselves may contribute non-trivially to floral resource availability in conventional plots, partially buffering the effect of management on pollinator abundance. Conversely, the proportionally larger response in olive systems suggests that these low-diversity, high-intensity cropping contexts may represent particularly high-priority targets for management intervention, where the marginal conservation benefit of incorporating a diverse cover crop is greatest (Grass et al., 2019). In absolute terms, however, stone fruit systems supported higher overall pollinator abundance and diversity than olive systems under both management regimes. This likely reflects the combined effect of crop phenology, farm size, and regional landscape context (Garibaldi et al., 2011; Lonsdorf et al., 2009). The farms cultivating stone fruits are located in more heterogeneous, lower-elevation landscapes with greater proximity to natural vegetation than the superintensive olive orchards, which are embedded in the more homogeneous Castilian plateau. Landscape context is a well-established modulator of local pollinator communities and of their response to within-field management (Tscharntke et al., 2012; Kennedy et al., 2013), and its influence cannot be disentangled from crop type effects in the present study design.

The cover crop approach evaluated here operates through multiple, non-exclusive mechanisms: it directly increases local floral resource availability, reduces bare soil extent and associated thermal stress, and may improve nesting substrate quality for ground-nesting bee species, whose brood cells are concentrated in the upper 20 cm of the soil profile and are thus particularly vulnerable to conventional tillage regimes (Tschanz et al., 2024). Critically, these benefits were achieved without modifying any other aspect of the farming system, including fertilization regimes, phytosanitary treatments, or irrigation protocols, demonstrating that meaningful biodiversity gains can be decoupled from wholesale changes in farm management. This finding is particularly relevant in the Mediterranean context, where smallholder and medium-scale perennial farms face competing agronomic and economic pressures that often constrain the adoption of more transformative land-use changes. The practical implementation of the mixture using standard farm equipment, commercially available seed, and established sowing protocols indicates that the primary barriers to adoption are informational and economic rather than technical, and that targeted advisory support and incentive structures could substantially accelerate uptake across the region.

Pollinator abundance, species richness and family richness all showed a declining trend across the three years; for abundance, however, the reduction was statistically significant only in the final year relative to the first two years, which did not differ significantly from each other. This pattern could reflect several factors, including inter-annual climatic variability, changes in cover crop productivity over time, or natural population fluctuations (Hallmann et al., 2017; Winfree et al., 2009). The Mediterranean semi-arid climate of several study sites, with pronounced drought periods and high interannual rainfall variability (Calatrava et al., 2011), may also have contributed to year-to-year variation in cover crop establishment and floral resource provision. Analysis of open-access meteorological records (AEMET, n.d.) for the five farms confirmed that the study period was not climatically homogeneous: mean annual temperature was significantly higher in the final year than in the first two years (paired t-tests across farms: year 1 vs. year 3, $t = -13.26$, $df = 4$, $P < 0.001$; year 2 vs. year 3, $t = -5.58$, $df = 4$, $P = 0.005$), whereas total annual precipitation did not differ significantly among years ($P > 0.3$ for all pairwise comparisons). This indicates that the decline in pollinator metrics in the final year cannot be attributed to reduced rainfall, but coincides with warmer conditions, consistent with evidence that rising temperatures can alter pollinator phenology, activity patterns and community structure (Duchenne et al., 2020; Calovi et al., 2021). Despite this decline, the positive effect of sustainable management remained statistically significant and ecologically substantial across all three years, indicating that the management signal is robust to inter-annual variability. The temporal decline we observed contrasts with evidence from long-term monitoring of floral margins in intensive vegetable systems, where insect abundance showed a sustained increase over a decade (Peris-Felipo et al., 2025), and with results from Brittain et al. (2022), who found that sown margins supported higher pollinator abundance than controls regardless of margin age in a large-scale European study. These apparent discrepancies may be partly due to differences in management continuity, landscape context, and the agronomic context of perennial versus annual systems. In perennial orchards, soil management practices including cover crop mowing are integrated into the annual agricultural calendar and may interact with pollinators differently than permanently maintained margins in annual cropping systems. Our results highlight the need for multi-year monitoring to separate true temporal trends from stochastic inter-annual variation. Given the observed decline, periodic cover crop renewal (for example, re-sowing every two to three years) may be required to sustain biodiversity gains over longer timeframes, as suggested by Brittain et al. (2022).

As reported above (Results), a substantial proportion of variation in community composition remained unexplained, probably due to among-farm heterogeneity in landscape context, local flora, and farm history. This partitioning is consistent with the understanding that local management and landscape-scale factors jointly structure pollinator communities, and that their relative importance depends on the spatial scale of analysis (Tscharntke et al., 2012; Garibaldi et al., 2011). Although the honeybee was among the most abundant species recorded, the sustained presence of numerous wild bee species, hoverflies, and other non-Apis pollinators under sustainable management is ecologically significant. Wild pollinators contribute disproportionately to crop pollination effectiveness relative to their abundance (Garibaldi et al., 2013; Dainese et al., 2019), and their diversity provides insurance against the loss of any single species or functional group. The substantially higher number of species and families recorded under sustainable management suggests that the cover crop mixture supports a functionally richer community with greater potential resilience to environmental perturbations (Winfree et al., 2015). The high species richness recorded at the stone fruit farms points to these systems as important reservoirs of wild pollinator diversity in the agricultural matrix of Mediterranean Spain, consistent with findings from similar Iberian landscapes (Santa et al., 2021; Miranda-Barroso et al., 2021).

While this study focused on pollinators as a focal taxon, the ecosystem service implications of the observed community shifts extend well beyond pollination. The substantially higher abundance of hoverflies (Syrphidae) recorded under regenerative management is particularly noteworthy, as larvae of the Syrphinae subfamily are voracious predators of aphids and other soft-bodied pest insects, positioning this family as a dual provider of pollination and biological pest control services (Doré et al., 2021; Jiang and Wu, 2025). Notably, *Episyrphus balteatus*, one of the most abundant species recorded in this study, is among the 25 most important biological control agents used in augmentative biological control globally, capable of suppressing aphid populations by more than 80% under field conditions (Jiang and Wu, 2025). The cover crop also contributes directly to soil ecosystem services through organic matter addition, improvement of soil aggregate stability, and reduction of erosive surface runoff, processes of particular relevance in the silt loam, semi-arid soils characteristic of several study farms, where conventional bare-soil tillage is a recognized driver of soil degradation (Calatrava et al., 2011). Quantifying these co-benefits in future research would strengthen the multifunctional case for regenerative cover crop management as an integrated conservation intervention rather than a measure justified solely by its effects on pollinators.

The results of this study have direct implications for the design and implementation of agri-environment schemes aimed at reversing pollinator declines. Europe's Common Agricultural Policy and national biodiversity strategies increasingly require soil cover management in perennial crops (Batáry et al., 2015; Pe'er et al., 2019). Our findings support the scientific basis for such policies by demonstrating that carefully designed seed mixtures of native or naturalized species, implemented consistently on commercial farms, can generate pollinator responses comparable to those previously documented only in experimental settings (Scheper et al., 2013; Albrecht et al., 2020). The particularly large increase in pollinator abundance in olive systems is relevant given the rapid expansion of superintensive olive cultivation across the

Mediterranean basin, a trend associated with widespread soil degradation and biodiversity loss.

Despite these clear benefits, uptake of multi-species cover crops remains limited across much of the Mediterranean basin. The barriers to adoption are not technical: the mixture evaluated here relies on standard farm equipment, commercially available seed, and established sowing protocols. Rather, uptake is constrained primarily by the upfront cost of seed relative to conventional bare-soil management, a lack of technical advisory support tailored to perennial cropping systems, and limited grower awareness of the yield and pest-control co-benefits documented here and elsewhere (Grass et al., 2019). Existing and emerging policy instruments could directly address these barriers: the European Union's Common Agricultural Policy eco-schemes, including Spain's national eco-regimens, already reward the maintenance of vegetation cover in permanent crops, and extending direct payments or capital grants to offset initial seed and establishment costs, combined with targeted technical assistance programs, would substantially lower the practical barriers to adoption identified here.

The capacity of within-field management to support pollinator communities is not independent of the broader landscape context in which farms are embedded: the marked differences in species richness between stone fruit and olive farms suggest that landscape composition modulates the pool of pollinator species available to respond to local management (Bishop et al., 2025). This landscape dependency could not be directly tested in the present study design and is addressed further below as a priority for future research.

This study has several limitations. Sampling used only Malaise traps, which may under sample certain ground-nesting bee taxa or species with restricted flight periods (Nieto et al., 2014). Future work should include pan traps, transect counts, or nesting assessments to provide a more complete picture of wild bee community responses. Although farms were included as a random effect, only five farms were studied, which limits statistical power to characterize farm-level variation and prevents robust inference about landscape-scale drivers or generalizability beyond these farms. An additional limitation is the absence of procedural control that would allow the effects of the sown multi-species mixture to be disentangled from those resulting from the reduction or cessation of conventional vegetation-control practices. Consequently, the observed increases in pollinator abundance, richness, and diversity cannot be attributed unequivocally to the establishment or specific composition of the sown mixture itself. Part of the observed response may instead have resulted from the increased availability of spontaneous vegetation and associated floral resources, together with reduced soil disturbance following less intensive vegetation management. This distinction is particularly relevant because spontaneous vegetation can itself provide substantial resources and habitat for pollinators and other beneficial arthropods, whereas the additional ecological benefits associated with specifically sown mixtures appear to vary among taxa, vegetation types, management regimes, and environmental contexts (Haaland et al., 2011; Karamaouna et al., 2019; Sáenz-Romo et al., 2019; Albrecht et al., 2020; Rocher et al., 2024). Future studies should therefore incorporate a spontaneous, unsown vegetation treatment alongside conventional vegetation control and sown multi-species covers to explicitly disentangle the effects of reduced vegetation control and increased ground cover from those attributable specifically to sowing and seed-mixture composition.

The study did not directly measure pollination services (e.g., fruit set, seed production) or assess the contribution of observed pollinators to crop yield, which would be needed to quantify the ecosystem service value of the management practices (Klein et al., 2007; Garibaldi et al., 2013). The lack of landscape-level data (e.g., proportion of semi-natural habitat in the surroundings, connectivity to other green infrastructure) prevents evaluation of how landscape context modulates the local effect of management. Because landscape composition is a key determinant of wild bee abundance and diversity at the farm level (Ricketts et al., 2008; Kennedy et al., 2013), future studies should incorporate landscape-scale metrics to separate local from regional drivers. Finally, future research should integrate pollination function assessments with biodiversity monitoring to provide a fuller picture of the agricultural and conservation co-benefits of cover crop management, and should prioritize replicated landscape-scale designs that separate crop type from landscape context. In particular, future work should test whether cover crops function as stepping stones facilitating pollinator recolonization in landscapes with limited semi-natural habitat, below the approximately 15–20% cover threshold identified by Bishop et al. (2025) as necessary to sustain adequate wild pollinator visitation, a mechanism that the present design could not directly evaluate.

Our study demonstrates that the implementation of a multi-species cover crop mixture under commercial perennial cropping conditions in Mediterranean Spain is associated with consistent and ecologically meaningful gains in pollinator abundance, species richness, and community diversity across crop types and multiple years. These findings provide direct, real-world evidence in support of biodiversity-oriented cover crop management as a practical tool for mitigating the negative effects of agricultural intensification on insect pollinators. They are particularly timely in the context of the global pollinator crisis and the urgent need to translate conservation science into actionable agri-environment policies and on-farm practices (IPBES, 2016; Dicks et al., 2021). We encourage broader adoption of evidence-based cover crop strategies in Mediterranean and other intensively managed agricultural landscapes as part of integrated efforts to conserve pollinator diversity and safeguard the ecosystem services on which food production depends.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

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

Author contributions

JF-G: Visualization, Investigation, Conceptualization, Supervision, Writing – review & editing, Data curation, Methodology. OA-M: Investigation, Writing – review & editing, Methodology, Data curation. AG-Q: Writing – review & editing, Supervision, Data curation, Methodology. IH: Data curation, Investigation, Methodology, Writing – review & editing. JG-P: Methodology, Writing – review & editing, Supervision, Investigation. LM-B: Conceptualization, Supervision, Methodology, Investigation, Writing – review & editing. MD: Writing – original draft, Visualization, Formal analysis, Conceptualization, Supervision, Writing – review & editing, Methodology. FP-F: Resources, Project administration, Writing – original draft, Methodology, Visualization, Conceptualization, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Funding

The author(s) declared that this work received funding from Syngenta. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

Acknowledgments

We express our sincere gratitude to Marisa and Paula (El Ciruelo; Alhama de Murcia), Luis Ramirez (Mula), Alberto Díez (Frutas Díez Soria; Almunia de Doña Godina), and the owners and technical stuff from Pago de Valdecuevas (Medina de Rioseco), and Pozaldez for graciously permitting us to carry out this study in their farms. Additionally, our heartfelt thanks go to Federico González (Syngenta) for his invaluable contributions throughout the project, and to the Idener team for their assistance with data processing.

Conflict of interest

Author OA-M was employed by the company Andrena Iniciativas y Estudios Medioambientales S.L. Author LM-B was employed by the company Syngenta España.

The remaining 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.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Generative AI (Claude 3.5 Sonnet, Anthropic) was used solely for language editing; all scientific interpretations and conclusions were produced by the authors.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2026.1871779/full#supplementary-material.

References

AEMET (Agencia Estatal de Meteorología) (2026). *Datos Abiertos* (Ministerio para la Transición Ecológica y el Reto Demográfico, Gobierno de España). Available online at: https://www.aemet.es/es/datos_abiertos (Accessed April 6, 2026).

Aguado, L. O., Viñuelas, E., and Ferreres, A. (2016). *Guía De Polinizadores De La Península Ibérica Y De Los Archipiélagos Balear Y Canario* (Madrid, Spain: Ediciones Mundiprensa & Syngenta).

Albrecht, M., Kleijn, D., Williams, N. M., Tschumi, M., Blaauw, B. R., Bommarco, R., et al. (2020). The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: A quantitative synthesis. *Ecol. Lett.* 23, 1488–1498. doi: 10.1111/ele.13576

Amiet, F., Herrmann, M., Müller, A., and Neumeyer, R. (2001). *Fauna Helvetica Apidae 3: Halictus, Lasioglossum* (Bern, Switzerland: Centre suisse de cartographie de la faune (CSCF Info Fauna) Schweizerische Entomologische Gesellschaft (SEG/SES).

Amiet, F., Herrmann, M., Müller, A., and Neumeyer, R. (2007). *Fauna Helvetica Apidae 5: Ammobates, Ammobatoides, Anthophora, Biastes, Ceratina, Dasypoda, Epeoloides, Epeolus, Eucera, Macropis, Melecta, Melitta, Nomada, Pasites, Tetralonia, Thyreus, Xylocopa* (Bern, Switzerland: Centre suisse de cartographie de la faune (CSCF Info Fauna) Schweizerische Entomologische Gesellschaft (SEG/SES).

Amiet, F., Herrmann, M., Müller, A., and Neumeyer, R. (2010). *Fauna Helvetica Apidae 6: Andrena, Meliturga, Panurginus, Panurgus* (Bern, Switzerland: Centre suisse de cartographie de la faune (CSCF Info Fauna) Schweizerische Entomologische Gesellschaft (SEG/SES).

Batáry, P., Dicks, L. V., Kleijn, D., and Sutherland, W. J. (2015). The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.* 29, 1006–1016. doi: 10.1111/cobi.12536

Bishop, G. A., Kleijn, D., Albrecht, M., Bartomeus, I., Isaacs, R., Kremen, C., et al. (2025). Critical habitat thresholds for effective pollinator conservation in agricultural landscapes. *Science* 389, 1314–1319. doi: 10.1126/science.adr2146

Brittain, C., Benke, S., Pecze, R., Pott, S. G., Peris-Felipo, F. J., and Vasileiadis, V. (2022). Flower margins: Attractiveness over time for different pollinator groups. *Land* 11, 1933. doi: 10.3390/land11111933

Calatrava, J., Barberá, G. G., and Castillo, V. M. (2011). Farming practices and policy measures for agricultural soil conservation in semi-arid Mediterranean areas: The case of the Guadalentín basin in southeast Spain. *Land Degrad. Dev.* 22, 58–69. doi: 10.1002/ldr.1013

Calovi, M., Grozinger, C. M., Miller, D. A., and Goslee, S. C. (2021). Summer weather conditions influence winter survival of honey bees (Apis mellifera) in the northeastern United States. *Sci. Rep.* 11, 1553. doi: 10.1038/s41598-021-81051-8

Carvell, C., Meek, W. R., Pywell, R. F., Goulson, D., and Nowakowski, M. (2007). Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *J. Appl. Ecol.* 44, 29–40. doi: 10.1111/j.1365-2664.2006.01249.x

Ceballos, A., Martínez-Fernández, J., Santos, F., and Alonso, P. (2002). Soil-water behaviour of sandy soils under semi-arid conditions in the Duero Basin (Spain). *J. Arid. Environ.* 51, 501–519. doi: 10.1016/s0140-1963(02)90973-0

Cobos, A. (1986). *Fauna Ibérica De Coleópteros Buprestidae* (Madrid, Spain: Consejo Superior de Investigaciones Científicas).

Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., et al. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* 5, eaax0121. doi: 10.1126/sciadv.aax0121

Deng, L., Wang, T., Hu, J., Yang, X., Yao, Y., Jin, Z., et al. (2022). Effects of pollen sources on fruit set and fruit characteristics of 'Fengtangli' plum (Prunus salicina Lindl.) based on microscopic and transcriptomic analysis. *Int. J. Mol. Sci.* 23, 12959. doi: 10.3390/ijms232112959

Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., et al. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nat. Ecol. Evol.* 5, 1453–1461. doi: 10.1038/s41559-021-01534-9

Doré, M., Fontaine, C., and Thébault, E. (2021). Relative effects of anthropogenic pressures, climate, and sampling design on the structure of pollination networks at the global scale. *Global Change Biol.* 27, 1266–1280. doi: 10.1111/gcb.15474

Duchenne, F., Thébault, E., Michez, D., Elias, M., Drake, M., Persson, M., et al. (2020). Phenological shifts alter the seasonal structure of pollinator assemblages in Europe. *Nat. Ecol. Evol.* 4, 115–121. doi: 10.1038/s41559-019-1062-4

Dufrêne, M., and Legendre, P. (1997). Species assemblages and indicator species:the need for a flexible asymmetrical approach. *Ecological Monographs.* 67, 345–366. doi: 10.1890/0012-9615(1997)067[0345:Saaist]2.0.Co;2

Fernández-Rubio, F. (1991a). *Guía De Las Mariposas Diurnas De La Península Ibérica, Baleares, Canarias, Azores Y Madeira. 1. Libytheidae, Nymphalidae, Riodinidae Y Lycaenidae* (Madrid, Spain: Ediciones Pirámide).

Fernández-Rubio, F. (1991b). *Guía De Las Mariposas Diurnas De La Península Ibérica, Baleares, Canarias, Azores Y Madeira. 2. Papilionidae, Pieridae, Danaidae, Satyridae Y Hesperiidae* (Madrid, Spain: Ediciones Pirámide).

Fernández-Rubio, F. (2006). Clave para la determinación de las especies españolas del género Zygaena Fabricius 1775 (Insecta: Lepidoptera). *Graellsia* 62, 3–12. doi: 10.3989/graellsia.2006

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., et al. (2011). Solutions for a cultivated planet. *Nature* 478, 337–342. doi: 10.1038/nature10452

Fründ, J., Dormann, C. F., Holzschuh, A., and Tscharntke, T. (2013). Bee diversity effects on pollination depend on functional complementarity and niche shifts. *Ecology* 94, 2042–2054. doi: 10.1890/12-1620.1

Garibaldi, L. A., Aizen, M. A., Klein, A. M., Cunningham, S. A., and Harder, L. D. (2011). Global growth and stability of agricultural yield decrease with pollinator dependence. *Proc. Natl. Acad. Sci.* 108, 5909–5914. doi: 10.1073/pnas.1012431108

Garibaldi, L. A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., et al. (2013). Wild pollinators enhance fruit set of crops regardless of honeybee abundance. *Science* 339, 1608–1611. doi: 10.1126/science.1230200

Giovanetti, M. (2018). Do bees like olive? A preliminary analysis of honey bee behaviour on flowers of the wind-pollinated species Olea europaea. *Acta Hortic.* 1199, 121–126. doi: 10.17660/actahortic.2018.1199.20

González-Pérez, J., Sillero-Medina, J. A., Hueso-González, P., Ruiz-Sinoga, J. D., Peris-Felipo, F. J., and Gayán-Quijano, A. L. (2025). Effects of a multifunctional cover crop (LivinGro) on soil quality indicators in Zaragoza, Spain. *Land* 14, 27. doi: 10.3390/land14010027

Grass, I., Kubitza, C., Krishna, V. V., Bäuml, L., Muszta, A., Nainu, M., et al. (2019). Trade-offs between multifunctionality and profit in tropical smallholder landscapes. *Nat. Commun.* 10, 1186. doi: 10.1038/s41467-020-15013-5

Haaland, C., Naisbit, R. E., and Bersier, L.-F. (2011). Sown wildflower strips for insect conservation: a review. *Insect Conservation And Diversity.* 4, 60–80. doi: 10.1111/J.1752-4598.2010.00098.X

Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., et al. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PloS One* 12, e0185809. doi: 10.1371/journal.pone.0185809

IPBES (2016). *The Assessment Report on Pollinators, Pollination and Food Production* (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services).

Jiang, X., and Wu, J. (2025). Research advances in biological control using predatory hoverflies as natural enemies. *Entomol. Exp. Appl.* 173, e70110. doi: 10.1111/eea.70110

Karamaouna, F., Kati, V., Volakakis, N., Varikou, K., Garantonakis, N., Economou, L., et al. (2019). Ground cover management with mixtures of flowering plants to enhance insect pollinators and natural enemies of pests in olive groves. *Agric. Ecosyst. Environ.* 274, 76–89. doi: 10.1016/j.agee.2019.01.004

Kennedy, C. M., Lonsdorf, E., Neel, M. C., Williams, N. M., Ricketts, T. H., Winfree, R., et al. (2013). A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecol. Lett.* 16, 584–599. doi: 10.1111/ele.12082

Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., et al. (2007). Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B. Biol. Sci.* 274, 303–313. doi: 10.1098/rspb.2006.3721

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* 15, 259–263. doi: 10.1127/0941-2948/2006/0130

Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guernion, M., Burel, F., et al. (2021). Enhancing flowering plant functional richness improves wild bee diversity in vineyard inter-rows in different floral kingdoms. *Ecol. Evol.* 11, 7927–7945. doi: 10.1002/ece3.7623

Lonsdorf, E., Kremen, C., Ricketts, T., Winfree, R., Williams, N., and Greenleaf, S. (2009). Modelling pollination services across agricultural landscapes. *Ann. Bot.* 103, 1589–1600. doi: 10.1093/aob/mcp069

López-Bermúdez, F., Romero-Díaz, A., Martínez-Fernández, J., and Martínez-Fernández, J. (1998). Vegetation and soil erosion under a semi-arid Mediterranean climate: A case study from Murcia (Spain). *Geomorphology* 24, 51–58. doi: 10.1016/S0169-555X(97)00100-1

Marshall, E. J. P., and Moonen, A. C. (2002). Field margins in northern Europe: Their functions and interactions with agriculture. *Agric. Ecosyst. Environ.* 89, 5–21. doi: 10.1016/s0167-8809(01)00315-2

Martín-Piera, F., and López-Colón, J. I. (2000). *Coleóptera Scarabaeoidea I* Vol. 14. Ed. M. A. Ramos (Madrid, Spain: Museo Nacional de Ciencias Naturales).

Michener, C. D. (2007). *The Bees of the World. 2nd ed* (Baltimore, MD, USA: Johns Hopkins University Press).

Miñarro, M., and Prida, E. (2013). Hedgerows surrounding organic apple orchards in north-west Spain: Potential to conserve beneficial insects. *Agric. For. Entomol.* 15, 95–104. doi: 10.1111/afe.12025

Miranda-Barroso, L., Aguado-Martín, L. O., Falcó-Garí, J. V., Lopez, D., SChade, M., Vasileiadis, V., et al. (2021). Multifunctional areas as a tool to enhance biodiversity and promote conservation in alfalfa fields. *J. Insect Biodivers. Syst.* 7, 251–261. doi: 10.52547/jibs.7.3.251

Nieto, A., Roberts, S. P. M., Kemp, J., Rasmont, P., Kuhlmann, M., García Criado, M., et al. (2014). *European Red List of Bees* (Madrid, Spain: IUCN).

Oosterbroek, P. (2006). *The European Families of the Diptera: Identification, Diagnosis, Biology* (Utrecht, The Netherlands: KNNV Publishing).

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P. H., et al. (2019). Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People Nat.* 1, 379–387. doi: 10.1002/pan3.10080

Peris-Felipo, F. J., Santa, F., Aguado-Martin, O., Gayan-Quijano, A. L., Aguado-Sanz, R., Miranda-Barroso, L., et al. (2025). A decade of protecting insect biodiversity: The impact of multifunctional margins in an intensive vegetable system. *Insects* 16, 118. doi: 10.3390/insects16020118

Ploeg, R., Ballesteros, A. R., Bartomeus, I., Kleijn, D., Scheper, J., and Alonso, E. V. (2025). Green covers effectively increase arthropod biodiversity in orchards, even at high management intensity. *Agric. Ecosyst. Environ.* 381, 109436. doi: 10.2139/ssrn.4819783

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W. E. (2010). Global pollinator declines: Trends, impacts and drivers. *Trends Ecol. Evol.* 25, 345–353. doi: 10.1016/j.tree.2010.01.007

Rey, P. J., Manzaneda, A. J., Valera, F., Alcántara, J. M., Tarifa, R., Isla, J., et al. (2019). Landscape-moderated biodiversity effects of ground herb cover in olive groves: Implications for regional biodiversity conservation. *Agric. Ecosyst. Environ.* 277, 61–73. doi: 10.1016/j.agee.2019.03.007

Ricketts, T. H., Regetz, J., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., Bogdanski, A., et al. (2008). Landscape effects on crop pollination services: Are there general patterns? *Ecol. Lett.* 11, 499–515. doi: 10.1111/j.1461-0248.2008.01157.x

Rocher, L., Melloul, E., Blight, O., and Bischoff, A. (2024). Effects of sown and spontaneous inter-row vegetation on weeds and beneficial arthropods in vineyards. *Basic Appl. Ecol.* 81, 17–24. doi: 10.1016/j.baae.2024.10.001

Sáenz-Romo, M. G., Veas-Bernal, A., Martínez-García, H., Campos-Herrera, R., Ibáñez-Pascual, S., Martínez-Villar, E., et al. (2019). Ground cover management in a Mediterranean vineyard: Impact on insect abundance and diversity. *Agric. Ecosyst. Environ.* 283, 106571. doi: 10.1016/j.agee.2019.106571

Sánchez-Bayo, F., and Wyckhuys, K. A. G. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biol. Conserv.* 232, 8–27. doi: 10.1016/j.biocon.2019.01.020

Santa, F., Aguado, O., Falcó-Garí, J. V., Jiménez-Peydró, R., SChade, M., Vasileiadis, V., et al. (2021). Effectiveness of multifunctional margins in insect biodiversity enhancement and RTE species conservation in intensive agricultural landscapes. *Agronomy* 11, 2093. doi: 10.3390/agronomy11112093

Scheper, J., Holzschuh, A., Kuussaari, M., Potts, S. G., Rundlöf, M., Smith, H. G., et al. (2013). Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss—A meta-analysis. *Ecol. Lett.* 16, 912–920. doi: 10.1111/ele.12128

Scheuchl, E. (2000). *Illustrierte Bestimmungstabellen Der Wildbienen. Band I: Anthophoridae* (Landshut, Germany: Preisinger KG).

Scheuchl, E. (2006). *Illustrierte Bestimmungstabellen Der Wildbienen Deutschlands Und Österreichs. Band Ii: Megachilidae–Melittidae. 2. Erweiterte Auflage* (Velden/Vils: Eigenverlag Erwin Scheuchl).

Séméria, Y., and Berland, L. (1988). *Atlas Des Névroptères De France Et D'europe. Mégaloptères, Raphidioptères, Névroptères Planipennes, Mécoptères* (Paris, France: Société Nouvelle des Éditions Boubée).

Ssymank, A., Kearns, C. A., Pape, T., and Thompson, F. C. (2008). Pollinating flies (Diptera): A major contribution to plant diversity and agricultural production. *Biodiversity* 9, 86–89. doi: 10.1080/14888386.2008.9712892

Sterk, G., López, M. V., and Arrúe, J. L. (1999). Saltation transport on a silt loam soil in northeast Spain. *Land Degrad. Dev.* 10, 545–554. doi: 10.1002/(sici)1099-145x(199911/12)10:6<545::aid-ldr354>3.0.co;2-s

Tschanz, P., Walter, A., Keller, T., and Albrecht, M. (2024). A review of soil tillage impacts on ground-nesting wild bees: mechanisms, implications, and future research perspectives. *Agric. Ecosyst. Environ.* 375, 109224. doi: 10.1016/j.agee.2024.109224

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. *Ecol. Lett.* 8, 857–874. doi: 10.1111/j.1461-0248.2005.00782.x

Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batáry, P., et al. (2012). Landscape moderation of biodiversity patterns and processes—Eight hypotheses. *Biol. Rev.* 87, 661–685. doi: 10.1111/j.1461-0248.2005.00782

Vives, E. (2000). “Coleóptera, cerambycidae,” in *Fauna Ibérica*, vol. 12 . Ed. M. A. Ramos (Museo Nacional de Ciencias Naturales. CSIC).

Winfree, R., Aguilar, R., Vázquez, D. P., LeBuhn, G., and Aizen, M. A. (2009). A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology* 90, 2068–2076. doi: 10.1890/08-1245.1

Winfree, R., Fox, J. W., Williams, N. M., Reilly, J. R., and Cariveau, D. P. (2015). Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. *Ecol. Lett.* 18, 626–635. doi: 10.1111/ele.12424