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Insect abundance and pest prevalence across landscape types and seasons in arabica coffee plantations of West Java, Indonesia

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Abstract. *Maharani Y, Utari A, Andriani TS, Maxiselly Y, Rasiska S, Sudarjat, Hutapea D, Hidayat P. 2025. Insect abundance and pest prevalence across landscape types and seasons in arabica coffee plantations of West Java, Indonesia. Biodiversitas 26: 5438-5448.* West Java is renowned for being a leading producer of high-quality arabica coffee in Indonesia and has received international recognition for its products. The presence of insects, particularly pests, and the extent of the damage they cause are critical factors that influence coffee productivity. This study investigated the effects of landscape composition and climate on insect abundance and pest damage severity in Arabica coffee plantations in West Java, Indonesia. Sampling was conducted across three landscape types: settlements, agricultural, and agroforestry systems, during dry and rainy seasons in Cilengkrang and Pangalengan Sub-districts. For each landscape type, five plots measuring 10 × 10 m were established for data collection. Insect sampling combined brocap traps, beating sheets, a yellow pan trap, and direct collection, while pest intensity was evaluated on fruiting coffee plants. The study revealed that insect community composition varied significantly across coffee plantations, influenced by landscape type and seasonal changes. Insect abundance was notably higher during the dry season, with 5,938 individuals counted, compared to 2,024 individuals during the rainy season. Climatic conditions had a significant impact on insect distribution and community structure. Non-Metric Multidimensional Scaling (NMDS) revealed more distinct community composition among landscapes in the dry season, while rainy-season communities were more homogeneous. Herbivorous insects were most abundant in agricultural areas, regardless of the season. Pest damage was mostly low, except for *Hypothenemus hampei* (coffee berry borer), which caused consistently high damage in settlements and agricultural areas regardless of season and exceeded economic thresholds (>5%). Findings highlight the strong influence of landscape structure and seasonal climate on insect community dynamics and pest pressure. The study's implications for pest management practices suggest that promoting habitat heterogeneity through agroforestry and diversified vegetation could enhance natural pest control and support sustainable Arabica coffee production.

Keywords: Agricultural, agroforestry systems, dry season, herbivorous insects, rainy season

INTRODUCTION

Coffee is a vital crop in global trade, supporting millions of smallholder farmers. In Indonesia, it plays a crucial role in the national economy as a key export commodity. The country ranks among the top three coffee-producing nations, with a total production of 711,000 tons in 2022 (USDA 2023). According to the Center Statistic Agency Indonesia (CSA 2025), Indonesia's coffee production in 2024 was 807,580 tons, which this value increased from 2023, 758,720 tons, and 775,000 tons in 2022. Coffee production does not consistently increase every year, as various factors influence it. These factors include climate conditions, community activities such as land conversion and cultivation techniques, as well as pest and disease attacks on coffee plants. However, the growing popularity of coffee among the Indonesian population has led to high demand in the local market. This increased demand has resulted in many agricultural and forest lands being converted into coffee plantations, often through agroforestry practices.

In Indonesia, the majority of coffee plantations are managed by smallholder farmers, either individually or as part of farming cooperatives (Syakir and Surmaini 2017; Campera et al. 2022). In West Java, coffee cultivation spans a variety of landscape types, including agricultural areas (agricultural landscapes), forested regions (agroforestry landscapes), and residential zones (settlement landscapes) (Syakir and Surmaini 2017; Maharani et al. 2024). Differences in landscapes will affect the diversity and richness of species in local ecosystems. This, in turn, impacts the functions and services provided by these ecosystems. Apart from landscape type, climate also has a substantial influence on the existence of insect groups. Therefore, location-specific information is needed to study the abundance and function of insects in the local ecosystem.

Despite the ecological and economic benefits of coffee agroecosystems, various factors influence crop cultivation and productivity. One of the most significant challenges is insect pest infestation, which can result in both direct damage to the crop and indirect economic losses (Góngora et al. 2023). The presence, abundance, and infestation rates of insect pests are influenced by a combination of environmental and agronomic factors, including climate, altitude, land use, and soil conditions (Koutouleas et al. 2022). Landscapes characterized by higher ecological complexity, such as those found in agroforestry systems, tend to support greater biodiversity, which can enhance natural pest control through predator-prey interactions (Karp et al. 2013). By integrating coffee plants with shade trees and a variety of other vegetation, agroforestry systems promote ecological balance and resilience. In contrast, monoculture systems, such as unshaded coffee plantations, often create conditions that are more conducive to pest outbreaks due to reduced biodiversity and ecological simplification (Bukomeko et al. 2018; Koutouleas et al. 2022). Monoculture plantations usually have abundant host vegetation, which serves as a food source and shelter for pests, leading to rapid pest population growth. To manage this growth, it's important to have natural enemies, such as predators and parasitoids, that can control pest populations. However, the presence of these natural enemies in monoculture plantations is typically low because the diversity of local vegetation is limited (Maharani et al. 2024).

Monitoring pest presence and understanding infestation severity are essential first steps in preventing crop losses. Intensive agricultural systems with low vegetation diversity often lack the ecological functions necessary for pest control. Monoculture coffee plantations, particularly those without shade, are more vulnerable to infestations and associated damage (Alarcón-Segura et al. 2022; Maharani et al. 2024). Therefore, effective control strategies should be tailored to specific pest species and infestation levels, requiring careful planning to ensure success (Schmidt-Jeffris et al. 2021). Examining how different types of coffee plantations and seasonal or weather changes affect pest presence and their attack levels is essential for developing effective and sustainable coffee cultivation practices. Thoughtful planning based on this research can lead to maximum production.

Landscape type influences the presence of vegetation, which in turn influences the presence and abundance of insects. Seasons also significantly impact insect abundances, especially pests, which, of course, affect crop damage. Further investigation is required to assess the intensity of insect pest infestations across various Arabica coffee plantation landscapes and to understand how dry and rainy seasons in West Java influence these dynamics. This study focuses on agroforestry, agricultural, and settlement landscapes to determine the presence and abundance of dominant insect species. The findings provided a foundation for developing targeted plant protection strategies tailored to local ecological conditions. The insights gained are expected to support coffee farmers in adopting sustainable pest management practices, thereby improving coffee quality and supporting long-term ecosystem stability.

MATERIALS AND METHODS

Study area

The insect survey was conducted in key coffee-producing regions of West Java Province, Indonesia, encompassing the Cilengkrang and Pangalengan Sub-districts. Within each sub-district, three representative coffee plantation landscape types were selected: settlement, agricultural area, and agroforestry system, resulting in six sampling sites in total. The geographic coordinates of each site were as follows: Cilengkrang: settlement (6°52'29.31"S, 107°41'30.59"E), agriculture (6°52'11.75"S, 107°42'47.85"E), and agroforestry (6°51'15.43"S, 107°42'28.30"E); Pangalengan: settlement (7°09′57.87″S, 107°34′17.72″E), agriculture (7°12′51.65″S, 107°34′43.14″E), and agroforestry (7°11′38.21″S, 107°31′00.76″E). The spatial distribution of sampling sites across the two sub-districts is presented in Figure 1.

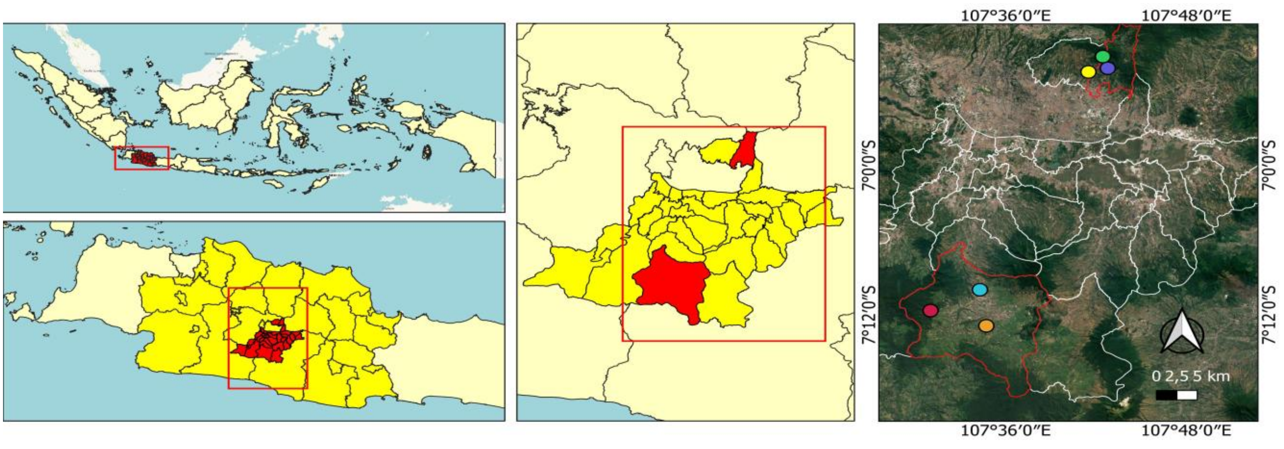

Figure 1. Location of study sites in Pangalengan and Cilengkrang Sub-districts of Bandung District, West Java Province, Indonesia. Cilengkrang: ●: Agriculture, ●: Agroforestry, ●: Settlements; Pangalengan: ●: Agriculture, ●: Agroforestry, ●: Settlements

The settlements' coffee landscape consists of plantations near residential areas (>100 meters away from settlements), where the crop is often grown alongside other crops, such as bananas (*Musa* spp.), surian (*Toona sureni* (Blume) Merr.), galangal (*Alpinia galanga* (L.) Willd.), ginger (*Zingiber officinale* Roscoe), and turmeric (*Curcuma longa* L.). The agricultural landscape is characterized by monoculture coffee cultivation, either grown without shade or intercropped with horticultural crops such as chili (*Capsicum annuum* L.), cabbage (*Brassica oleracea* L.), and shallots (*Allium cepa* var. *aggregatum*). Meanwhile, agroforestry systems include plantations established within secondary forest areas, commonly interplanted with pine (*Pinus* spp.), eucalyptus (*Eucalyptus* spp.), and clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry) trees. To ensure consistency in pest observations, all sampled plants were required to bear ripe, reddish coffee cherries, which serve as a primary host.

Collection of insects

Insect sampling was conducted five times over five weeks in each 10 × 10 m observation plot, with a minimum distance of 500 m between plots (Figure 2). Insects were collected using three complementary methods: brocap traps for the coffee berry borer, the knockdown method with beating sheets for canopy-dwelling insects, and direct hand collection for passive insects. Sampling was performed between 07:00 and 11:00 a.m. during the observation periods. All specimens were preserved in 50 mL plastic tubes filled with 70% ethanol and subsequently transported to the laboratory for identification. Weather data, including temperature, precipitation, and relative humidity, were recorded from the weather station of the Indonesian Agency for Meteorology, Climatology, and Geophysics BMKG regional station in Bandung District.

Identification

The collected insect samples were sorted, identified, and counted under an Olympus SZ61 binocular microscope. Taxonomic identification was conducted based on CISIRO (1996). All identification procedures were performed at the Entomology Laboratory, Faculty of Agriculture, Universitas Padjadjaran. Data on herbivorous insects were analyzed to evaluate species diversity, evenness, and dominance. These community indices were calculated using the Shannon-Wiener Diversity Index (H′), Pielou's Evenness Index (E), and Simpson's Dominance Index (D).

Diversity Index (H')

$$H' = -\sum_{i=1}^{S} Pi \ln Pi$$

Where:
H': Species diversity
S: The number of species
Pi: The ratio of the number of individuals of the i-th species to the total number of individuals of the entire species

The diversity index is grouped into three categories, namely low, moderate, and high at H' < 1, 1 ≤ H' ≤ 3, and H' > 3, respectively.

Evenness Index (E)

$$E = \frac{H'}{\ln(S)}$$

Where:
H': Shannon's diversity index
S: the number of species

In the range of evenness index values, E approaching 0 and 1 indicate that the distribution of individuals among types is uneven, and the spread of individuals between species is flattening, respectively.

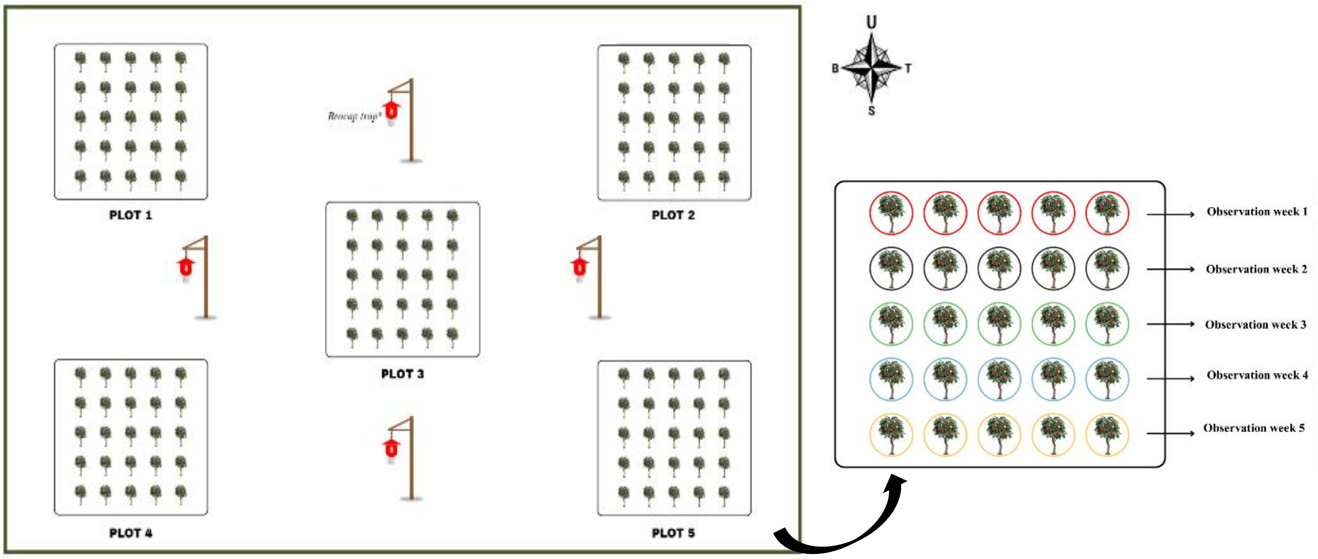

Figure 2. Layout of sampling plots for insect collection and damage assessment across different landscape types

Table 1. Plant part damage scale value

Scale	Damage categories
0	No damaged plant parts
1	There are damaged parts of the plant by 1-25%
2	There are parts of the plant that are damaged by 26-50%
3	There are parts of the plant that are damaged by 51-75%
4	There are parts of the plant that are damaged as much as >75%

Table 2. Damage categories by pest species

Damage categories	Percentage of intensity value
No damage	Attack intensity percentage = 0%
Minor damage	Attack intensity percentage <25%
Moderate damage	Attack intensity percentage 25%<IS>50%
Heavy damage	Attack intensity percentage 50%<IS>85%
The damage is very heavy	Attack intensity percentage >85%

Dominance Index

$$D = \sum (\frac{ni}{N})^2$$

Where:
D: Simpson's dominance index
ni: Number of individuals of ith species
N: Number of individuals of the entire species

The indicators ranged from 0 to 1, with values closer to 1 signifying the dominance of a particular species.

Pest intensity and prevalence

Pest infestation intensity was evaluated five times over five weeks in each observation plot (Figure 2), during the red-ripening fruit stage of coffee. Damage severity was assessed at four cardinal orientations (north, south, east, and west) of each tree. Four infested trees were selected per plot, yielding a total of 20 sampled trees with a two-tree interval between samples. Visual assessments recorded damage caused by the coffee berry borer (*Hypothenemus hampei* (Ferrari, 1867)), branch borer (*Xylosandrus compactus* (Wood & Bright, 1992)), stem borer (*Zeuzera coffeae* (Nietner, 1861)), leaf miner (*Leucoptera coffeella* (Guérin-Méneville, 1842)), and green coffee scale (*Coccus viridis* (Green, 1889)). Damage scoring and classification were conducted following the technical guidelines for pest observation and reporting (Directorate General of Plantation 2017).

Pest damage was categorized into two types, namely absolute and relative. Absolute damage refers to infestations targeting critical plant parts, such as fruits, stems, and roots, leading to significant production losses. Pests under this category included coffee berry borer (*H. hampei*), branch borer (*X. compactus*), and stem borer (*Z. coffeae*).

The absolute damage index calculation adopted the following formula:

$$IS = \frac{n}{N} \times 100\%$$

Where:
IS: Attack intensity (%)
n: Number of damaged plant parts
N: Number of observed plant parts

Relative damage occurred on non-essential parts of the plant, such as leaves, flowers, branches, or twigs, without causing significant economic losses. Pests in this category include coffee leaf miner (*L. coffeella*) and green coffee scale (*C. viridis*). The relative damage was calculated using the following formula:

$$ISr = \left\{\frac{(\sum(nxv))}{(ZxN)}\right\} x\ 100\%$$

Where:
IS: Attack intensity (%)
n: Number of damaged plant parts on v-scale
v: Scale value of crop damage
N: Number of observed plant parts
Z: Highest damage scale value used

The scale value of plant part damage refers to Table 1. The damage caused by pests was categorized into five groups based on Kyalo et al. (2025), as presented in Table 2.

Data analysis

Data preparation and preliminary analyses were conducted using Microsoft Excel 2021. The relative abundance of individual arthropod samples was calculated and analyzed with Microsoft Excel 2021. Variables such as individual abundance, species richness, the Shannon-Wiener index, and the Simpson index were analyzed with ANOVA, and significant differences among treatments were assessed with Tukey's HSD test. The composition of herbivorous insects across the three land-use types was visualized using Non-Metric Multidimensional Scaling (NMDS) based on the Bray-Curtis dissimilarity matrix. Differences in herbivore composition among landscapes, as indicated by NMDS, were tested using Analysis of Similarities (ANOSIM) with 999 permutations. All statistical analyses were performed in RStudio (version 4.2.1).

RESULTS AND DISCUSSION

Abundance and diversity of insects in three coffee landscape types during the observation period

Climate plays a significant role in influencing insect presence and abundance, thereby shaping the dynamics of both herbivorous pest species and beneficial insects. The results indicated that insect populations were significantly higher during the dry season, with 5,938 individuals recorded compared to 2,024 in the rainy season. The total morphospecies found during the observation were 137, divided into two observation seasons (Figure 3). In general, the composition of insect species in each season differs. In the dry season, 93 morphospecies were obtained, 74 of which are only found in the dry season. Meanwhile, in the rainy season, insects obtained 63 morphospecies, of which 44 species are only found in the rainy season. Although each season has its own species specificity, 19 species always exist in each season, i.e, 3 species of herbivorous groups (*C. viridis*, *H. hampei,* and *X. compactus*), 12 species of predator groups (Family Coccinellidae, Formicidae, and Forficulidae), 3 species of parasitoid groups (Braconidae, Pteromalidae, and Scelionidae), and 1 species of omnivores (Gryllidae).

The local landscape significantly influences insect abundance and ecological functions. The composition and number of insects in all three types of coffee landscapes change across the two seasons. Landscape type plays an important role in the presence of insects, especially beneficial ones like parasitoids, predators, and pollinators (Figure 4). Generally, settlement and agricultural landscapes have markedly different insect communities between the dry and rainy seasons. This study showed that agricultural ecosystems, often dominated by monocultures, tend to support a higher proportion of herbivorous insects, many of which are pests. In contrast, agroforestry landscapes show less variation in insect composition between the rainy and dry seasons. The study also found that parasitoids in settlement landscapes appear only during the rainy season, while pollinators are found only in the dry season. These findings demonstrate that seasons and weather also influence the presence of certain insect groups.

In addition to climate, landscape types affect the abundance and diversity of insect populations. Seasonal variations had a significant impact on insect community composition. The rainy season provided favorable conditions for many species, possibly due to increased resource availability, higher humidity, and enhanced plant growth. In agricultural landscapes, this period was marked by notably higher species richness. The richness, diversity, evenness, and dominance of species in each landscape type are presented in Figure 5. Overall, insect richness in coffee plantation landscapes was significantly higher during the dry season (Agricultural: 32.80 ± 4.44; Agroforestry: 16.40 ± 0.28; Settlement: 17.80 ± 5.31; $p < 0.05$) compared to the rainy season (Agricultural: 11.60 ± 1.51; Agroforestry: 12.60 ± 1.81; Settlement: 11.40 ± 4.28; $p < 0.05$). Across all seasons, insect communities in agroforestry landscapes tended to have lower richness than those in agricultural and settlement landscapes ($p < 0.05$). The results showed that agricultural landscapes support a higher insect abundance and diversity than their settlement and agroforestry landscapes.

Seasonal and landscape effects on insect diversity in arabica coffee plantations

Non-Metric Multidimensional Scaling (NMDS) revealed strong seasonal and landscape-related variation in insect community composition across Arabica coffee-growing areas. In the rainy season, communities were not clearly separated, whereas in the dry season, a distinct separation emerged (Figure 6). ANOSIM confirmed this pattern, with $R^2 = 0.742$ ($P = 0.0001$) in the rainy season and $R^2 = 0.808$ ($P = 0.0001$) in the dry season, based on 999 permutations using the Bray-Curtis index. In both cases, stress values were below 0.2 (0.124 in the rainy season and 0.078 in the dry season), indicating that the ordination accurately represented the dissimilarities among samples.

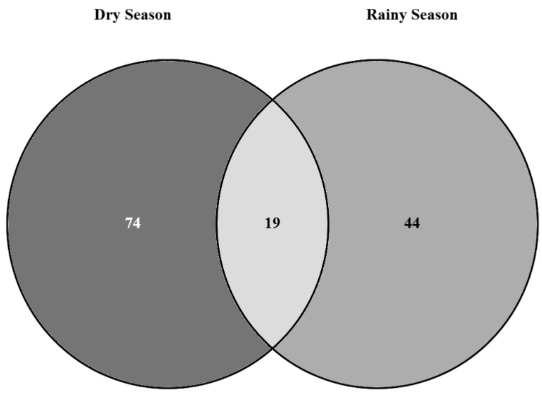

Figure 3. The proportion of collected insect species during the observation period, in both the dry and rainy seasons

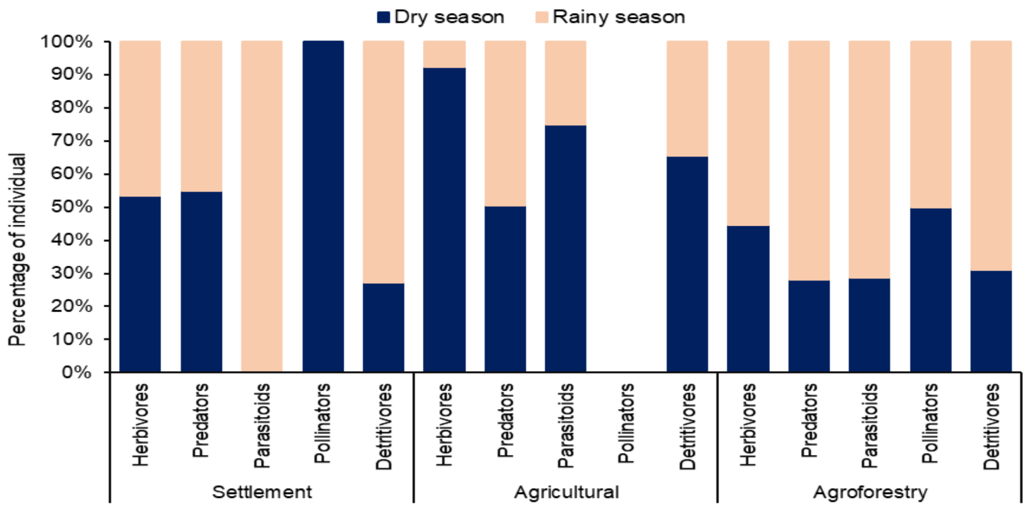

Figure 4. Percentage distribution of insect populations according to their ecological roles within coffee ecosystems across different landscape types

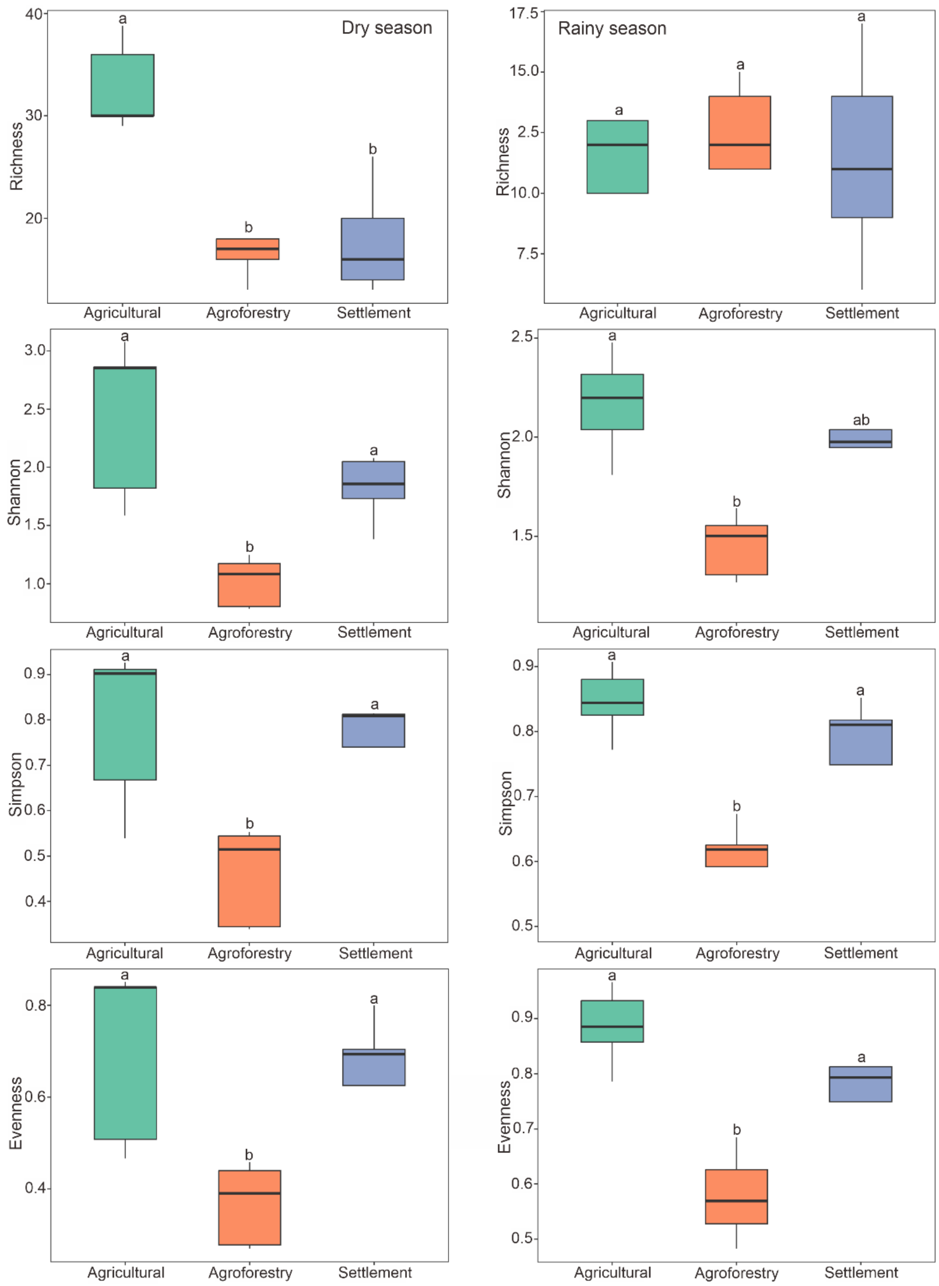

Figure 5. Boxplots comparing species richness, Shannon diversity, dominance, and evenness of insect communities across three Arabica coffee landscape types. Shared letters indicate no significant differences in estimated marginal means according to Tukey's test (*$p < 0.05$*)

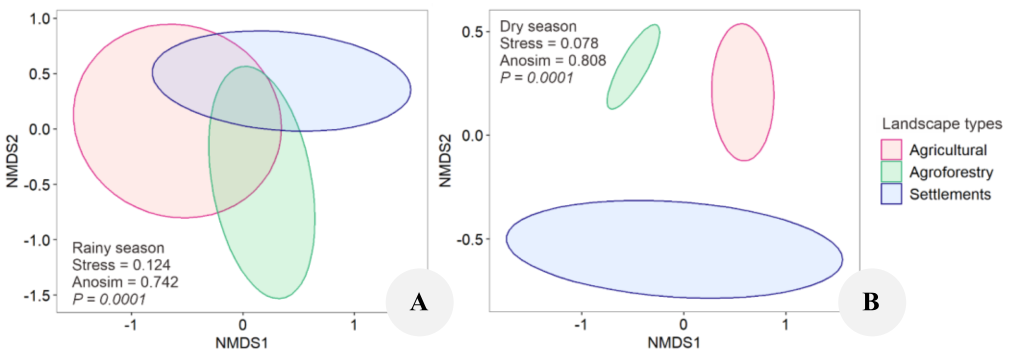

Figure 6. Non-Metric Multidimensional Scaling (NMDS) of insect community composition in coffee plantations for rainy season (stress = 0.124, p = 0.0001) (A) and dry season (stress = 0.078, p = 0.0001) (B) with ellipsoids representing 95% confidence intervals for each landscape type

Non-Metric Multidimensional Scaling (NMDS) analysis, visualized through Shepard diagrams, showed a strong correlation between observed dissimilarity and coordination distance, with values of 0.984 and 0.994 for the rainy and dry seasons, respectively (Figure 7). These differences in match quality reflected seasonal variations in habitat heterogeneity and biotic interactions. The results showed the importance of landscape heterogeneity in supporting insect biodiversity within coffee agroecosystems. Sustainable land management strategies, particularly those incorporating agroforestry practices, were essential for maintaining ecological resilience.

Analysis of observational dissimilarity and sorting distance showed R^2 values consistently above 0.9, indicating a strong model fit, especially in the dry season. These results support previous findings that stable environmental conditions promote predictable ecological patterns. In contrast, the rainy season introduces greater variability due to increased resources, species movement, and habitat shifts caused by heavy rainfall, leading to slightly lower R^2 values. Thus, while heterogeneous conditions in the rainy season foster ecological variability, the stability of the dry season favors consistent community composition and more predictable species interactions.

Pest prevalence in arabica coffee plantations

The analysis of pest intensity and crop damage in coffee plantations further underscores the influence of seasonal dynamics on ecological processes. Five primary pest species were identified as major threats to coffee yield, showing persistent presence and economic significance. Among the most damaging pests in global coffee production are *H. hampei* (Coleoptera: Curculionidae), *C. viridis* (Hemiptera: Coccidae), *L. coffeella* (Lepidoptera: Lyonetiidae), *Z. coffeae* (Lepidoptera: Cossidae), and *X. compactus* (Coleoptera: Curculionidae) (Table 3). The overall intensity and level of damage by pests are categorized as low, except for damage by the Coffee Berry Borer (*H. hampei*), which is high in each season in various types of landscapes, except in agroforestry systems.

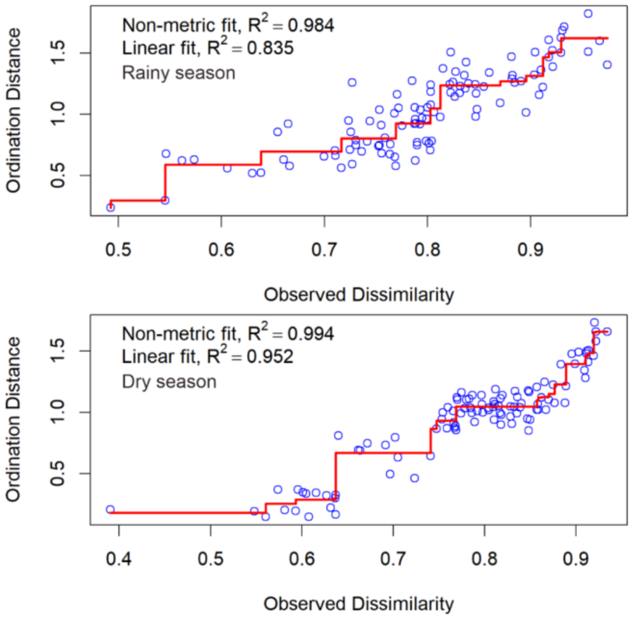

Figure 7. Non-Metric Multidimensional Scaling (NMDS) Shepard plot of insect community composition across the entire coffee plant landscape in the rainy and dry seasons

Table 3. Pest prevalence in three types of coffee landscape

Pest species	Common name	Type of landscape	Dry season	Category	Rainy season	Category
Hypothenemus hampei (Ferrari, 1867)	Coffee Berry Borer	Settlement	17.71 b	High	20.78 c	High
		Agricultural	21.78 b	High	15.77 b	High
		Agroforestry	3.34 a	Low	2.02 a	Low
Coccus viridis (Green, 1889)	Green Scale	Settlement	1.00 a	Low	4.50 b	Low
		Agricultural	5.20 b	Low	0.00 a	Low
		Agroforestry	0.40 a	Low	0.75 a	Low
Leucoptera coffeella (Guérin-Méneville, 1842)	Coffee leaf miner	Settlement	0.98 a	Low	-	-
		Agricultural	0.47 a	Low	-	-
		Agroforestry	4.04 b	Low	-	-
Zeuzera coffeae Nietner, 1861	Red coffee borer	Settlement	0.00 a	Low	-	-
		Agricultural	1.60 b	Low	-	-
		Agroforestry	0.00 a	Low	-	-
Xylosandrus compactus Wood & Bright, 1992	Hot-hole borer	Settlement	2.02 a	Low	0.10 a	Low
		Agricultural	8.04 a	Low	1.32 a	Low
		Agroforestry	3.41 a	Low	0.46 a	Low

Discussion

Species richness is a key indicator of biodiversity, with higher levels reflecting more stable and resilient ecosystems. Seasons exert a strong influence on the presence and abundance of insects in an ecosystem. Seasonal variation has a significant impact on the composition of insect communities. The rainy season provides favorable conditions for many species, perhaps due to increased resource availability, higher humidity, and increased plant growth. In the agricultural landscape, this period is characterized by a much higher wealth of species. These findings are consistent with Turner et al. (2022), who reported increased insect activity in response to vegetation dynamics. However, during the dry season, the agricultural landscape is dominated by certain herbivorous insects, which reduce species evenness. Low evenness index values indicate that some species are disproportionately abundant, potentially disrupting ecological interactions. A similar pattern has been found in monoculture coffee plantations, where habitat diversity loss favors phytophage species, especially pests (Maharani et al. 2024). For example, Coffee Berry Borer (*H. Hampei*) presence and prevalence are high in monoculture land (agricultural landscape), and it has exceeded the economic threshold (5%) (Chuaire et al. 2016), thereby reducing coffee yield and market value.

Analysis of observation differences and sorting distances reveals that the linear suitability of R^2 exceeds 0.9 and is close to 1, indicating strong model suitability and high explanatory power, especially in the dry season. These results are consistent with previous research, which suggests that reduced environmental variability promotes more stable and predictable ecological patterns. Seasonal fluctuations play a key role in shaping species composition, with dynamic environmental changes playing a significant role in this process. These changes, which include factors such as increased availability of resources and greater movement of species during the rainy season, contribute to increased ecological variability. Factors such as heavy rainfall can modify habitat availability and connectivity, leading to shifts in species distribution and community structure. The slightly lower R^2 values observed during this season reflect the complexity, supporting the assertion that heterogeneous environments promote variability in species distribution. In contrast, dry seasons have more stable environmental conditions, leading to more predictable species interactions and ecological processes. Limited water availability and relatively stable habitat contribute to a more consistent community composition, as indicated by the higher R^2 values. This pattern is consistent with ecological theories that suggest that environmental stability promotes a more uniform distribution of species and community structure.

In the rainy season, insect communities across agricultural, agroforestry, and residential landscapes overlap substantially, suggesting that higher humidity and vegetation growth encourage a more uniform distribution of species. This is consistent with previous findings that rainfall and dense vegetation facilitate insect dispersal, reducing differences in community composition driven by landscape (Tscharntke et al. 2012a). In contrast, dry seasons result in a more pronounced separation between landscapes, likely due to differences in microhabitats, resource availability, and environmental stresses such as higher temperatures and lower humidity. Resource scarcity during the dry season can intensify competition and increase dependence on landscape-specific refugia (Terlau et al. 2023).

Dry seasons introduce greater differentiation among insect communities, especially in residential landscapes. This variation can be attributed to differences in microclimate, human activity, and changes in vegetation cover. It is known that anthropogenic factors, such as habitat fragmentation and pollution, selectively favor certain groups of insects while reducing overall diversity (McKinney 2006). Urbanization often leads to biotic homogenization, in which generalist and specialist species develop and decline, respectively (du Toit et al. 2020). Among the types of land use studied, agroforestry appears to provide greater ecosystem stability, supporting more consistent insect communities throughout the seasons. The ability of these systems to maintain diverse vegetation structure and microclimate stability plays an important role in reducing seasonal fluctuations and preserving insect diversity (Perfecto et al. 2014). In contrast, agricultural and residential landscapes show more pronounced seasonal variations in insect composition, due to resource scarcity and environmental stress during dry seasons.

Seasonal fluctuations in temperature and precipitation are known to regulate the emergence and phenology of insects. For example, the onset of warm temperatures in the spring can disrupt plant-insect interactions by desynchronizing activity timing, which affects ecosystem stability (Forrest 2016). In addition, seasonal rainfall patterns affect vegetation growth and herbivore abundance, as food shortages during dry periods often lead to a decline in herbivore populations (Chen et al. 2019; Adams et al. 2020). This seasonal pattern is in line with findings from previous research, which has shown that species richness and abundance generally are higher in warmer, drier environments (Adams et al. 2020; Arroyo et al. 2022).

Land use practices and seasonal variations play an important role in shaping the structure, composition, and function of ecological communities. These factors affect biodiversity, species interactions, and ecosystem services, often acting synergistically or in conflict. Coffee plantations near forests or natural habitats tend to support higher insect diversity (Campera et al. 2022). This seasonal variation has critical implications for the coffee agroecosystem. The increasing abundance of pest species during the dry season suggests that warm and dry conditions improve pest survival and reproductive rates. For example, in this study, the coffee stem borer (*Z. coffeae*) was only found in agricultural areas during the dry season. This pest, however, has a broad host range beyond coffee plants. In agroforestry systems, this pest can also attack eucalyptus, pine, and other shade trees, which serve as alternative hosts (Suheri et al. 2022). This dynamic helps mitigate pressure on coffee crops while maintaining pest populations at manageable levels. In contrast, in open agricultural landscapes lacking shade trees, coffee plants become the primary hosts for *Z. coffeae*, leading to a higher intensity of infestation and greater crop damage. This underscores the importance of incorporating diverse vegetation structures within coffee plantations to regulate pest populations and enhance ecological stability. This condition also affects the dynamics of natural enemy populations. Several studies have reported that some parasitoids and predators become more active during dry periods, potentially counteracting pest spikes in diverse landscapes (Jamieson et al. 2017). However, climate-induced changes in insect phenology lead to trophic incompatibilities, where the main natural enemies fail to coincide with peak pest infestations. Such temporal incompatibilities reduce the effectiveness of biological control and can undermine the ecological stability of coffee production systems (Chen et al. 2019; Subedi et al. 2023).

Climate change poses additional challenges by changing temperatures and rainfall regimes, which spike pest pressure and negatively impact beneficial insects. Raven and Wagner (2021) predict that rising global temperatures could extend the pest mating season, increase infestation rates, and shift insect distribution, which requires adaptive management strategies. Sustainable farming practices such as agroforestry, habitat diversification, and biological pest control can help reduce these risks by increasing climate resilience in coffee production systems (Perfecto et al. 2014; Mahata et al. 2023).

Agroforestry landscapes, which integrate shade trees and diverse vegetation, provide important habitat for pollinators and natural enemies, contributing to higher ecological stability (Perfecto et al. 2014; Agathokleous et al. 2020). Therefore, insect abundance in agroforestry landscape systems remains stable across seasons with low pest abundance. Settlement and agroforestry systems support greater diversity of pollinators and parasitoids, which is mainly due to plant heterogeneity in larger habitats, especially flowering plants. The presence of flowering plants attracts pollinators and becomes a food source for parasitoid imagos. Pollinating insects, such as bees, flight activity is strongly influenced by sunlight. During the rainy season, with low intensity of sunlight, bee activity and presence decline (Czekońska et al. 2023). The role of canopy cover in regulating temperature and humidity is well documented, as the shaded environment buffers extreme climatic conditions, creating a more suitable habitat for diverse insect communities (Mahata et al. 2023). Shade plants help control microclimatic conditions, offer cooler and humid environments that promote predator-prey interactions and support beneficial insect populations (Ibarra-Isassi et al. 2021; Campera et al. 2022). Canopy cover in agroforestry systems is very beneficial for the growth of coffee plants. A shady microhabitat strengthens coffee growth so that it is more resistant to the presence of pests (Medeiros et al. 2019a). Agroforestry systems, with their complex structures, appear to buffer these conditions by providing shade, moisture retention, and alternative food sources, thus supporting higher insect diversity than open-pit farms (Philpott et al. 2014; Mahata et al. 2023).

In contrast, coffee plantations exposed to full sun often experience higher pest infestations due to the absence of natural enemies, reduced habitat complexity, and increased plant stress (Cerda et al. 2017; Wintle et al. 2018). Research has shown that a simple yet effective solution to these challenges is maintaining shade trees on coffee plantations. This practice not only reduces pest outbreaks but also provides important habitat for beneficial insect species (Barriosa et al. 2018). Environmental factors such as rainfall intensity, humidity, and temperature fluctuations create disturbances that affect species distribution patterns (Tudor et al. 2023). The results of the study show the importance of landscape heterogeneity in supporting insect biodiversity in coffee agroecosystems. Sustainable land management strategies, especially those that incorporate agroforestry practices, are essential for maintaining ecological resilience. By conserving habitat diversity and promoting cross-landscape connectivity, coffee farmers enhance biodiversity conservation while ensuring long-term agricultural sustainability (Gámez-Virués et al. 2020).

Cultivation practices will also affect the existence and abundance of insects, especially useful and beneficial insects such as natural enemies and pollinators. Intensive crop management practices, especially in high-input systems with frequent pesticide use, are associated with significant declines in populations of beneficial insects such as predators, parasitoids, and pollinators (Rowen et al. 2022). These results are consistent with a study by Landis (2017), in which monoculture farming disrupts ecological stability, leading to an increase in pest outbreaks due to the lack of natural enemies. These findings are in line with previous research, which suggests that monoculture systems offer an abundant food source for certain groups of insects, especially herbivores. However, these systems often lack the structural complexity necessary to sustain diverse ecological communities (Tscharntke et al. 2012b; Wintle et al. 2018). Landscape simplification through deforestation, monoculture expansion, and habitat fragmentation has led to a decline in the richness and diversity of major insect functional groups, including pollinators, parasitoids, and predators, as well as mycophage and saprophagous species (Medeiros et al. 2019b; Nicholson et al. 2024). This decline has significant ecological consequences through the disruption of essential ecosystem services such as pollination, pest regulation, and decomposition of organic matter. Reducing these impacts requires the implementation of sustainable agricultural practices that promote biodiversity conservation. Agroecological strategies, which refer to farming methods that mimic natural ecosystems, such as intercropping, Integrated Pest Management (IPM), and preservation of semi-natural habitats, increase beneficial insect populations while reducing dependence on chemical pesticides (Dainese et al. 2019). By maintaining landscape heterogeneity, farmers grow resilient agroecosystems that sustain productivity and biodiversity.

Combining agroecological practices is essential to balance biodiversity conservation with sustainable coffee production. Strategies such as intercropping, maintaining riparian buffers, and incorporating native shade trees increase functional insect diversity while stabilizing pest populations (Tscharntke et al. 2012a; Checa et al. 2014). By promoting landscape heterogeneity and supporting natural enemies, this practice contributes to a more resilient coffee agroecosystem that optimizes ecosystem productivity and services. The structural complexity in agroforestry systems, which include shade trees and diverse vegetation, creates many ecological niches and microhabitats that support a wide range of insect species (Curtis et al. 2018; Grab et al. 2018; Wintle et al. 2018). Previous studies have shown that increased vegetation diversity in agroforestry systems increases habitat availability for pollinators, decomposers, and natural enemies, thereby contributing to ecosystem health (Perfecto et al. 2014; Agathokleous et al. 2020).

The study revealed that effective pest management in coffee plantations must incorporate seasonal changes in decision-making to minimize economic losses and maintain ecological balance. The IPM approach, which focused on sustainable control methods, is essential to lowering pest impacts while preserving biodiversity in coffee agroecosystems (Schroth et al. 2015). By promoting habitat complexity and preserving populations of natural enemies, this approach helps reduce the negative impacts of intensive agriculture and supports long-term biodiversity conservation in coffee-growing landscapes. The urgency of preserving natural habitats is underscored by the fact that coffee plantations near forests or natural habitats tend to support higher insect diversity (Campera et al. 2022). In this context, forest edges serve as shelters and provide additional resources for a variety of species, including pollinators, predators, and decomposers (Pfeifer et al. 2017; Wintle et al. 2018). Connectivity between coffee plantations and the surrounding natural habitats facilitates insect movement, contributing to genetic diversity and population stability (Philpott et al. 2014; Medeiros et al. 2019a, b). Vegetative corridors are essential for pollinators and predatory insects, providing important pathways for dispersal and access to a diverse range of foraging and nesting resources. Sustainable coffee farming practices that combine agroforestry and habitat diversity to enhance ecosystem resilience and pest control are highly recommended. Future research should explore the long-term impacts of land-use changes on insect communities, the effectiveness of natural enemies in pest control, and the economic feasibility of biodiversity-friendly farming methods. By integrating ecological principles into coffee production, farmers can improve agricultural productivity and environmental sustainability.

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