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Duas Faces do Manejo Agroecológico: complexidade espacial, distúrbios, e controle biológico

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Dissertação de mestrado apresentada ao Programa de Pós-Graduação *stricto sensu* em Ecologia da Universidade de Brasília como parte dos requisitos para obtenção do título de Mestre em Ecologia.

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RESUMO

A agricultura sustentável tem como um de seus grandes objetivos a substituição de insumos sintéticos por serviços ecossistêmicos, como o controle biológico; no entanto, seu êxito depende da interação entre a configuração dos habitats agrícolas e a intensidade do manejo. Neste estudo, investigamos como práticas agroecológicas influenciam a estrutura das comunidades de parasitoides e o controle biológico de afídeos em propriedades orgânicas. Entrevistas semiestruturadas foram conduzidas para caracterizar práticas relacionadas à complexidade estrutural (por exemplo, sistemas agroflorestais, plantas de cobertura e áreas de pousio seminatural) e à intensidade de distúrbio (preparo do solo, uso de produtos fitossanitários certificados para a agricultura orgânica e bioinsumos). Os parasitoides foram amostrados em habitats cultivados e não cultivados em propriedades distribuídas ao longo de gradientes de complexidade espacial e intensidade de distúrbio no Distrito Federal, Brasil. As comunidades de parasitoides apresentaram elevada sobreposição composicional entre os habitats de cultivo e de bordadura, evidenciando a vegetação não cultivada como um reservatório de inimigos naturais. A complexidade espacial não exerceu efeito significativo sobre a abundância ou a riqueza de parasitoides, enquanto a intensificação dos distúrbios reduziu a equitabilidade das comunidades. A maior riqueza de parasitoides não esteve consistentemente associada ao aumento do controle biológico; por outro lado, o controle esteve principalmente relacionado à equitabilidade da comunidade. Sistemas sob manejo de alta intensidade favoreceram poucos táxons tolerantes ao distúrbio, resultando em desequilíbrios funcionais que facilitaram surtos de afídeos, frequentemente intensificados pelo uso de insumos ricos em nitrogênio. Os resultados revelam um descompasso entre a diversificação de habitats e os regimes de distúrbio adotados, indicando que o redesenho de habitats agrícolas é insuficiente quando práticas intensivas persistem. Assim, uma transição agroecológica robusta requer o acoplamento entre a diversificação espacial e a redução de distúrbios físicos e químicos, de modo a assegurar a provisão estável de serviços ecossistêmicos.

PALAVRAS-CHAVE: Transição Agroecológica, biodiversidade, Cerrado, controle biológico conservativo, serviços ecossistêmicos, agricultura tropical

ABSTRACT

Sustainable agriculture seeks to replace synthetic inputs with ecosystem services such as biological control, but its success depends on the interplay between farm habitat design and management intensity. We investigated how agroecological practices influence parasitoid community structure and aphid biological control in organic farms. Semi-structured interviews characterized practices affecting structural complexity (e.g., agroforestry, cover crops, seminatural fallows) and disturbance intensity (soil preparation, organic-certified phytosanitary products, bioinputs). Parasitoids were sampled in crop and non-crop habitats across farms distributed along gradients of spatial complexity and disturbance intensity in Federal District, Brazil. Parasitoid communities showed high compositional overlap between crop and margin habitats, highlighting non-crop vegetation as a reservoir of natural enemies. Spatial complexity did not affect parasitoid abundance or richness, whereas intensive disturbance reduced community evenness. Greater parasitoid richness did not consistently enhance biological control; instead, control was primarily associated with community evenness. High-intensity management favored a few disturbance-tolerant taxa, creating functional imbalances that facilitated aphid outbreaks, often intensified by nitrogen-rich amendments. Our findings reveal a mismatch between habitat diversification and disturbance regimes: redesigning farm habitats is insufficient if intensive practices persist. A robust agroecological transition requires coupling spatial diversification with reduced physical and chemical disturbances to ensure stable delivery of ecosystem services.

KEYWORDS: Agroecological transition, biodiversity, Cerrado, conservation biological control, ecosystem services, tropical agriculture.

SUMMARY

INTRODUCTION

Reconciling global demand for food production with biodiversity conservation is a critical challenge for this century, since agricultural expansion remains the main threat to biodiversity and ecosystem services (Tilman et al., 2011; Caro et al., 2022). Addressing this conflict requires a fundamental shift in agricultural paradigms toward management strategies grounded in ecological processes rather than artificial inputs, such as agrochemicals and fertilizers (Emmerson et al., 2016; Kremen, 2020). In this context, organic and agroecological agriculture play a central role, as they already implement and develop technologies aligned with the agroecological transition to sustainable food systems (C. R. Anderson et al., 2019; Fonseca et al., 2024; Lavandero et al., 2025). While organic agriculture serves as a vital step by prohibiting synthetic pesticides and herbicides, it often remains focused on the substitution of external inputs (e.g., off-farm organic amendments) (Durán-Lara et al., 2020). In contrast, agroecology represents a holistic approach that integrates cultural, political, economic, and ecological principles to redesign food systems (Wezel et al., 2020). To guide this transition, the Food and Agriculture Organization (FAO) established 10 interdependent elements of agroecology to foster diverse agricultural systems that minimize reliance on both artifical and external inputs, prioritizing instead internal biological regulation and strategic ecological labour to align societal values with the provision of ecosystem services at lower environmental cost (Bicksler et al., 2023; FAO, 2018).

The application of these elements involves integrating traditional and recent farming technologies to incorporate ecological processes into farming management strategies, thereby increasing the multifunctionality of agroecosystems (C. R. Anderson et al., 2019; Giagnocavo et al., 2022; Librán-Embid et al., 2023). For example, intercropping systems such as the Mesoamerican Milpa, a traditional polyculture of maize, beans and squash; and the African push-pull technology, which uses repellent "push" crops and attractive "pull" trap plants, leverage functional complementarity to enhance structural complexity. These systems attract natural enemies and repel pest insects while simultaneously increasing natural fertilization through nitrogen fixation and organic matter accumulation (Pickett et al., 2014; Fonteyne et al., 2023). Moving beyond the crop level, broader farm interventions, such as diversified windbreaks and semi-natural patches, provide low-intensity refuges that facilitate natural enemy spillover across habitats, promoting rapid crop colonization (Togni et al., 2019; Harterreiten-Souza et al., 2021). Combining these spatial management strategies with the temporal stability of local habitats can help mitigate the impacts of disturbance and resource gaps to beneficial arthropods, ensuring year-round retention of ecosystem service providers (Hatt et al., 2017; Wyckhuys et al., 2025; Petit & Landis, 2023).

Natural biological control is a critical ecosystem service for agriculture and a cornerstone of the agroecological transition by redesigning food systems to move away from industrial dependency toward more sustainable, ecologically-based production. Within this framework, conservation biological control (CBC) is the strategy most aligned with the agroecological principles, particularly for smallholder farmers (Bicksler et al., 2023; Venzon et al., 2019). This strategy is defined as the modification of the environment or existing farming practices to protect and enhance the performance of resident natural enemies (Eilenberg et al., 2001; Venzon et al., 2019). This approach is opperationalized across three different spatio-temporal scales: i) Crop-scale: Enhancing structural heterogeneity within the cultivated area (e.g., intercropping or cover cropping) to improve micro-habitat suitability for natural enemies while minimizing resources for pest insects; ii) Farm- scale: Preserving landscape complexity by maintaining diverse habitat types (e.g., hedgerows, woodlots, or fallow areas) across the entire property to ensure the retention and recruitment of distinct functional groups; and iii) modulating disturbance regimes to ensure temporal stability of natural enemy populations (Gonthier et al., 2014; Gillespie et al., 2016; Tamburini et al., 2016; Petit & Landis, 2023).

Parasitoid wasps are good models for evaluating this management approach because of their life-history traits. The larvae develop as obligate parasites on a specific host, whereas adults are free-living and rely mainly on floral nectar (Boivin et al., 2012; Gillespie et al., 2016). Increasing floral resource availability within or near the crop area reduces the time adults spend foraging for food, thereby maximizing parasitism efficiency (Bianchi & Wäckers, 2008; Snyder, 2019). At the same time, habitat heterogeneity at the farm scale supports parasitoid communities by providing alternative hosts and food sources, while enhanced structural complexity mitigates negative interactions among natural enemies. Parasitoids are also highly susceptible to agricultural disturbances, such as soil tillage and pesticide toxicity, which hinders their biological control potential (Biondi et al., 2013; Tamburini et al., 2016). However, determining how different combinations of crop and farm scales agroecological management interact to support parasitoid communities remains a critical knowledge gap.

Bridging this gap is fundamental, as ecosystem services should be understood as a collaborative co-production between humans and nature (Bengtsson, 2015; Fischer & Eastwood, 2016). In agroecosystems, ecological labour should fulfill the conditions required for ecosystem services provisioning (Bengtsson et al., 2005; Landis, 2017; Petit & Landis, 2023). However, the response of parasitoid communities to management practices is often nonlinear and context-dependent. Consequently, single interventions may fail to deliver the expected benefits when local and surrounding habitats and disturbance regimes are unfavorable (Letourneau et al., 2015; Lindgren et al., 2018). This complexity underscores the suitability of embedding CBC strategies within a broader agroecological framework. By implementing agroecological practices, such as diversifying crop systems and minimizing articial inputs, farmers establish the multi-scale environmental conditions required to support biological control and other ecosystem services (Boeraeve et al., 2020; Fonseca et al., 2024; Kremen, 2020).

Our aim was to assess how different farm management practices drive parasitoid community diversity and the delivery of natural biological control on smallholder organic farms in a tropical region. Specifically, we asked the following questions: (1) How do organic and agroecological farms differ in relation to farming practices associated with local heterogeneity (LH), disturbance regimes (DR), and farm-scale heterogeneity (FH)? (2) How do crop and non-crop habitats shape parasitoid community structure? and (3) Do these variations in management strategies and biodiversity translate into increased biological control? We hypothesize that enhancing resource continuity through local crop diversity and a diversified farm design with natural patches will benefit parasitoid wasps by providing stable refuge and complementary resources (Simpson et al., 2011; Gurr et al., 2017; Snyder, 2019). Combining less intensive farming practices based on crop and habitat diversity is expected to harness more diverse parasitoid communities and, consequently, increase the provision of biological control in organic farms.

MATERIAL AND METHODS

Study sites

This study was conducted on 11 organic farms cropping *Brassica* species (mostly collards) in the Federal District, Brazil (15º47'S 47º54'W), from July to October 2024. The region is located in the core of the Cerrado biome, the Brazilian tropical savanna that covers 25% of Brazilian territory (IBGE, 2016). The climate of the region is type Aw according to the Köppen classification system, with a marked dry (May to October) and rainy seasons (November to March) (da Silva et al., 2008). The Cerrado comprises a mosaic of vegetation types, ranging from grasslands to forest formations near watersheds, and is considered a priority hotspot for biodiversity conservation (Myers et al., 2000; Françoso et al., 2019; Sano et al., 2019). Nevertheless, almost 60% of the native vegetation was converted to anthropogenic land uses, especially large-scale soybean crops and pasture (Sano et al., 2019).

Most of the Brazilian organic production is held by smallholder farmers who commonly employ family labor. In these farms, crops tend to be highly diverse, and non-crop vegetation hedgerows are usually present as a strategy to maintain the soil cover and reduce labor (Togni et al., 2019). In our study region, *Brassica oleracea* varieties, particularly collards, are among the main cash crops for these farmers during the dry season, (Emater-DF, 2024). Aphids stand out as one of the main pest insects of this crop, and parasitoids are among their primary natural enemies (Sampaio et al., 2017). For these reasons, we selected these brassica crops as the model for our study. Sampling was conducted during the 2024 dry season to avoid potential negative effects of rainfall on aphid populations, which could mask the effects of parasitoids and other biological control agents.

All sampled farms were small-sized (10 ± 2.78 ha SE) and had been certified as organic for at least five years. Study sites consisted of collard fields (500–2.500 m²) typically arranged in 2 × 50 m beds, each containing at least two plant rows. These farms consistently employed management practices that can influence parasitoid community, such as intercropping accompanied by non-crop plants (i.e.: herbaceous, native, or naturalized plant species) and the application of organically allowed phytosanitary products or homemade mixtures using plants (e.g., neem oil, castor bean extracts) (Harterreiten-Souza et al., 2021; Togni et al., 2019). Despite these general similarities, the specific combination and implementation of these management practices varied among farmers.

Farm management practices

We characterized agricultural management through semi-structured interviews and direct field observations at each farm (approved by the Research Ethics Committee CAAE: 67444323.0.0000.5650). Participants were selected based on the following inclusion criteria: (i) active organic certification, (ii) presence of brassica crops at the time of the visit and (iii) willingness to provide detailed historical management data. Participants who did not meet the certification standards or lacked consistent management records were excluded. The study protocol was approved by the Institutional Ethics Committee, and all participants provided informed consent prior to data collection. Data derived from the survey were assigned into three categories (i.e., local heterogeneity (LH), disturbance regime (DR), and farm-scale heterogeneity (FH)) on conservation biological control principles. (Blassioli-Moraes et al., 2022; Venzon et al., 2019; Wyckhuys et al., 2025) (Table S1).

We characterized agricultural management through semi-structured interviews and direct field observations at each farm (approved by the Research Ethics Committee, CAAE: 67444323.0.0000.5650). Participants were selected based on three inclusion criteria: (i) active organic certification, (ii) presence of Brassica crops at the time of the visit, and (iii) willingness to provide detailed historical management data. The study protocol followed Institutional Ethics Committee guidelines, and all participants provided informed consent. Based on conservation biological control principles (Venzon et al., 2019; Wyckhuys et al., 2025), data were assigned into three categories: Local Heterogeneity (LH), Disturbance Regime (DR), and Farm-Scale Heterogeneity (FH) (Table S1).

Local Heterogeneity (LH) refers to the structural complexity and resource availability within sampled plots, encompassing intercropping arrangements, soil coverage, and spontaneous vegetation. These features were selected as proxies for habitat permeability and resource provision (Simpson et al., 2011). To transform categorical field data into a continuous index, we calculated a Soil Coverage Score (*SC*):

$$SC = w \times n$$

Where w is the weighted score for coverage type (0: no coverage; 1: inert/plastic mulch; 2: dead mulch; 3: living coverage; 4: combined dead and living coverage) and n is the number of distinct components (species or material types) identified in the field.

The disturbance regime quantifies practices that induce parasitoid mortality or emigration (Schellhorn et al., 2014). We focused on soil preparation and the use of phytosanitary inputs, generating two continuous indices:

1. Soil Preparation Index (*SP*): This index quantifies the cumulative physical impact of tillage and amendment intensity:

   $$SP = (M \times \bar{A}) \times f_{soil}$$

   Where M is the machinery weight score (0: no tillage to 4: heavy machinery), $\bar{A}$ is the mean amendment intensity (weighted average of mineral, organo-mineral, and organic classes relative to total amendment diversity), and f_{soil} is the annual frequency of soil management operations.

2. Phytosanitary Pressure Index (*PP*): This index measures cumulative toxicity and disturbance stress, accounting for lethal and sublethal effects even in organic-certified systems (Biondi et al., 2013). It was calculated as:

   $$PP = \sum(D \times T) \times f_{app}$$

   Where D is the diversity of unique products of each toxicity class, T is the toxicity weight based on the IOBC hazard classification (Thomson & Hoffmann, 2006), and f_{app} is the application frequency throughout the crop cycle.

The farm-scale heterogeneity category was intended to evaluate the presence and quality of alternative habitats within farm boundaries. This category included the implementation of agroforestry systems, overall crop diversity, the maintenance of fallow areas, and the maintenance of seminatural patches. These elements were included to account for source-sink dynamics, as they provide refuge and shelter that sustain natural enemies even during unfavorable periods (Letourneau et al., 2015; Landis, 2017; da Silva et al., 2025).

Experimental design and insect sampling

Parasitic hymenopterans were sampled using pan-traps to evaluate their abundance, species richness, and community composition in crop and non-crop areas. These traps were made with fluorescent-yellow painted 250 mL plastic bowls attached to 1.2 m stakes and filled with 200 mL of a solution of 50% water, 30% propylene glycol, and 20% alcohol. On each farm, we installed nine traps in crop areas and nine on margins with non-crop plants (n = 18 traps per farm), since parasitoid species could move between both habitats. Crop and non-crop areas were separated by at least 10 m, while pan-traps were arranged in triads spaced 5 m apart, with 2 m between individual traps. This design was selected to reduce the chance of sample loss and to increase the attractiveness of the sampling points. The traps were exposed in the field for four days, after which the parasitoids were taken to the laboratory for sorting and identification. Individuals were identified at the family level and classified into morphospecies. This procedure was made in order to assess diversity, species richness and community composition of parasitic wasps in the crop area and immediate margins. Each farm was sampled once, concurrently with the assembly of the biological control experiments (see next section).

To estimate host densities in the crop area, we randomly selected 40 collard plants in the vegetative stage.. Samples occurred on the same day we assembled the pan-traps. On each plant, we randomly selected three leaves at different heights and counted the number of aphids on each leaf. After that, we summed the number of aphids per leaf to obtain an estimate of the number of aphids per plant. Aphids were counted, identified to the species level, and for each species we counted the number of apterous, winged and parasitized aphids on each leaf.

Biological control services

We estimated aphid biological control using an exclusion experiment based on Gardiner et al. (2009), which was assembled on the same day as aphid sampling and remained active for four days. For each site, we randomly selected 30 collard plants in the vegetative stage, all infested with aphids. On each plant, one infested leaf was enclosed in an exclusion bag (30 × 20 cm, voile fabric) to restrict access by parasitoids and other insects (treatment). Another infested leaf in the same plant was then marked with a string and left open, providing free access for natural enemies (control). This procedure was used to avoid differences caused by plant physiology and factors that could affect aphids and their natural enemies. During setup, all organisms other than aphids were removed from the leaves. The numbers of apterous, winged, and parasitized aphids were counted for each treatment and control. We selected leaves with similar aphid abundance in the same plant to maintain comparability among treatments and controls. The leaves used in this experiment contained between 10 and 100 aphids, depending on the aphid infestation level at each farm. This experiment allowed estimation of the efficiency of biological control and the contributions of parasitoids to aphid natural biological control. To evaluate the Biological Control Service Index (BSI) and parasitism ratios, differences in mean aphid population values between the two treatments were calculated as the reduction in aphid abundance on open leaves relative to caged treatments after four days. The BSI ranges from 0 to 1, with 0 indicating no control and 1 indicating complete control (Gardiner et al., 2009).

Statistical analyses

All statistical analyses were carried out using R 4.5.2 (R Core Team, 2025). To characterize farm management, we first standardized the continuous management variables and indices calculated in the previous section to z-scores, ensuring that variables with different measurement units contributed equally to the multivariate analysis (Paas & Groot, 2017; Vázquez-González et al., 2024). We then performed a Spearman correlation analysis to avoid multicollinearity and remove highly redundant variables ($r > |0.7|$). The remaining variables were subjected to a Principal Component Analysis (PCA) using the *factoMineR* package (Lê et al., 2008). We retained the first two principal components which explained more than 50% of the cumulative variance (PC1 and PC2). We interpreted the axes considering variables with loadings $> |0.5|$ as significant drivers of farm separation.

To evaluate sampling completeness, we plotted individual-based rarefaction and extrapolation curves for crop and non-crop habitats using the Chao-1 estimator in the *iNEXT* package (Chao et al., 2014; Hsieh et al., 2025). We further compared community structure using

Hill numbers of order $q = 0$ (Species Richness), $q = 1$ (Shannon diversity) and $q=2$ (Simpson Diversity). To assess differences in community composition between habitats, we performed Non-Metric Multidimensional Scaling (NMDS) based on Bray-Curtis dissimilarities using the *vegan* package (Oksanen et al., 2025). We tested for statistical differences in composition using Permutational Multivariate Analysis of Variance (PERMANOVA, *adonis2* function) and verified homogeneity of multivariate dispersion using PERMDISP (*betadisper* function).

To evaluate parasitoid diversity, we calculated total abundance (N), species richness (S), the Shannon-Wiener (H') and inverse Simpson's diversity indexes (1/D), and the Shannon evenness (J) for each sampling site. We analyzed the effects of farm management intensity and community structure using a two-step modelling approach: First, we used Generalized Linear Models (GLM) to assess how farm management influences the community parameters. We modeled parasitoid community metrics (abundance, richness, diversity, evenness, dominance) and aphid infestation (apterous, alate and parasitized abundance, and BSI) as response variables, with the PCA scores (PC1 and PC2) as fixed explanatory variables. We then performed linear models (LMs) to assess whether the biological control service was driven by parasitoid community structure. We modeled log- transformed aphid density (per plant) and the BSI as response variables against parasitoid abundance, richness, transformed Shannon diversity ($e^{H'}$), inverse Simpson diversity, Pielou's evenness, and the Berger-Parker dominance index.

The error distributions were selected based on data properties and validated by comparing AIC values and residual diagnostics. Count data (e.g., abundance, richness) were modeled using negative binomial distributions to account for overdispersion. Continuous indices bound between 0 and 1 (e.g., Pielou's evenness, Berger-Parker) were modeled using Beta distributions (logit link), while positive continuous indices (e.g., inverse Simpson, BSI) were modeled using gamma distributions (log link). Standard linear models (Gaussian distribution) were used for log-transformed density data, when residuals met normality assumptions. Model fit was validated by visual inspection of residuals (Q-Q plots and residual vs. predicted plots), using the DHARMa package (Hartig et al., 2024).

RESULTS

Agroecological management practices used by local farmers

Analysis of the local heterogeneity (LH) variables revealed that 72% of the sampled plots utilized intercropping systems. Soil coverage management varied, with 73% of farms maintaining living or dead coverage, while 27% utilized inert protection (mulch plastic) or bare soil. Regarding the disturbance regime, 55% of the farmers employed light-weight or no mechanization, whereas 18% utilized heavy machinery such as sub-compact tractors and harrows. The frequency of phytosanitary management varied considerably, with an average of 1.38 ± 0.53 (SE), and 45% of the farms applied high-impact products such as neem oil, while 27% did not apply any phytosanitary product for pest management. Regarding farm-scale heterogeneity, 64% of farms incorporated agroforestry systems into their production matrix. Additionally, 45% of the farms maintained permanent preservation areas (APPs) or native buffers near cultivated plots.

The farmers employed a diverse array of management practices across the sampled farms, but PCA identified two distinct gradients that explained 54.9% of the variation among farms (Figure 1; Table 1). The first principal component (PC1) described a gradient of farm-scale spatial management strategies. This axis distinguished farms by the type of spatial management, with positive loadings for green manure (0.75) and agroforestry systems (0.66). Conversely, practices related to passive vegetation maintenance produced negative loadings for fallow areas (-0.61) and semi-natural vegetation (-0.60). The second axis (PC2) represented the intensity of disturbances, characterized by positive loadings for soil preparation (0.73) and the frequency of phytosanitary product use (0.68).

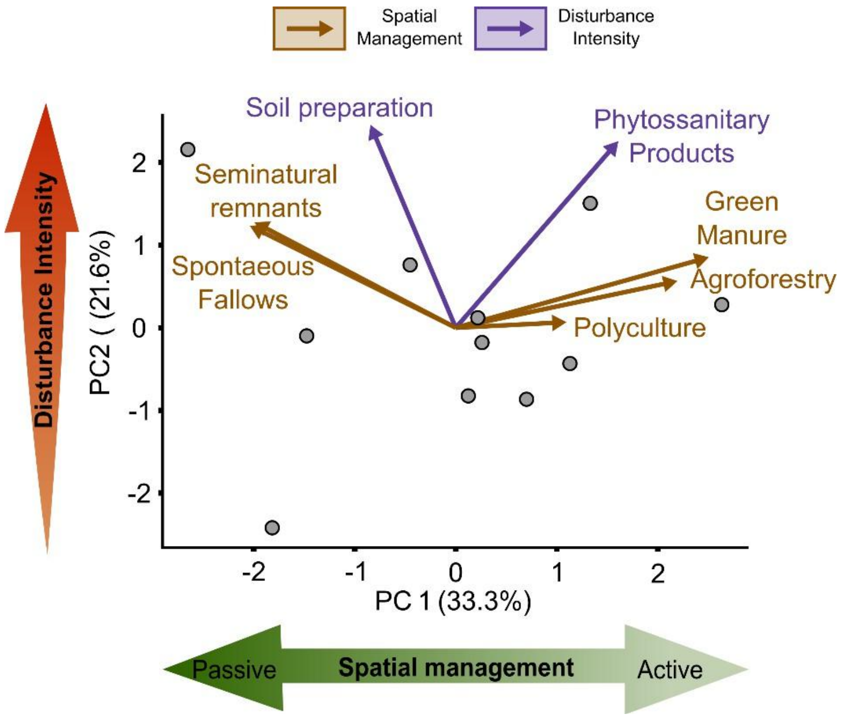

FIGURE 1. Principal Component Analysis (PCA) characterizing agricultural management intensity across 11 organic-certified farms in Distrito Federal, Brazil. PC1 (33.3% variance)

represents a gradient of spatial management. PC2 (21.6% variance) represents the disturbance regime, associated with soil preparation and phytosanitary pressure. Arrows indicate the direction and strength of variable loadings along PC1 (yellow) and PC2 (purple); points represent individual farm properties.

TABLE 1. Results of the Principal Component Analysis (PCA) assessing the distribution of surveyed farming practices. Bold values indicate absolute factor loadings > 0.50, representing the inputs most strongly associated with each PCA axis (PC1 and PC2).

Variable	PC1	PC2
Green Manure	**0.754**	0.257
Agroforestry	**0.656**	0.169
Polycylture	**0.312**	0.019
Soil Preparation	0.257	**0.733**
Phytosanitary Pressure	0.483	**0.678**
Seminatural Patches	**-0.596**	0.382
Unmanaged Fallows	**-0.610**	0.369
Eigenvalue	2.119	1.373
Variance explained	33.3%	21.6%

Insect communities and the influence of agroecological management practices

In total, we recorded 32,483 aphid individuals across the sampled farms. We found three aphid species infesting collards, *Brevicoryne brassicae, Myzus persicae, and Lipaphis pseudobrassicae*, with a mean density of 68.79 ± 19.75 (mean ± SE) aphids per plant, considering all farms. *Brevicoryne brassicae* was the dominant species (49.98 ± 16.02), representing 67% of total aphid abundance, followed by *L. pseudobrassicae* (18.21± 4.51) and *M. persicae* (5.48 ± 1.80). We sampled 863 parasitoid individuals, forming a more diverse assemblage comprising 211 morphospecies across 28 families, with a mean abundance of 78.36 ± 13.19 individuals per farm. The community was dominated by the families Scelionidae (*n*= 196 individuals), Figitidae (*n*= 144) and Diapriidae (*n*= 91), which together accounted for 49.9% of parasitoid total abundance (Table 2). At the morphospecies level, Figitidae-01 (*n*= *57)*, Figitidae-02 (*n*= *29)* and Scelionidae-02 (*n*= 20) were the most abundant morphospecies found on crop areas. In non-crop areas, the dominant morphospecies were Diapriidae-01 (*n*= 42), Scelionidae-02 (*n*= 34) and Scelionidae-07 (*n*=17).

TABLE 2: Taxonomic composition and abundance distribution of hymenopteran parasitoids collected in cultivated areas (crop) and semi-natural borders (non-crop).

Parasitoid Family	Crop	Non-crop	Total
Scelionidae	74	122	196
Diapriidae	21	70	91
Encyrtidae	34	56	90
Figitidae	98	46	144
Eulophidae	17	27	44
Braconidae	9	23	32
Pteromalidae	16	21	37
Mymaridae	20	19	39
Ceraphronidae	5	19	24
Ichneumonidae	10	14	24
Platygastridae	6	11	17
Tanaostigmatidae	2	11	13
Dryinidae	6	10	16
Chalcididiae	4	9	13
Eupelmidae	1	6	7
Torymidae	2	5	7
Bethylidae	1	5	6
Perilampidae	1	4	5
Aphelinidae	22	3	25
Trichogrammatidae	15	2	17
Epichrysomallidae	2	2	4
Evaniidae	1	2	3
Signiphoridae	1	1	2
Crabronidae	1	1	
Eurytomidae	1	1	
Ismaridae		1	1
Trigonalidae	2		2
Agaonidae	1		1

Our sampling effort gathered 80% of the estimated parasitoid species richness in the crop (N= 371, S_{obs}= 120) and 85% non-crop areas (N= 491, S_{obs}= 168), based on the Chao-1 estimator. Rarefaction curves revealed that while species richness (q= 0) did not differ significantly between habitats, non-crop areas exhibited higher diversity at the orders of q= 1 (Shannon) and q= 2 (Simpson) (Figure 3). However, non-crop (J'= 0.88, BP= 0.08) and crop areas (J'= 0.83, BP= 0.15) supported similarly even communities, because community structure in both habitats were represented by several rare species (Figure 2). Regarding community composition, crop and non-crop parasitoid assemblages showed a high degree of overlap (Figure 4; Stress = 0.16), which was statistically confirmed by a PERMANOVA (F = 1.12, R^2 = 0.053, df = 20, p = 0.12). Furthermore, we found no significant heterogeneity in multivariate dispersions based on the PERMDISP analysis (F= 2.96, *d.f.= 20, p= 0.11),* confirming that the PERMANOVA results were not biased by differences in sample variance between habitats.

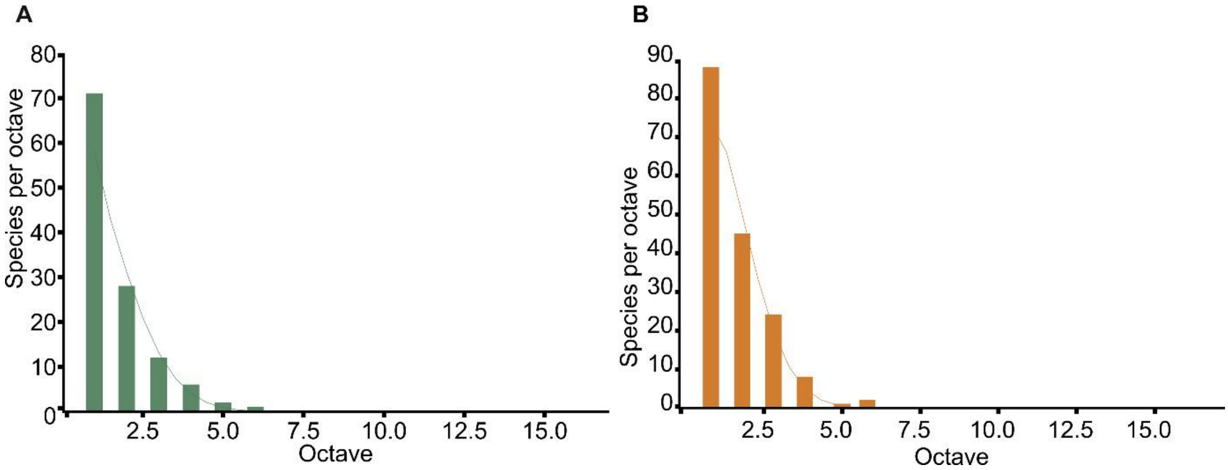

FIGURE 2. Species abundance distributions for parasitoid communities in (A) non-crop and (B) crop habitats in farms cropping organic collards in the Federal District, Brazil. The histograms display the frequency of species grouped into abundance octaves (*Log_2* scale). Solid lines represent the fitted Preston Log-Normal distribution model. The high frequency of species in the first octaves indicates a community characterized by a large proportion of rare species in both habitat types.

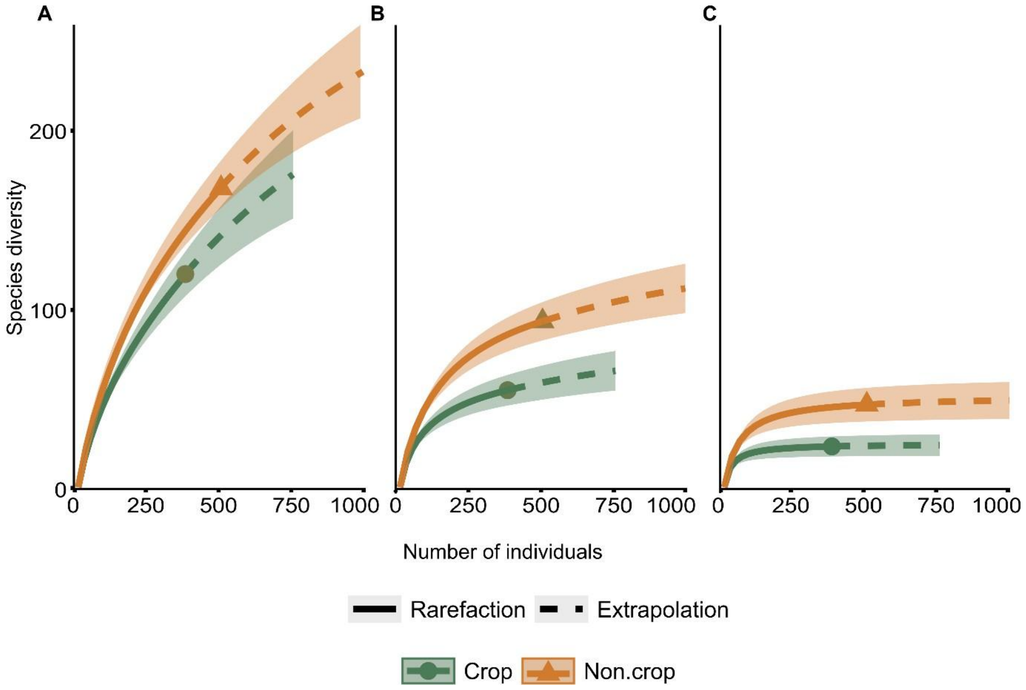

FIGURE 3. Individual based curves (solid lines) and extrapolation (dashed lines) curves for parasitoid community in Brassica fileds (green) and non-crop fields (orange). Diversity is estimated using Hill numbers of order q: A) species richness (q = 0), B) Shannon diversity (q = 1) and C) Simpson diversity (q = 2). Shaded areas represent the 95% confidence intervals based on bootstrap resampling.

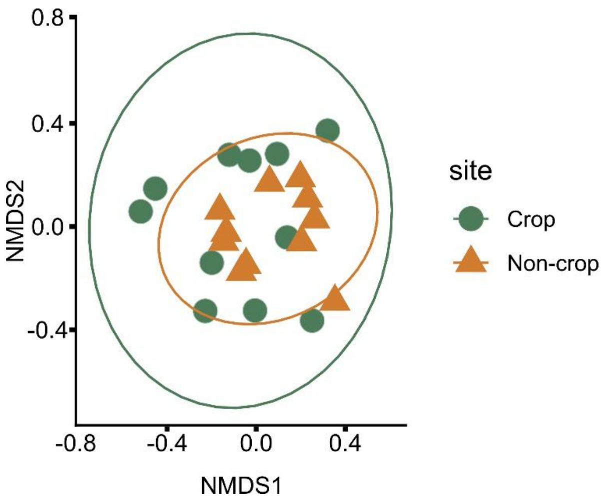

FIGURE 4. Community composition based on the Bray-Curtis dissimilarities in crop (green) and non-crop habitats (orange). Points represent individual sampling sites, and ellipses indicate the 95% confidence intervals. Stress value = 0.16.

Regarding farm-scale spatial management (PC1), the presence of agroforestry systems, green manuring, and semi-natural habitats showed no significant effects on total parasitoid abundance, species richness, or community evenness (Table 3). In contrast, while the intensity disturbance (PC2) similarly failed to explain variations in total parasitoid abundance or species richness (Table 3), it emerged as a primary driver of community structure across the farms (Figure 5). Specifically, Pielou's Evenness (J) was negatively associated with the intensity of disturbances (PC2) (Figure 5A; Table 3). This decline in evenness was further corroborated by the Simpson Diversity index, which increased significantly with higher disturbance intensity (Figure 5B; Table 3).

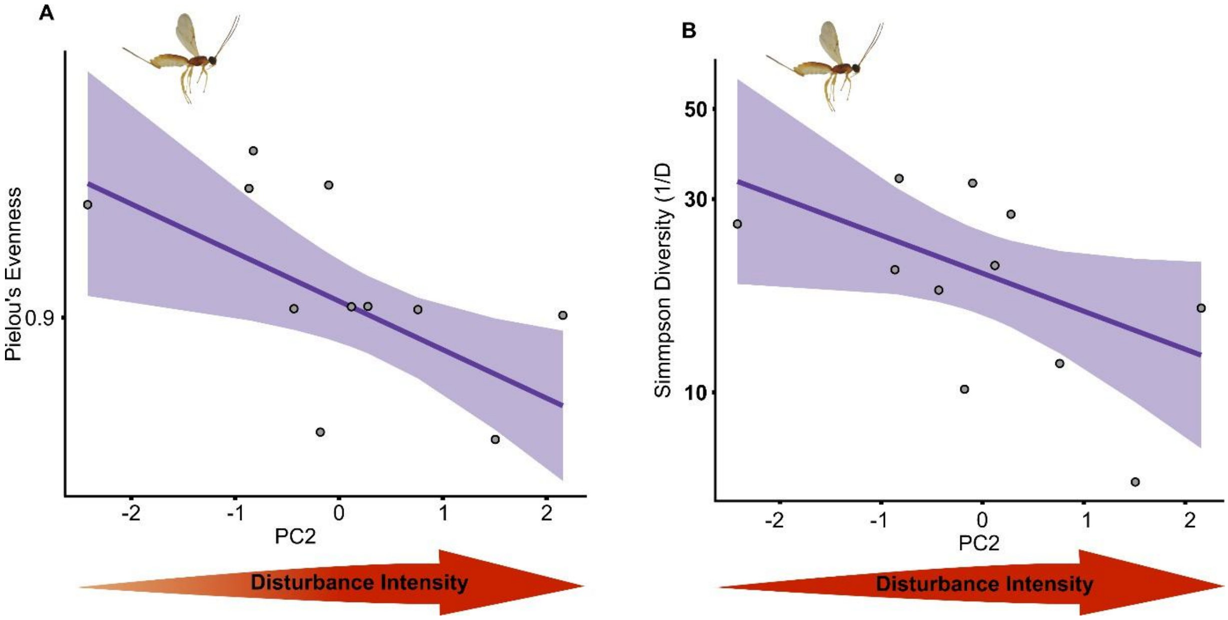

FIGURE 5. Impact of disturbance intensity employed in organic farms cropping collards in the Federal District, Brazil, on parasitoid community structure in terms of Pielou's Evenness (J) (A) and Simpson Diversity Index (B). Shaded regions represent 95% confidence intervals.

TABLE 3. Results of the Generalized Linear Models assessing the relationship between Parasitoid abundance, richness, Shannon diversity, inverse of Simpson diversity and composition with farming practices related to spatial complexity and disturbance intensity (PC1 and PC2 as described in the 'Farming practices' section).

Response Variable	*Parameter*	*Estimate*	*SD*	*Z-value*	*P*
Parasitoid Abundance (N)	PC1	0.13	0.09	1.45	0.147
Parasitoid Abundance (N)	PC2	0.04	0.12	0.34	0.737
Species Richness	PC1	0.07	0.05	1.38	0.168
Species Richness	PC2	-0.04	0.07	-0.61	0.543
Shannon Diversity	PC1	0.02	0.05	0.32	0.751
Shannon Diversity	PC2	-0.12	0.07	-1.78	0.075
Pielou's Evenness (J)	PC1	-0.17	0.10	-1.71	0.087
Pielou's Evenness (J)	**PC2**	**-0.3G**	**0.15**	**-2.56**	**0.010**
Inverse Simpson (1/D)	PC1	-0.04	0.08	-0.50	0.616
Inverse Simpson (1/D)	**PC2**	**-0.22**	**0.11**	**-1.G2**	**0.054**
Berger-Parker	PC1	0.13	0.09	1.34	0.180
Berger-Parker	**PC2**	**0.31**	**0.14**	**2.18**	**0.02G**

Aphid infestation and natural biological control

Aphid abundance and biological control were significantly affected by farm management intensity. Specifically, the spatial management complexity was a positive predictor of apterous (Fig 6- B*)*, alate and parasitized absolute abundance. Similarly, disturbance intensity) had a neutral effect on alate aphids, but a positive effect on the density of apterous (Figure 6B) and parasitized aphids. However, despite this increase in the absolute number of parasitized aphids, the BSI decreased significantly with the presence of agroforestry systems and green mulched areas (Figure 6A; Table 4). Regarding the parasitoid community metrics, neither parasitoid total abundance per farm nor species richness affected the provision of biological control services. Instead, Pielou's evenness (*J'*) exerted a strong negative effect on apterous aphid densities (Figure 6C), while the Berger-Parker dominance index benefitted aphid infestation (Figure 6D; Table 5), suggesting that more even assemblages of parasitoids were more effective in regulating aphid populations.

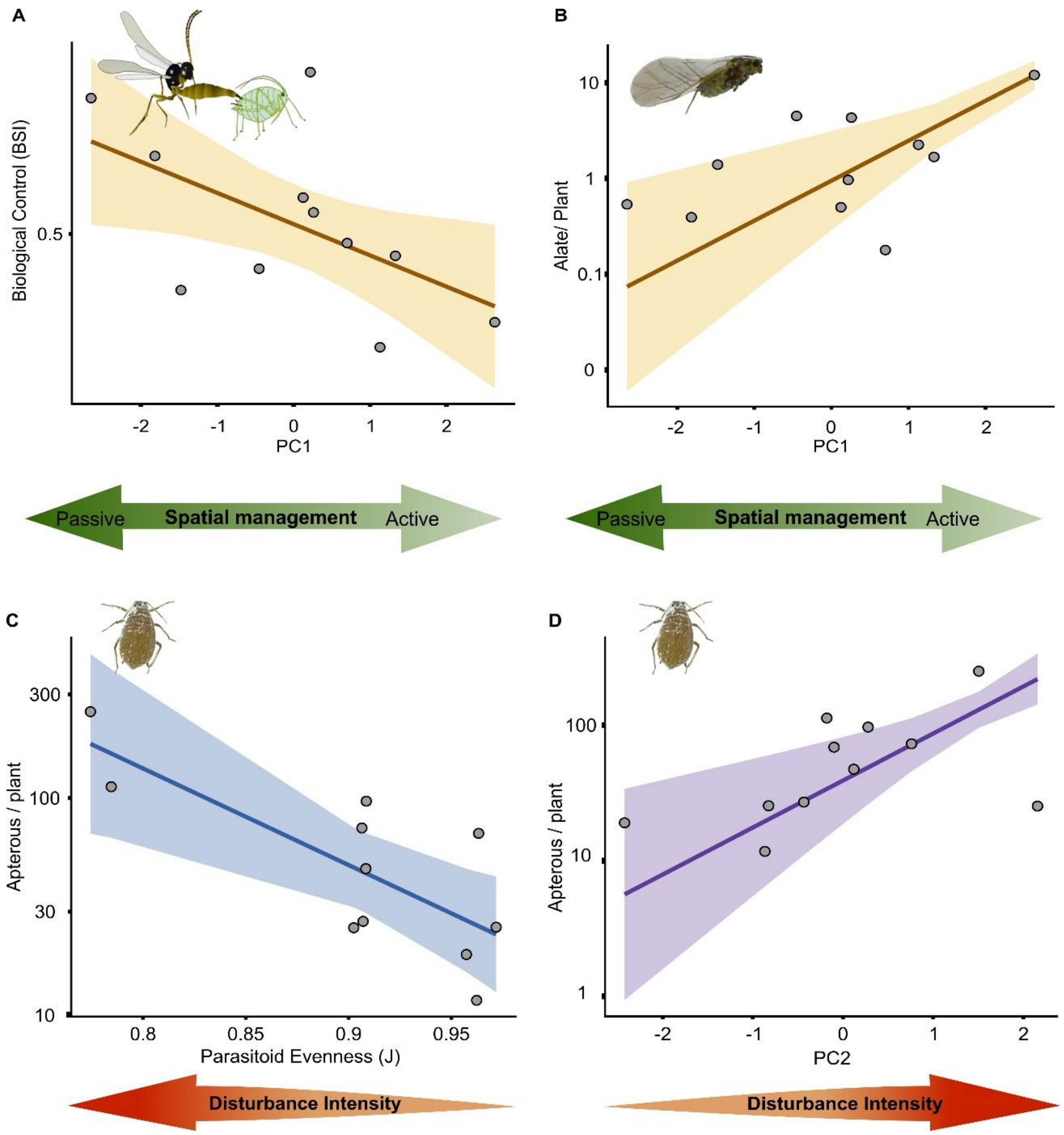

FIGURE 6. Effects of farm management intensity and parasitoid community composition on biological control and pest dynamics. (A) The response of the Biological Control Service Index (BSI) and (B) apterous aphid abundance to the gradient of spatial management intensity (PC1). (C) The relationship between apterous aphid abundance and parasitoid community evenness (Pielou’s J) and (D) Disturbance intensity (PC2). Solid lines represent model estimates, and shaded areas indicate 95% confidence intervals. Green arrows indicate the quality of the spatial management; red arrows indicate the direction of distubance gradients; points represent observed values for each farm.

TABLE 4. Results of the Generalized Linear Models assessing the relationship between biological control, aphid density per plant (apterous, alate and parasitized) with farming practices related to spatial complexity and disturbance intensity (PC1 and PC2 as described in the 'Farming practices' section). All model families were selected according to data distribution, later confirmed by analysis of the residuals (residuals *df = 7)*.

Model	*Parameter*	*Estimate*	*SE*	*Z-value*	*P*
Biological Control Service Index (BCI)	PC1	-0.16	0.07	-2.23	**0.026**
Biological Control Service Index (BCI)	PC2	0.02	0.09	0.24	0.809
Aphid Density (Apterous/plant)	PC1	0.40	0.11	3.64	**< 0.001**
Aphid Density (Apterous/plant)	PC2	0.80	0.23	3.46	**< 0.001**
Aphid Density (Alates/plant)	PC1	0.96	0.26	3.73	**< 0.001**
Aphid Density (Alates/plant)	PC2	-0.06	0.29	-0.22	0.825
Parasitized Aphid abundance	PC1	1.08	0.20	5.42	**< 0.001**
Parasitized Aphid abundance	PC2	2.69	0.41	6.51	**< 0.001**

TABLE 5. Influence of parasitoid community structure on pest regulation. Model estimates showing the relationship between diversity indices (abundance, richness, evenness) and aphid infestation levels alongside biological control provision

Response Variable	**Predictor**	**Estimate**	**SE**	**Statistic**	**P-value**
Apterous aphids/plant	Abundance	0.011	0.006	1.934	0.085
	Species Richness	0.024	0.024	1.006	0.341
	Shannon Diversity	-0.028	0.035	-0.807	0.441
	Pielou’s Evenness	-10.240	2.908	-3.522	**0.006**
	Inverse Simpson	-0.043	0.030	-1.443	0.183
	Berger-Parker Dominance	6.029	2.348	2.568	**0.030**
Alate aphids/plant	Abundance	-0.001	0.003	-0.249	0.809
	Species Richness	-0.006	0.012	-0.496	0.632
	Shannon Diversity	0.293	2.168	0.135	0.895
	Inverse Simpson	-0.002	0.016	-0.096	0.926
	Pielou’s Evenness	0.293	2.168	0.135	0.895
	Berger-Parker Dominance	-0.693	1.478	-0.469	0.650
Biocontrol Service Index	Abundance	0.018	0.007	2.374	**0.042**
	Species Richness	0.057	0.030	1.922	0.087
	Shannon Diversity	0.010	0.050	0.205	0.842
	Pielou’s Evenness	-8.837	5.397	-1.638	0.136
	Inverse Simpson	-0.032	0.044	-0.722	0.489
	Berger-Parker Dominance	3.960	4.027	0.983	0.351

DISCUSSION

Our findings demonstrate that non-crop habitats act as reservoirs of local parasitoid species, with significantly higher richness and evenness, serving as sources for dispersal into cultivated areas. This indicates that the diversity within parasitoid assemblages on crops depends on the constant spillover of parasitoids from the surrounding non-crop habitats. However, we observed a clear trade-off in farm-scale spatial management: shifting from passive features, such as spontaneous fallows and native vegetation remnants, toward active management such as agroforestry systems and green manuring, was associated with reduced biological control and increased aphid outbreaks. Simultaneously, higher disturbance intensity, characterized by frequent soil management and phytosanitary applications, further simplified the parasitoid community and hampered biological control service provision. These findings highlight that agroecological interventions must be guided by frameworks that prioritize conserving the existing seminatural habitats, as they are crucial for natural enemy recruitment, ensuring that any increase in planned structural complexity is accompanied by a decisive reduction in mechanical and chemical disturbances to protect the community’s functional stability.

We found a wide diversity of agroecological pathways followed by organic and agroecological farmers, varying primally along a gradient of spatial complexity (PC1). This variation reflects two complementary strategies supported by our data. First, the maintenance of passive spatial features and the active integration of structural complexity within the crop. Second, the contribution of farm-scale heterogeneity to the spatial axis highlights the importance of passive features, such as spontaneous fallows and semi-natural fragments. These areas function not as “unproductive” land, but as essential ecological infrastructure. Our results suggest that these features support parasitoid diversity (Simpson) and evenness (J) probably by providing microclimatic stability and shelter (Gurr et al., 2017; Venzon et al., 2019). Furthermore, these undisturbed areas likely serve as critical repositories for alterative non-pest hosts, allowing specialized parasitoid populations to persist locally (Isbell et al., 2017; Togni et al., 2019). In practical terms, farmers should prioritize the preservation and integration of these existing semi-natural patches as permanent ecological infrastructure that ensures a continuous spillover of natural enemies into the productive system (Blassioli-Moraes et al., 2022; da Silva et al., 2025).

Complementing these farm-scale features, the local heterogeneity variables, specifically the implementation of agroforestry systems and green mulch represent an active strategy to reproduce natural succession and vertical stratification (Elevitch et al., 2018; Paudel et al., 2025). Theoretically, these features are cultivated to deliver specific ecosystem services as they facilitate parasitoid recruitment by increasing nectar availability, essential for parasitoid longevity and fecundity and release volatile chemical attractants that signals host availability, concentrating natural enemy activity within the crop matrix (Simpson et al., 2011; Foti et al., 2017). Simultaneously, these plant assemblages are expected to disrupt pest colonization through chemical repellence, where the emission of non-host plant volatiles masks the chemical signature of the crop, or directly deters aphid settlement (Togni et al., 2010, 2019). However, contrary to the expectation that complexity linearly enhances biological control, we observed that farms scoring high on this spatial axis exhibited increased densities of alate aphids and a reduction in the BSI. This result indicates that these environments can inadvertently provide superior conditions for pests, like nutritional pulses, which can favor pest outbreaks (Simon & Peccoud, 2018). While effective for active recruitment, planned systems often lack the microclimatic buffering of spontaneous fallows (Altieri & Nicholls, 2019; Togni et al., 2019). Consequently, our findings suggest that actively managed features should supplement, rather than replace resident biodiversity (Balmer et al., 2014; Peñalver-Cruz et al., 2019). Robust agroecological transition guidelines must therefore prioritize a synergistic design by implementing planned diversity to enhance immediate trophic interactions while maintaining the resident vegetation to allow community persistence (Wyckhuys et al., 2025).

The parasitoid community was characterized by a high taxonomic diversity, extending far beyond specific aphid parasitoids. This elevated richness reinforces the environmental benefits of organic and agroecological farming, demonstrating that these systems serve as critical habitats for parasitoids (Vargas et al., 2023). However, while the spillover from these borders ensures high taxonomic richness within the farms, this did not translate into an effective functional composition for aphid control. The crop community was dominated by generalist Scelionidae and Figitidae, whereas the primary aphid specialists (Braconidae and Aphelinidae) represented a minor fraction of total abundance.

The implications of community composition for ecosystem services have been reported across multiple taxa (Crowder & Jabbour, 2014; Isbell et al., 2017). Since many figitids function as hyperparasitoids in aphid systems, their dominance may exert a top-down pressure on aphid primary parasitoids, limiting the efficacy of biological control (Tougeron & Tena, 2019; Ferrer-Suay et al., 2021). Consequently, despite the potential for functional redundancy provided by high diversity, the complementarity provided by evenly abundant parasitoid communities is key for achieving biocontrol service effectiveness (Crowder et al., 2010; Snyder, 2019).

While practices such as green manuring and agroforestry provide resources, their conservation value is limited by the associated disturbance regimes (Balmer et al., 2014; Tscharntke et al., 2016; Kremen, 2020). For instance, incorporating green manure through tillage disrupts soil habitats, negatively affecting parasitoid species with soil-dwelling pupal stages (Tamburini et al., 2016; Shimales et al., 2023). Simultaneously, organic pesticides likely select a few resilient generalists over sensitive specialist (Biondi et al., 2013; Laterza et al., 2024).

This combination of attractive spatial features and high disturbance intensity likely creates an ecological trap that recruits and kills natural enemies (Crowder et al., 2010, 2012; Snyder, 2019). To increase the abundance of beneficial specialists, management must unlink resource provision from disturbance. This requires a transition towards minimum disturbance regimes, reducing tillage for soil management to protect soil-dwelling pupal stages and replace the calendar-based spraying to threshold interventions, thereby restoring the functional complementarity required for aphid suppression(Tamburini et al., 2016; Snyder, 2019).

Non-crop borders provide resource continuity by offering accessible floral resources which increase the longevity and fecundity of parasitoids (Venzon et al., 2019). Preserving these habitats features poses as an effective and low-cost management strategy that helps structuring trophic interactions in cropped areas and ecosystem services delivery (Harrison et al., 2019; Fountain, 2022; Petit & Landis, 2023). Our results confirm that non-crop habitats maintain significantly higher parasitoid diversity than crop areas, reinforcing their role as the primary reservoir of beneficial insects (Assunção et al., 2022; Marins et al., 2024; da Silva et al., 2025).

The effectiveness of top-down regulations was limited by farming practices that simultaneously enhanced host plant quality through bottom-up stimulation (Awmack & Leather, 2002; Stiling & Moon, 2005). We observed that increased aphid densities were closely associated with agroforestry systems and green mulch areas. These management practices likely triggered rapid pest growth by increasing nitrogen concentrations, an effect that appears exacerbated in farms with low natural cover (Dollinger & Jose, 2018; Sileshi et al., 2020). These bottom-up effects are upscaled by the use of nitrogen-rich soil amendments such as organic fertilizers, which increase the concentration of soluble nitrogen in the phloem (Simon & Peccoud, 2018). This high-quality food supply accelerates the reproductive rate of apterous aphids, thus stimulating a density-dependent migratory response due to the rapid population growth (Sinha et al., 2018). To mitigate these outbreaks, farmers should diversify nutrient management strategies and pre-schedule its implementation to avoid excessive nitrate pulses (Li et al., 2017). Furthermore, transitioning from high-input fertilization towards locally closed nutrient cycles, as those fostered by agroforestry and intercropping, can stabilize host plant quality over time (Sileshi et al., 2020; Akchaya et al., 2025). By managing the bottom-up drivers of pest growth, farmers can create a more predictable environment where biological control agents are not overwhelmed by sudden pest outbreaks (Altieri & Nicholls, 2019; Vargas et al., 2023).

Conclusion

In summary, our study provides evidence to answer fundamental questions regarding the transition to sustainable agroecological organic systems. First, regarding management strategies, we found that farms are primarily characterized by a trade-off between spatial design and the intensity of agricultural disturbance. Second, we demonstrate that non-crop plants are an essential source of parasitoid diversity and evenness, as it maintains the local species pool and facilitates the continuous spillover of these species into cultivated fields. Finally, concerning natural biological control efficiency, our results reveal that the potential for top-down regulation is not determined by species richness, but by community evenness. We found that variations in spatial management only translate into increased biological control when paired with reduced physical and chemical disturbances, as they disrupt parasitoids evenness. To bridge the remaining research gaps, future studies should investigate the temporal stability of these communities to determine if management effects persist across seasons. Additionally, a deeper exploration of hyperparasitoid ecology is vital to understanding how to evade these negative interactions that may limit the performance of high diverse systems. Ultimately, achieving a robust agroecological transition requires a holistic approach that addresses both structural and disturbance-driven dimensions.

REFERENCES

Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M. R. A. F., Rajpoot, S. K., & Choudhary, A. K. (2025). Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1527256

Altieri, M. A., & Nicholls, C. I. (2019). Vegetational Designs to Enhance Biological Control of Insect Pests in Agroecosystems. In B. Souza, L. L. Vázquez, & R. C. Marucci (Eds.), *Natural Enemies of Insect Pests in Neotropical Agroecosystems: Biological Control and Functional Biodiversity* (pp. 3–13). Springer International Publishing. https://doi.org/10.1007/978-3-030-24733-1_1

Anderson, A., Mccormack, S., Helden, A., Sheridan, H., Kinsella, A., & Purvis, G. (2011). The potential of parasitoid Hymenoptera as bioindicators of arthropod diversity in agricultural grasslands. *Journal of Applied Ecology*, *48*(2), 382–390. https://doi.org/10.1111/J.1365-2664.2010.01937.X;JOURNAL:JOURNAL:13652664;ISSUE:ISSUE:DOI

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., Pimbert, M. P., Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., & Pimbert, M. P. (2019). From Transition to Domains of Transformation: Getting to Sustainable and Just Food Systems through Agroecology. *Sustainability*, *11*(19). https://doi.org/10.3390/su11195272

Assunção, R. M., Nícholas, ·, Camargo, F., Luan, ·, Souza, S., Rocha, E. M., Tostes, G. M., Sujii, E. R., Pires, C. S. S., & Togni, P. H. B. (2022). Landscape conservation and local interactions with non-crop plants aid in structuring bee assemblages in organic tropical agroecosystems. *Journal of Insect Conservation*, *26*, 933–945. https://doi.org/10.1007/s10841-022-00438-8

Awmack, C. S., & Leather, S. R. (2002). Host plant quality and fecundity in herbivorous insects. *Annual Review of Entomology*, *47*(Volume 47, 2002), 817–844. https://doi.org/10.1146/ANNUREV.ENTO.47.091201.145300/CITE/REFWORKS

Balmer, O., Géneau, C. E., Belz, E., Weishaupt, B., Förderer, G., Moos, S., Ditner, N., Juric, I., & Luka, H. (2014). Wildflower companion plants increase pest parasitation and yield in cabbage fields: Experimental demonstration and call for caution. *Biological Control*, *76*, 19–27. https://doi.org/10.1016/J.BIOCONTROL.2014.04.008

Bengtsson, J. (2015). Biological control as an ecosystem service: Partitioning contributions of nature and human inputs to yield. *Ecological Entomology*, *40*(S1), 45–55. https://doi.org/10.1111/een.12247

Bengtsson, J., Ahnström, J., & Weibull, A. C. (2005). The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *Journal of Applied Ecology*, *42*(2), 261–269. https://doi.org/10.1111/J.1365-2664.2005.01005.X;PAGE:STRING:ARTICLE/CHAPTER

Bianchi, F. J. J. A., & Wäckers, F. L. (2008). Effects of flower attractiveness and nectar availability in field margins on biological control by parasitoids. *Biological Control*, *46*(3), 400–408. https://doi.org/10.1016/J.BIOCONTROL.2008.04.010

Bicksler, A. J., Mottet, A., Lucantoni, D., Sy, M. R., & Barrios, E. (2023). The 10 Elements of Agroecology interconnected: Making them operational in FAO's work on agroecology. *Elementa: Science of the Anthropocene*, *11*(1), 00041. https://doi.org/10.1525/elementa.2022.00041

Biondi, A., Desneux, N., Siscaro, G., & Zappalà, L. (2012). Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: Selectivity and side effects of 14 pesticides on the predator Orius laevigatus. *Chemosphere*, *87*(7), 803–812. https://doi.org/10.1016/J.CHEMOSPHERE.2011.12.082

Biondi, A., Zappalà, L., Stark, J. D., & Desneux, N. (2013). Do Biopesticides Affect the Demographic Traits of a Parasitoid Wasp and Its Biocontrol Services through Sublethal Effects? *PLOS ONE*, *8*(9), e76548. https://doi.org/10.1371/JOURNAL.PONE.0076548

Blassioli-Moraes, M. C., Venzon, M., Silveira, L. C. P., Gontijo, L. M., Togni, P. H. B., Sujii, E. R., Haro, M. M., Borges, M., Michereff, M. F. F., de Aquino, M. F. S., Laumann, R. A., Caulfield, J., & Birkett, M. (2022). Companion and Smart Plants: Scientific Background to Promote Conservation Biological Control. *Neotropical Entomology*, *51*(2), 171–187. https://doi.org/10.1007/s13744-021-00939-2

Boeraeve, F., Dendoncker, N., Cornélis, J. T., Degrune, F., & Dufrêne, M. (2020). Contribution of agroecological farming systems to the delivery of ecosystem services. *Journal of Environmental Management*, *260*. https://doi.org/10.1016/j.jenvman.2019.109576

Boivin, G., Hance, T., & Brodeur, J. (2012). Aphid parasitoids in biological control. *Canadian Journal of Plant Science*, *92*(1), 1–12. https://doi.org/10.4141/CJPS2011-045

Caro, T., Rowe, Z., Berger, J., Wholey, P., & Dobson, A. (2022). An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conservation Letters*, *15*(3), e12868. https://doi.org/10.1111/CONL.12868;PAGE:STRING:ARTICLE/CHAPTER

Chao, A., Chiu, C. H., & Jost, L. (2014). Unifying species diversity, phylogenetic diversity, functional diversity, and related similarity and differentiation measures through hill numbers. *Annual Review of Ecology, Evolution, and Systematics*, *45*, 297–324. https://doi.org/10.1146/annurev-ecolsys-120213-091540

Crowder, D. W., & Jabbour, R. (2014). Relationships between biodiversity and biological control in agroecosystems: Current status and future challenges. *Biological Control, The Impact of Global Change on Biological Control*, *75*, 8–17. https://doi.org/10.1016/j.biocontrol.2013.10.010

Crowder, D. W., Northfield, T. D., Gomulkiewicz, R., & Snyder, W. E. (2012). Conserving and promoting evenness: Organic farming and fire-based wildland management as case studies. *Ecology*, *93*(9), 2001–2007. https://doi.org/10.1890/12-0110.1

Crowder, D. W., Northfield, T. D., Strand, M. R., & Snyder, W. E. (2010). Organic agriculture promotes evenness and natural pest control. *Nature*, *466*(7302), 109–112. https://doi.org/10.1038/nature09183

da Silva, A. C., Oliveira, L. C., Costa, J. G., Venzon, M., Frizzas, M. R., Sujii, E. R., & Togni, P. H. B. (2025). Floral availability outweighs aphid presence in supporting coccinellid abundance across life stages and promotes aphid predation. *Basic and Applied Ecology*, *89*, 92–97. https://doi.org/10.1016/j.baae.2025.10.008

Dollinger, J., & Jose, S. (2018). Agroforestry for soil health. *Agroforestry Systems*, *92*(2), 213–219. https://doi.org/10.1007/s10457-018-0223-9

Durán-Lara, E. F., Valderrama, A., & Marican, A. (2020). Natural Organic Compounds for Application in Organic Farming. *Agriculture*, *10*(2). https://doi.org/10.3390/agriculture10020041

Eilenberg, J., Hajek, A., & Lomer, C. (2001). Suggestions for unifying the terminology in biological control. *BioControl*, *46*(4), 387–400. https://doi.org/10.1023/A:1014193329979

Elevitch, C. R., Mazaroli, D. N., Ragone, D., Elevitch, C. R., Mazaroli, D. N., & Ragone, D. (2018). Agroforestry Standards for Regenerative Agriculture. *Sustainability*, *10*(9). https://doi.org/10.3390/su10093337

Emater-DF. (2024). *Relatório de Informações Agropecuárias (RIA): Distrito Federal 2024* (No. 2024). Empresa de Assistência Técnica e Extensão Rural do Distrito Federal.

Emmerson, M., Morales, M. B., Oñate, J. J., Batáry, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., Pärt, T., Tscharntke, T., Weisser, W., Clement, L., & Bengtsson, J. (2016). How Agricultural Intensification Affects Biodiversity and Ecosystem Services. In *Advances in Ecological Research* (Vol. 55, pp. 43–97). Academic Press Inc. https://doi.org/10.1016/bs.aecr.2016.08.005

FAO. (2018). *The 10 elements of agroecology*. FAO ; https://openknowledge.fao.org/handle/20.500.14283/i9037en

Ferrer-Suay, M., Selfa, J., & Pujade-Villar, J. (2021). A review of the subfamily Charipinae (Hymenoptera: Cynipoidea: Figitidae), hyperparasitoids potentially affecting the biological control of aphids. *Annales de La Société Entomologique de France (N.S.)*, *57*(6), 481–498. https://doi.org/10.1080/00379271.2021.1999328

Fischer, A., & Eastwood, A. (2016). Coproduction of ecosystem services as human–nature interactions—An analytical framework. *Land Use Policy*, *52*, 41–50. https://doi.org/10.1016/j.landusepol.2015.12.004

Fonseca, A. F., Polita, F., Madureira, L., Fonseca, A. F., Polita, F., & Madureira, L. (2024). How Agroecological Transition Frameworks Are Reshaping Agroecology: A Review. *Land*, *13*(11). https://doi.org/10.3390/land13111930

Fonteyne, S., Castillo Caamal, J. B., Lopez-Ridaura, S., Van Loon, J., Espidio Balbuena, J., Osorio Alcalá, L., Martínez Hernández, F., Odjo, S., & Verhulst, N. (2023). Review of agronomic research on the milpa, the traditional polyculture system of Mesoamerica. *Frontiers in Agronomy*, *5*. https://doi.org/10.3389/fagro.2023.1115490

Foti, M. C., Rostás, M., Peri, E., Park, K. C., Slimani, T., Wratten, S. D., & Colazza, S. (2017). Chemical ecology meets conservation biological control: Identifying plant volatiles as predictors of floral resource suitability for an egg parasitoid of stink bugs. *Journal of Pest Science*, *90*(1), 299–310. https://doi.org/10.1007/s10340-016-0758-3

Fountain, M. T. (2022). Impacts of Wildflower Interventions on Beneficial Insects in Fruit Crops: A Review. *Insects*, *13*(3), 304. https://doi.org/10.3390/insects13030304

Françoso, R. D., Dexter, K. G., Machado, R. B., Pennington, R. T., Pinto, J. R. R., Brandão, R. A., & Ratter, J. A. (2019). Delimiting floristic biogeographic districts in the Cerrado and assessing their conservation status. *Biodiversity and Conservation 2019 29:5*, *29*(5), 1477–1500. https://doi.org/10.1007/S10531-019-01819-3

Gardiner, M. M., Landis, D. A., Gratton, C., DiFonzo, C. D., O'Neal, M., Chacon, J. M., Wayo, M. T., Schmidt, N. P., Mueller, E. E., & Heimpel, G. E. (2009). Landscape diversity enhances biological control of an introduced crop pest in the north-central USA. *Ecological Applications*, *19*(1), 143–154. https://doi.org/10.1890/07-1265.1

Géneau, C. E., Wäckers, F. L., Luka, H., Daniel, C., & Balmer, O. (2012). Selective flowers to enhance biological control of cabbage pests by parasitoids. *Basic and Applied Ecology*, *13*(1), 85–93. https://doi.org/10.1016/J.BAAE.2011.10.005

Giagnocavo, C., de Cara-García, M., González, M., Juan, M., Marín-Guirao, J. I., Mehrabi, S., Rodríguez, E., van der Blom, J., & Crisol-Martínez, E. (2022). Reconnecting Farmers with Nature through Agroecological Transitions: Interacting Niches and Experimentation and the Role of Agricultural Knowledge and Innovation Systems. *Agriculture (Switzerland)*, *12*(2). https://doi.org/10.3390/agriculture12020137

Gillespie, M. A. K., Gurr, G. M., & Wratten, S. D. (2016). Beyond nectar provision: The other resource requirements of parasitoid biological control agents. *Entomologia Experimentalis et Applicata*, *159*(2), 207–221. https://doi.org/10.1111/eea.12424

Gonthier, D. J., Ennis, K. K., Farinas, S., Hsieh, H.-Y., Iverson, A. L., Batáry, P., Rudolphi, J., Tscharntke, T., Cardinale, B. J., & Perfecto, I. (2014). Biodiversity conservation in agriculture requires a multi-scale approach. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1791), 20141358. https://doi.org/10.1098/rspb.2014.1358

Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. (2017). Habitat Management to Suppress Pest Populations: Progress and Prospects. *Annual Review of Entomology*, *62*, 91–109. https://doi.org/10.1146/annurev-ento-031616-035050

Harrison, R. D., Thierfelder, C., Baudron, F., Chinwada, P., Midega, C., Schaffner, U., & van den Berg, J. (2019). Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management*, *243*, 318–330. https://doi.org/10.1016/j.jenvman.2019.05.011

Harterreiten-Souza, É. S., Togni, P. H. B., Capellari, R. S., Bickel, D., Pujol-Luz, J. R., & Sujii, E. R. (2021). Spatiotemporal dynamics of active flying Diptera predators among different farmland habitats. *Agricultural and Forest Entomology*, *23*(3), 334–341. https://doi.org/10.1111/afe.12435

Hartig, F., Lohse, L., & leite, M. de S. (2024). *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models* (Version 0.4.7) [Computer software]. https://cran.r-project.org/web/packages/DHARMa/index.html

Hatt, S., Lopes, T., Boeraeve, F., Chen, J., & Francis, F. (2017). Pest regulation and support of natural enemies in agriculture: Experimental evidence of within field wildflower strips. *Ecological Engineering*, *98*, 240–245. https://doi.org/10.1016/j.ecoleng.2016.10.080

Hsieh, T. C., Ma, K. H., & Chao, A. (2025). *iNEXT: Interpolation and Extrapolation for Species Diversity* (Version 3.0.2) [Computer software]. https://cran.r-project.org/web/packages/iNEXT/index.html

IBGE. (2016). *Brasil: Uma visão geográfica e ambiental no início do século XXI*. Ibge.

Isbell, F., Adler, P. R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D. K., Liebman, M., Polley, H. W., Quijas, S., & Scherer-Lorenzen, M. (2017). Benefits of increasing plant diversity in sustainable agroecosystems. *Journal of Ecology*, *105*(4), 871–879. https://doi.org/10.1111/1365-2745.12789

Iuliano, B., & Gratton, C. (2020). Temporal Resource (Dis)continuity for Conservation Biological Control: From Field to Landscape Scales. *Frontiers in Sustainable Food Systems*, *4*. https://doi.org/10.3389/fsufs.2020.00127

Kremen, C. (2020). Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. *Emerging Topics in Life Sciences*, *4*(2), 229–240. https://doi.org/10.1042/ETLS20190205

Landis, D. A. (2017). Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic and Applied Ecology*, *18*, 1–12. https://doi.org/10.1016/J.BAAE.2016.07.005

Laterza, I., Vitale, M. L., Agostinacchio, M. F., Bennani, Z., de Lillo, E., Tamburini, G., Verrastro, V., Cavallo, G., Desneux, N., Biondi, A., Santovito, E., & Cornara, D. (2024). Novel approaches to assess lethal and sublethal effects when evaluating risks of biopesticides toward beneficial arthropod. *CABI Agriculture and Bioscience*, *5*(1). https://doi.org/10.1186/S43170-024-00249-8;SUBPAGE:STRING:FULL

Lavandero, B., González-Chang, M., Jara-Rojas, R., Gallardo, I., & Wyckhuys, K. (2025). Enhancing agroecological transitions: From locally-adapted protocols to a global transdisciplinary applied approach. *Farming System*, *3*(3), 100154. https://doi.org/10.1016/j.farsys.2025.100154

Lê, S., Josse, J., & Husson, F. (2008). FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software*, *25*, 1–18. https://doi.org/10.18637/jss.v025.i01

Letourneau, D. K., Allen, S. G. B., Kula, R. R., Sharkey, M. J., & Stireman, J. O. (2015). Habitat eradication and cropland intensification may reduce parasitoid diversity and natural pest control services in annual crop fields. *Elementa*, *3*. https://doi.org/10.12952/journal.elementa.000069

Li, S., Li, J., Zhang, B., Li, D., Li, G., & Li, Y. (2017). Effect of different organic fertilizers application on growth and environmental risk of nitrate under a vegetable field. *Scientific Reports*, *7*(1), 17020. https://doi.org/10.1038/s41598-017-17219-y

Librán-Embid, F., Olagoke, A., & Martin, E. A. (2023). Combining Milpa and Push-Pull Technology for sustainable food production in smallholder agriculture. A review. *Agronomy for Sustainable Development*, *43*(4), 45. https://doi.org/10.1007/s13593-023-00896-7

Lindgren, J., Lindborg, R., & Cousins, S. A. O. (2018). Local conditions in small habitats and surrounding landscape are important for pollination services, biological pest control and seed predation. *Agriculture, Ecosystems and Environment*, *251*, 107–113. https://doi.org/10.1016/j.agee.2017.09.025

Marins, G., Aquino, M. F. S. D., Da Silva, A. C., De Queiroz, H. A. C., Laumann, R. A., & Togni, P. H. B. (2024). Through the green mosaic: Different tropical vegetation types have complementary effects on parasitoid diversity and biological control in organic agroecosystems. *Agriculture, Ecosystems & Environment*, *374*, 109162. https://doi.org/10.1016/j.agee.2024.109162

Myers, N., Mittermeiert, R. A., Mittermeiert, C. G., Da Fonsecat, G. A. B., & Kent, J. (2000). *Biodiversity hotspots for conservation priorities*. www.nature.com

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Borman, T., Carvalho, G., Chirico, M., Caceres, M. D., … Weedon, J. (2025). *vegan: Community Ecology Package* (Version 2.7-2) [Computer software]. https://cran.r-project.org/web/packages/vegan/index.html

Paas, W., & Groot, J. C. J. (2017). Creating adaptive farm typologies using Naive Bayesian classification. *Information Processing in Agriculture*, *4*(3), 220–227. https://doi.org/10.1016/j.inpa.2017.05.005

Paudel, S., Bhandari, S., & Upadhaya, S. (2025). Agroforestry for pollinator support and food security: A review. *Frontiers in Sustainable Food Systems*, *9*. https://doi.org/10.3389/fsufs.2025.1703823

Peñalver-Cruz, A., Alvarez-Baca, J. K., Alfaro-Tapia, A., Gontijo, L., & Lavandero, B. (2019). Manipulation of Agricultural Habitats to Improve Conservation Biological Control in South America. *Neotropical Entomology*, *48*(6), 875–898. https://doi.org/10.1007/s13744-019-00725-1

Petit, S., & Landis, D. A. (2023). Landscape-scale management for biodiversity and ecosystem services. *Agriculture, Ecosystems & Environment*, *347*, 108370. https://doi.org/10.1016/J.AGEE.2023.108370

Pickett, J. A., Woodcock, C. M., Midega, C. A., & Khan, Z. R. (2014). Push–pull farming systems. *Current Opinion in Biotechnology, Food Biotechnology ⬢ Plant Biotechnology*, *26*, 125–132. https://doi.org/10.1016/j.copbio.2013.12.006

Sampaio, M. V., Korndörfer, A. P., Pujade-Villar, J., Hubaide, J. E. A., Ferreira, S. E., Arantes, S. O., Bortoletto, D. M., Guimarães, C. M., Sánchez-Espigares, J. A., & Caballero-López, B. (2017). Brassica aphid (Hemiptera: Aphididae) populations are conditioned by climatic variables and parasitism level: a study case of Triângulo Mineiro, Brazil. *Bulletin of Entomological Research*, *107*(3), 410–418. https://doi.org/10.1017/S0007485317000220

Sano, E. E., Rodrigues, A. A., Martins, E. S., Bettiol, G. M., Bustamante, M. M. C., Bezerra, A. S., Couto, A. F., Vasconcelos, V., Schüler, J., & Bolfe, E. L. (2019). Cerrado ecoregions: A spatial framework to assess and prioritize Brazilian savanna environmental diversity for conservation. *Journal of Environmental Management*, *232*, 818–828. https://doi.org/10.1016/J.JENVMAN.2018.11.108

Schellhorn, N. A., Bianchi, F. J. J. A., & Hsu, C. L. (2014). Movement of Entomophagous Arthropods in Agricultural Landscapes: Links to Pest Suppression. *Annual Review of Entomology*, *59*(Volume 59, 2014), 559–581. https://doi.org/10.1146/annurev-ento-011613-161952

Shimales, T., Mendesil, E., Zewdie, B., Ayalew, B., Hylander, K., & Tack, A. J. M. (2023). Management intensity affects insect pests and natural pest control on Arabica coffee in its native range. *Journal of Applied Ecology*, *60*(5), 911–922. https://doi.org/10.1111/1365-2664.14410

Sileshi, G. W., Mafongoya, P. L., & Nath, A. J. (2020). Agroforestry Systems for Improving Nutrient Recycling and Soil Fertility on Degraded Lands. In J. C. Dagar, S. R. Gupta, & D. Teketay (Eds.), *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges—Vol.1* (pp. 225–253). Springer. https://doi.org/10.1007/978-981-15-4136-0_8

Simon, J.-C., & Peccoud, J. (2018). Rapid evolution of aphid pests in agricultural environments. *Current Opinion in Insect Science, Ecology • Parasites/Parasitoids/Biological Control*, *26*, 17–24. https://doi.org/10.1016/j.cois.2017.12.009

Simpson, M., Gurr, G. M., Simmons, A. T., Wratten, S. D., James, D. G., Leeson, G., Nicol, H. I., & Orre-Gordon, G. U. S. (2011). Attract and reward: Combining chemical ecology and habitat manipulation to enhance biological control in field crops. *Journal of Applied Ecology*, *48*(3), 580–590. https://doi.org/10.1111/J.1365-2664.2010.01946.X

Sinha, R., Singh, B., Rai, P. K., Kumar, A., Jamwal, S., & Sinha, B. K. (2018). Soil fertility management and its impact on mustard aphid, Lipaphis erysimi (Kaltenbach)

(Hemiptera: Aphididae). *Cogent Food & Agriculture*, *4*(1), 1450941. https://doi.org/10.1080/23311932.2018.1450941

Snyder, W. E. (2019). Give predators a complement: Conserving natural enemy biodiversity to improve biocontrol. *Biological Control*, *135*, 73–82. https://doi.org/10.1016/j.biocontrol.2019.04.017

Stiling, P., & Moon, D. C. (2005). Quality or quantity: The direct and indirect effects of host plants on herbivores and their natural enemies. *Oecologia*, *142*(3), 413–420. https://doi.org/10.1007/S00442-004-1739-4/FIGURES/3

Tamburini, G., De Simone, S., Sigura, M., Boscutti, F., & Marini, L. (2016). Conservation tillage mitigates the negative effect of landscape simplification on biological control. *Journal of Applied Ecology*, *53*(1), 233–241. https://doi.org/10.1111/1365-2664.12544

Thomson, L. J., & Hoffmann, A. A. (2006). Field validation of laboratory-derived IOBC toxicity ratings for natural enemies in commercial vineyards. *Biological Control*, *39*(3), 507–515. https://doi.org/10.1016/J.BIOCONTROL.2006.06.009

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20260–20264. https://doi.org/10.1073/PNAS.1116437108;WGROUP:STRING:PUBLICATION

Togni, P. H. B., Laumann, R. A., Medeiros, M. A., & Sujii, E. R. (2010). Odour masking of tomato volatiles by coriander volatiles in host plant selection of Bemisia tabaci biotype B. *Entomologia Experimentalis et Applicata*, *136*(2), 164–173. https://doi.org/10.1111/j.1570-7458.2010.01010.x

Togni, P. H. B., Venzon, M., Santos, J. P. C. R., & Sujii, E. R. (2019). Biodiversity provides whitefly biological control based on farm management. *Journal of Pest Science*, *92*(2), 393–403. https://doi.org/10.1007/s10340-018-1021-x

Tougeron, K., & Tena, A. (2019). Hyperparasitoids as new targets in biological control in a global change context. *Biological Control*, *130*, 164–171. https://doi.org/10.1016/j.biocontrol.2018.09.003

Tscharntke, T., Karp, D. S., Chaplin-Kramer, R., Batáry, P., DeClerck, F., Gratton, C., Hunt, L., Ives, A., Jonsson, M., Larsen, A., Martin, E. A., Martínez-Salinas, A., Meehan, T. D., O'Rourke, M., Poveda, K., Rosenheim, J. A., Rusch, A., Schellhorn, N., Wanger, T. C., … Zhang, W. (2016). When natural habitat fails to enhance biological pest control – Five hypotheses. *Biological Conservation*, *204*, 449–458. https://doi.org/10.1016/j.biocon.2016.10.001

Vargas, G., Rivera-Pedroza, L. F., García, L. F., & Jahnke, S. M. (2023). Conservation Biological Control as an Important Tool in the Neotropical Region. *Neotropical Entomology*, *52*(2), 134–151. https://doi.org/10.1007/s13744-022-01005-1

Vázquez-González, I., García-Suárez, E., Ruiz-Escudero, F., & Isabel García-Arias, A. (2024). A combined multi-variate statistical analysis to establish dairy farm typologies in Cantabria. *Computers and Electronics in Agriculture*, *221*, 109007. https://doi.org/10.1016/j.compag.2024.109007

Venzon, M., Amaral, D. S. S. L., Togni, P. H. B., & Chiguachi, J. A. M. (2019). Interactions of Natural Enemies with Non-Cultivated Plants. In B. Souza, L. L. Vázquez, & R. C. Marucci (Eds.), *Natural Enemies of Insect Pests in Neotropical Agroecosystems: Biological Control and Functional Biodiversity*. Springer International Publishing. https://doi.org/10.1007/978-3-030-24733-1

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., & Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, *40*(6), 40. https://doi.org/10.1007/s13593-020-00646-z

Wyckhuys, K. A. G., Bushley, K., Gratton, C., Gurr, G. M., Pozsgai, G., Tscharntke, T., Wanger, T. C., Lu, Y., & Elkahky, M. (2025). Restoring functional farmland biodiversity for biological pest control. *Trends in Plant Science*, *30*(10), 1097–1110. https://doi.org/10.1016/j.tplants.2025.03.012

APPENDIX

TABLE S1. Farm land and management characterization of organic-certified farm sites (*n*=11) in the Distrito Federal, Brazil. Data represent a synthesis of on-site surveys regarding diversification practices, soil management, and habitat conservation. Cert. (yrs): organic certification time. Main Crops: Primary functional groups cultivated during the study period. Green Manure (*S*): Species richness of plants utilized for green manuring. Soil Prep.: Tillage intensity, where "Minimal" indicates manual or selective disturbance and "Convent." indicates mechanized plowing. Barrier Struct.: Qualitative assessment of the density and height of vegetative borders surrounding the production area. AFS (yrs): Age of established Agroforestry Systems on the property. Nat. Veg.: Total area (hectares) of native vegetation remaining on the farm, including Permanent Preservation Areas (APP) and Legal Reserves. Pest Control: Organic-approved inputs, including biological agents (Bacillus thuringiensis), botanical extracts (Neem), and mineral applications (Sulfur/Copper).

Farm ID	Cert. (yrs)	Intercrop.	Main Crops	Crop Arrangement	Weeding Method	Fallow (ha)	Fallow Comp.	Green Manure (S)	Soil Cov.	Cover Comp.	Soil Prep.	Fert.	Pests Control	Barrier Struct.	AFS (yrs)	Nat. Veg(ha)
FM1	24	High	Veg/ Fruit	Border/ Mixed	Selective	1.0	Spont.	5	Partial	Mulch	Min.	Compost	Occas.	High	11	2.0 ha
FM2	24	Herbs	Veg	Border	Selective	0	N/A	3	Total	Mulch	Min.	Manure	Bi-weekly	Medium	0	0
FM3	10	Diverse														
FM4	10	Fruit	Veg/ Fruit	Border/ Mixed	Selective	6.0	Green Mulch plants	4	Partial	Mulch	Min.	Compost	Bi-weekly	High	8	1.0 ha
FM5	9	Fruit														

Veg/ Fruit	Mixed	Selective	0.3	Green Mulch	2	Total	Live	Min.	Biofert.	Occas.	High	17	1.0 ha
Veg/ Fruit	Mixed	Selective	1.0	Cover crops	3	Total	Live	Min.	Biofert.	Monthly	Medium	12	1.0 ha

FM6	17	No	Annuals	N/A	Total	1.0	Grasses	0	Total	Spont.	Min.	Manure	None	None	0	0
FM7	2	Yes	Veg/ Maize	Mixed	Selective	0	Green mulch	2	Partial	Mulch	Min.	Compost	Weekly	High	0	1.0 ha
FM8	8	No	Veg	N/A	Total	1.5	Spont.	0	Total	Spont.	Convent.	Manure	None	Low	0	0
FM9	21	No	Veg	N/A	Total	2.0	Spont.	0	Total	Spont.	Convent.	Manure	None	Low	0	0
FM10	17	No	Veg/ Herb	N/A	Total	1.0	Spont.	0	Total	Spont.	Convent.	Biofert.	Weekly	High	1	0.5 ha
FM11	17	No	Diverse	N/A	Total	0	N/A	0	Total	Spont.	Convent.	Manure	Monthly	Medium	0	0