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Land-use change outweighs seasonality in structuring soil entomofaunal communities

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Abstract

Land-use change is a major driver of biodiversity loss in soil ecosystems, yet its effects may interact with seasonal environmental variation, particularly in tropical regions. This study evaluated the influence of land use and seasonality on the abundance, taxonomic richness, diversity, evenness, and composition of soil entomofaunal communities in a tropical Atlantic Forest highland refuge (Brejo de Altitude) in northeastern Brazil. Five land-use systems were assessed: a forest remnant, an area invaded by *Sporobolus indicus*, an agroforestry system (AFS), a diversified horticultural system (Mandala), and a mango orchard. Soil entomofauna was sampled using pitfall traps during dry and rainy seasons and analyzed using generalized linear mixed models, mixed models, PERMANOVA, and SIMPER. Land use significantly affected all community attributes, whereas seasonal effects were weaker. Community composition was primarily structured by land use ($R^2 = 0.174$), which explained more variation than seasonality ($R^2 = 0.014$). The forest remnant exhibited the highest diversity and evenness values, while the Mandala system showed the highest abundance but the lowest diversity and evenness, reflecting strong dominance by a few taxonomic groups. Among the agricultural systems, the AFS displayed attributes most like those of the forest remnant, particularly regarding richness and evenness. Hymenoptera was the main group contributing to community dissimilarity among land-use systems. Richness and diversity increased during the rainy season across all systems. Overall, land use exerted a stronger influence than seasonality on soil entomofaunal communities, highlighting the importance of conserving forest remnants and promoting agroforestry systems to maintain soil biodiversity in tropical landscapes.

1. Introduction

Soil fauna constitutes one of the most important components of soil biodiversity (Meng et al., 2026). These organisms play a fundamental role in the functioning of terrestrial ecosystems, contributing to organic matter decomposition, nutrient cycling, soil aggregate formation, and the maintenance of soil structure and fertility (Delgado-Baquerizo et al., 2025). They also contribute to the maintenance of various ecological processes, acting as regulators of fertility and biological quality in natural and agricultural environments (Kudureti et al., 2023).

However, soil biodiversity is among the components most vulnerable to environmental changes resulting from human activities (Cambrón-Villalobos et al., 2026). Land-use changes alter vegetation cover, organic residue inputs, microclimatic conditions, and resource availability, directly influencing the abundance, diversity, and composition of soil communities (Zhang et al., 2025). These changes may favor certain taxonomic groups at the expense of others. This process promotes biological simplification and reduces the ecological complexity of soil communities (Sohlström et al., 2022), especially in agricultural systems.

A entomofauna edáfica é amplamente utilizada como bioindicadora da qualidade ambiental. Sua rápida resposta às alterações nas condições do solo e da vegetação permite avaliar mudanças nos

ecossistemas (Meurer & Barboza da Silva Ogliari, 2023). Recent studies have shown that different land-use and soil management practices affect the structure of these communities. The observed responses include variations in abundance, richness, diversity, and evenness (Araújo, 2021) (Rojas-Múnera et al., 2021),(Insfrán Ortiz et al., 2023)(Silva et al., 2024). Environments with greater plant diversity and higher organic matter inputs tend to support more complex and balanced communities. In contrast, systems subjected to more intensive management generally exhibit lower biological complexity (Mamabolo et al., 2024),(Santos et al., 2024).

Although the effects of land use on soil fauna are widely recognized, their magnitude may vary according to seasonality (Kudureti et al., 2023) (Meng et al., 2026). In tropical regions, dry and rainy seasons promote marked changes in temperature, moisture, and resource availability. These conditions directly influence the dynamics of soil communities (Feng et al., 2025) (Kudureti et al., 2023). However, recent evidence indicates that land-use changes exert a more persistent influence on the structure of these communities than seasonal variations (Sohlström et al., 2022) (Silva et al., 2024) (Zhang et al., 2025).

However, studies simultaneously evaluating the effects of land use and seasonality on soil entomological communities in tropical ecosystems remain scarce. Furthermore, the ecological mechanisms linking habitat attributes, soil conditions, and community structure are still poorly understood in Tropical Montane Forests (Brejos de Altitude). This knowledge gap is particularly relevant because the environmental heterogeneity characteristic of these ecosystems may significantly influence biodiversity and the biological functioning of soils.

Brejos de Altitude represent important biodiversity refuges within seasonal tropical landscapes. These ecosystems are characterized by enclaves of Atlantic Forest located at higher elevations and surrounded by the Caatinga, functioning as islands of humid forests within the semiarid region (Oliveira-Silva, 2025). They exhibit high species richness and high levels of endemism, characteristics associated with their geographic isolation and environmental heterogeneity (Oliveira-Silva, 2025). These environments also provide suitable natural systems for investigating how land-use changes affect soil organism communities and the associated ecological processes.

In this context, it is hypothesized that agricultural systems subjected to different management practices harbor entomological communities that are structurally distinct from those of the forest remnant, characterized by changes in abundance, diversity, evenness, and taxonomic composition as a consequence of the greater dominance of opportunistic groups. Additionally, land use is expected to exert a stronger influence on community structure than seasonality.

Therefore, the aim of this study was to evaluate how different land-use systems and seasonality influence the abundance, taxonomic richness, diversity, evenness, and composition of the soil entomological community, using a forest remnant of a Tropical Montane Forest (Brejo de Altitude) as an ecological reference to better understand the mechanisms associated with the structuring of these communities.

2. Materials and Methods

The study was conducted at the Center for Human, Social and Agricultural Sciences (CCHSA), Campus III of the Federal University of Paraíba (UFPB), in the municipality of Bananeiras, Paraíba, Brazil (06°45' S, 35°37' W), at an altitude of 520 m. The climate of the region is classified as As (tropical rainy climate with a dry summer) according to the Köppen classification. The mean annual temperature is approximately 24°C, and the mean annual rainfall is 1,163.3 mm, with precipitation concentrated mainly between April and July (Francisco, 2018).

Five land-use systems were evaluated: a forest remnant, an area invaded by Sporobolus indicus (L.) R.Br., an agroforestry system (AFS), a Mandala system, and a mango orchard. The forest remnant consists of an ecotonal fragment of Tropical Montane Forest (Brejo de Altitude) covering approximately 35.5 ha and composed predominantly of native Atlantic Forest species. The S. indicus-invaded area is used for livestock grazing and covers approximately 0.28 ha. The agroforestry system (approximately 0.68 ha) includes coffee (Coffea sp.) cultivated under the shade of Gliricidia sepium and other tree species, with a litter layer ranging from 3 to 5 cm in thickness. The Mandala system occupies approximately 0.38 ha and is used for diversified vegetable production, receiving organic fertilization and regular irrigation. The mango orchard covers approximately 0.25 ha and is managed using chemical fertilization, pruning, weeding, and crown maintenance practices.

Soil physicochemical characterization was performed using composite samples. The evaluated systems differed in their soil chemical attributes, particularly in terms of organic matter content, cation exchange capacity, pH, and base saturation (Table 1).

Table 1
Soil physicochemical properties of the evaluated land-use systems

Land-use system	pH	OM (g kg^{-1})	P (mg dm^{-3})	K (cmolc dm^{-3})	CEC (cmolc dm^{-3})	Base saturation (%)
Forest Remnant	5.03	36.13	1.88	0.018	10.13	44.64
Invaded Area	7.75	31.39	2.47	0.018	8.98	92.65
Mango Orchard	6.19	33.05	2.25	0.011	6.92	59.45
Mandala	7.32	28.47	2.97	0.039	7.96	83.42
AFS	6.38	32.55	1.71	0.008	10.67	62.88

The distribution of sampling units was standardized across land-use systems based on the smallest available area, ensuring equivalent sampling effort among the evaluated treatments. In each system, three 5 × 5 m (25 m^2) plots were established, positioned 10 m apart from one another. To minimize edge effects, all plots were installed at least 10 m from external boundaries, such as roads, agricultural areas, or contrasting vegetation fragments. Within each plot, five sampling points were arranged in an envelope

pattern (four peripheral points and one central point), totaling 15 sampling points per land-use system and 75 sampling points across the entire experiment, following an adaptation of the methodology proposed by (Lyubechanskii et al., 2023). A pitfall trap was installed at each sampling point.

The definition of seasonal periods was based on the climatological water balance of the municipality of Bananeiras, Paraíba, which indicates lower rainfall levels and water deficit between October and January, and higher rainfall levels between April and July (Francisco, 2018).

Pitfall traps were constructed using transparent polypropylene containers with a capacity of 500 mL, approximately 10 cm in height and 10 cm in diameter and were buried at soil surface level. Each trap was filled with approximately 100 mL of a solution consisting of water, neutral detergent, and 70% ethanol. The traps remained in the field for 48 h, after which they were collected for laboratory processing.

After collection, the samples were sieved and the organisms were transferred to vials containing 70% ethanol for preservation. Only organisms with a body length greater than 2 mm were considered in the analyses.

Identification was performed at the Entomology Laboratory (UFPB) using a stereomicroscope and specialized taxonomic literature. The organisms were identified and grouped into taxonomic orders. Abundance data were obtained by summing the number of individuals collected per trap in each sampling campaign.

The abundance of the soil entomofauna was analyzed using Generalized Linear Mixed Models (GLMMs), assuming a negative binomial distribution and a log-link function. Land-use systems, seasonal period, and the interaction between these factors were considered fixed effects, whereas plots were included as random effects. Model diagnostics were performed using the DHARMa package (Hartig, 2025). The significance of fixed effects was assessed using Type III analysis of variance (ANOVA) implemented in the *car* package (Fox, 2019). Adjusted means and multiple comparisons were obtained using the *emmeans* package (Lenth, 2025). Differences among land-use systems within each seasonal period were evaluated using Tukey's test, whereas comparisons between seasonal periods within each land-use system were performed using contrasts adjusted by the Sidak method.

The Shannon diversity (H'), Pielou evenness (J'), and taxonomic richness indices were calculated using the *vegan* package (Oksanen, 2025). Subsequently, these indices were analyzed using Gaussian mixed-effects models fitted with the glmmTMB package, considering land-use systems, seasonal period, and the interaction between these factors as fixed effects, and sampling plots as a random effect.

Community composition was analyzed using Permutational Multivariate Analysis of Variance (PERMANOVA) based on Bray-Curtis dissimilarity (Anderson, 2001), The contribution of taxonomic groups to the dissimilarity among land-use systems was determined using Similarity Percentage (SIMPER) analysis (CLARKE, 1993). All statistical analyses were performed using R software version

4.3.3 (R Core Team, 2024).

3. Results

The abundance of the soil entomofauna was significantly influenced by land-use system ($\chi^2 = 201.07$, $p < 0.001$), seasonality ($\chi^2 = 29.29$, $p < 0.001$), and the interaction between these factors ($\chi^2 = 57.85$, $p < 0.001$). During the dry season, the Mandala system (44.7) exhibited the highest abundance, followed by the agroforestry system (26.6), the invaded area (14.9), and the forest remnant (10.6), whereas the mango orchard showed the lowest abundance values (7.2). During the rainy season, the highest abundances were recorded in the Mandala system (30.7), the agroforestry system (26.9), and the forest remnant (23.4), with no significant differences among these systems. The mango orchard (14.9) and the invaded area (11.3) exhibited the lowest abundances (Fig. 1).

Comparisons between seasonal periods indicated a significant increase in abundance in the forest remnant and mango orchard ($p < 0.0001$), a decrease in the Mandala system ($p = 0.0067$), and no significant variation in the agroforestry system ($p = 0.91$) or the invaded area ($p = 0.06$).

Figure 1. Estimated abundance of soil entomofauna across different land-use systems during the dry and rainy seasons. Points represent estimated means obtained from the GLMM fitted with a negative binomial distribution, and error bars indicate 95% confidence intervals.

Community composition was significantly influenced by land use (PERMANOVA: $R^2 = 0.174$, $p = 0.001$), seasonal period ($R^2 = 0.014$, $p = 0.001$), and the interaction between these factors ($R^2 = 0.026$, $p = 0.001$). Land use acted as the main driver of community structure, explaining 17.4% of the total variation observed in community composition, whereas seasonality and the interaction effect exerted significant but secondary influences, accounting for 1.4% and 2.6% of the variation, respectively.

The composition of the soil entomofauna differed among land-use systems (Fig. 2). Hymenoptera was the most abundant order in all evaluated systems, representing 57.2% of individuals in the forest remnant, 84.7% in the agroforestry system, 92.7% in the Mandala system, 59.3% in the mango orchard, and 75.6% in the invaded area. The forest remnant exhibited the highest relative contribution of Orthoptera (20.8%), whereas the mango orchard showed the highest proportion of Coleoptera (21.4%). The invaded area exhibited the highest relative contributions of Diptera (13.1%) and Hemiptera (4.9%).

The Shannon diversity index was influenced by land-use system ($\chi^2 = 85.34$, $p < 0.001$), seasonality ($\chi^2 = 6.98$, $p = 0.008$), and the interaction between these factors ($\chi^2 = 10.58$, $p = 0.032$). During the dry season, the forest remnant exhibited the highest diversity values ($H' = 0.74$), whereas the Mandala system showed the lowest values ($H' = 0.18$). During the rainy season, the forest remnant maintained the highest diversity levels ($H' = 0.92$), not differing significantly from the mango orchard ($H' = 0.79$). The agroforestry system showed intermediate values ($H' = 0.73$), whereas the invaded area ($H' = 0.64$) and the Mandala system ($H' = 0.47$) exhibited the lowest diversity values (Fig. 3A).

Diversity was higher during the rainy season in all evaluated systems, with significant increases observed in the forest remnant ($p = 0.0085$), agroforestry system ($p < 0.0001$), Mandala system ($p < 0.0001$), mango orchard ($p < 0.0001$), and invaded area ($p = 0.0035$).

Taxonomic richness was influenced by seasonality ($\chi^2 = 9.42$, $p = 0.002$), but not by land-use system ($\chi^2 = 3.14$, $p = 0.535$) or by the interaction between factors ($\chi^2 = 2.27$, $p = 0.687$) (Fig. 3B). An increase in taxonomic richness during the rainy season was observed across all evaluated systems.

Pielou's evenness index (J') was influenced by land-use system ($\chi^2 = 142.93$, $p < 0.001$) and by the interaction between land-use system and seasonality ($\chi^2 = 28.11$, $p < 0.001$). During the dry season, the forest remnant exhibited the highest evenness values (J' = 0.80), whereas the agroforestry system (J' = 0.29) and the Mandala system (J' = 0.21) showed the lowest values. During the rainy season, the highest evenness values were recorded in the forest remnant (J' = 0.73) and the mango orchard (J' = 0.72), with no significant differences between these systems. The agroforestry system showed intermediate values (J' = 0.59), whereas the invaded area (J' = 0.57) and the Mandala system (J' = 0.46) exhibited the lowest evenness values (Fig. 3C).

Evenness increased significantly in the agroforestry system ($p < 0.0001$), Mandala system ($p < 0.0001$), mango orchard ($p = 0.0008$), and invaded area ($p = 0.0230$), whereas no significant variation was observed in the forest remnant ($p = 0.1780$).

4. Discussion

Land use was the main factor structuring the soil entomological community, exerting a stronger influence than seasonality on abundance, diversity, and taxonomic composition. Systems with greater vegetation cover, higher litter inputs, and greater environmental heterogeneity supported more diverse and balanced communities, corroborating findings reported by (Eckert et al., 2022, 2023).

Among the agricultural systems, the agroforestry system exhibited attributes most similar to those of the forest remnant, particularly with respect to richness and evenness. This pattern suggests that the presence of tree species, the continuous input of litter, and greater environmental heterogeneity favor the maintenance of soil fauna. Similar results have been reported by (Insfrán Ortiz et al., 2023) in agroforestry systems within the Paraguayan Atlantic Forest and by (Silva et al., 2024) who observed greater soil-faunal diversity in systems with tree cover.

In addition to vegetation structural attributes, the forest remnant and the agroforestry system exhibited the highest organic matter contents and cation exchange capacity values. These characteristics are often associated with greater resource availability and increased environmental stability for soil organisms. Consequently, these factors may have contributed to the higher diversity and evenness values observed in these systems, reinforcing the importance of maintaining favorable soil conditions for the conservation of soil biodiversity.

Hymenoptera was the main taxonomic group associated with differences in community composition among the evaluated systems. The high representation of this order is consistent with studies identifying ants as important bioindicators of environmental quality due to their high abundance and rapid response to environmental changes (Andersen et al., 2002; Tessaro, 2017).

The Mandala system exhibited the highest abundance of individuals but the lowest diversity and evenness values. This pattern suggests the dominance of a few taxonomic groups within the community, particularly Hymenoptera, which accounted for more than 90% of the individuals recorded in this system. Environments with lower structural heterogeneity tend to favor the dominance of groups capable of rapidly exploiting available resources, resulting in less balanced communities. Similar patterns were reported by (Kinnebrew et al., 2022), who observed that high abundance does not necessarily reflect more diverse or structurally complex communities.

The patterns observed for evenness reinforce the diversity results, indicating a more uniform distribution of individuals in the forest remnant and greater taxonomic dominance in the Mandala system. A similar result was reported by (Sohlström et al., 2022), who reported changes in arthropod community structure in response to land-use changes.

Taxonomic richness responded primarily to seasonality, exhibiting higher values during the rainy season. Increased moisture and greater availability of organic resources during this period may simultaneously favor different groups of the soil entomofauna, enhancing biological activity and habitat occupation (Kudureti et al., 2023).

Taken together, the results demonstrate that vegetation structure and environmental heterogeneity play a central role in shaping soil entomological communities. Systems with greater structural complexity supported more balanced communities, whereas simplified environments exhibited greater dominance by a few taxonomic groups.

Although the observed patterns allowed the detection of consistent responses to land use, the analyses were conducted at the taxonomic order level. Future studies based on species-level identification may improve our understanding of the mechanisms underlying soil-faunal responses to land-use changes.

5. Conclusions

Land use exerts a stronger influence on the soil entomological community than seasonality, affecting its abundance, diversity, evenness, and taxonomic composition. Among the evaluated systems, the agroforestry system exhibited characteristics most similar to those observed in the forest remnant, highlighting its greater potential for the conservation of soil biodiversity. These findings reinforce the importance of conserving forest remnants and adopting more diversified management systems to maintain biodiversity and the biological quality of soils.

Declarations

Author contributions

Angelica da Silva Salustino contributed to investigation, formal analysis, and writing, review and editing. Wernney Ararry Soares e Oliveira and Edmilson Costa da Silva contributed to investigation, data collection, and writing of the original draft. Alex da Silva Barbosa contributed to conceptualization, methodology, supervision, and writing, review and editing.

Declaration of generative AI use

Microsoft Copilot (Microsoft Corporation, 2026) was used for grammatical and linguistic review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

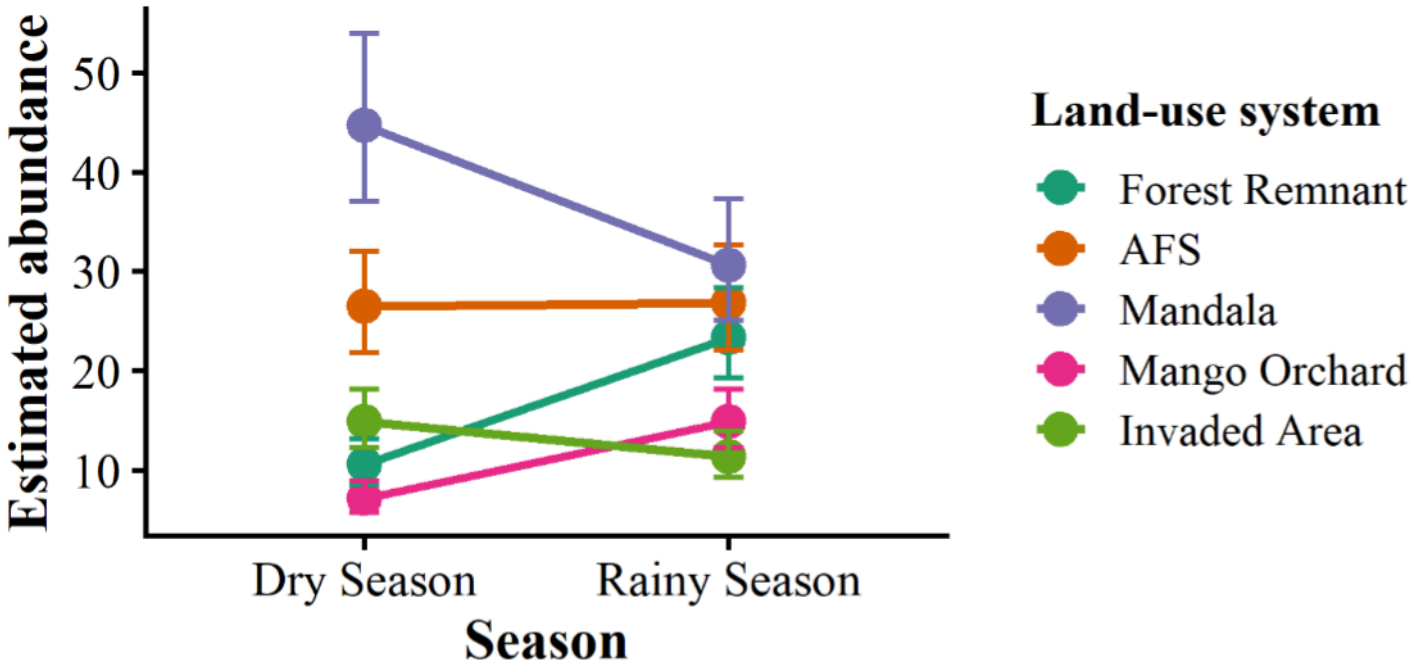

Figure 1

Estimated abundance of soil entomofauna across different land-use systems during the dry and rainy seasons. Points represent estimated means obtained from the GLMM fitted with a negative binomial distribution, and error bars indicate 95% confidence intervals.

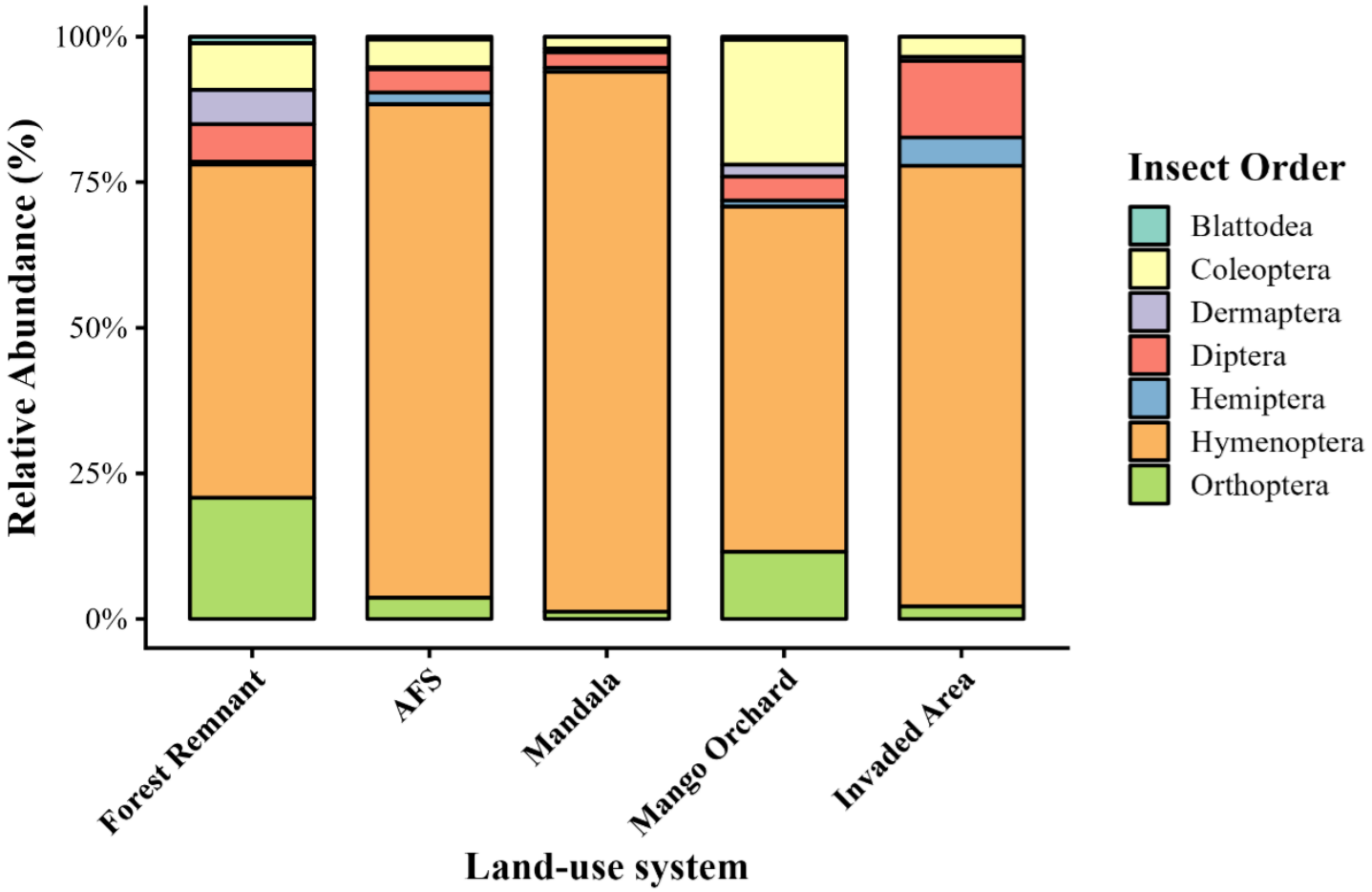

Figure 2

Composition of the soil entomological community across different land-use systems, expressed as the relative abundance (%) of the main taxonomic orders recorded. Each bar represents the proportion of individuals belonging to each order relative to the total abundance observed in the respective land-use system.

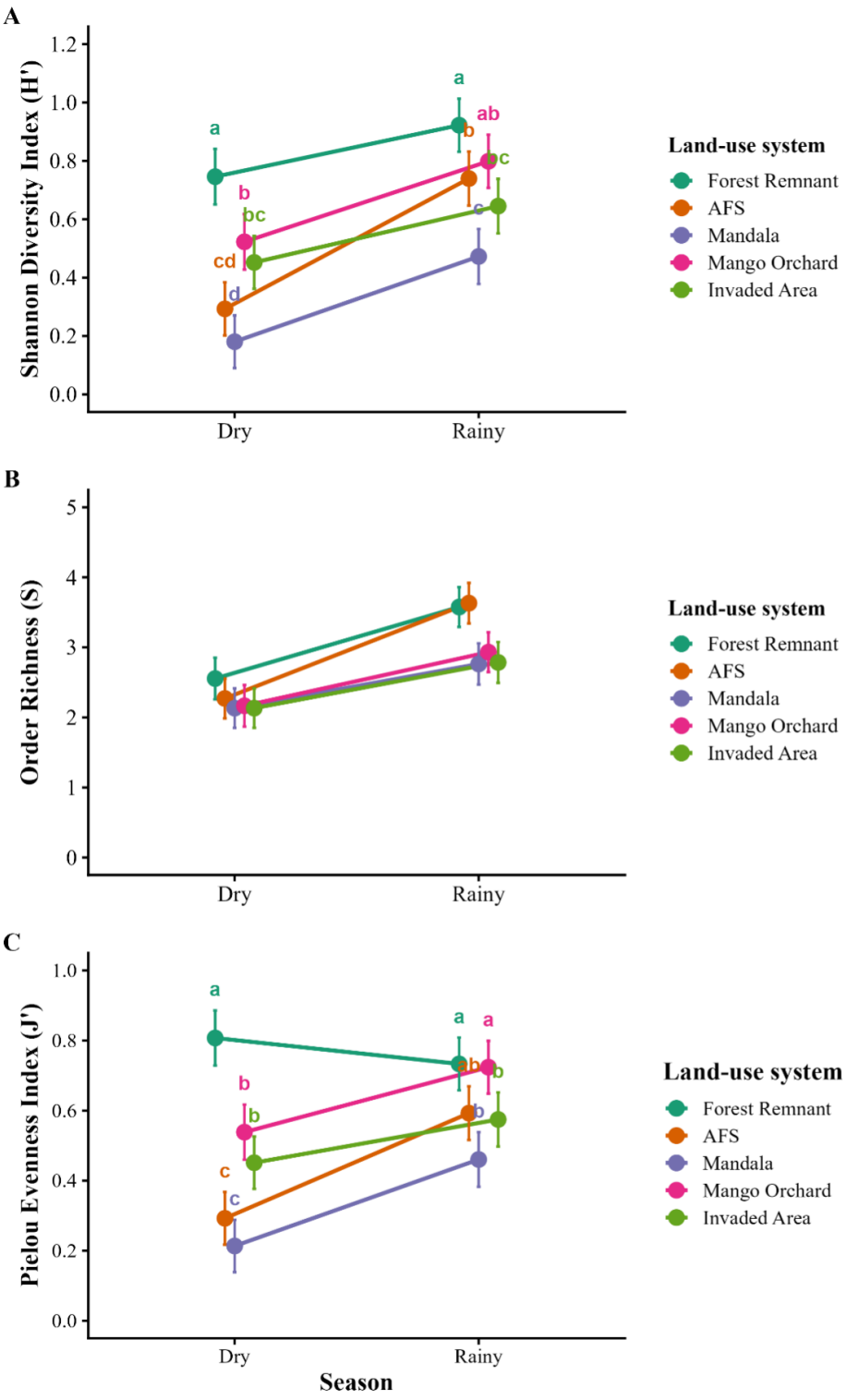

Figure 3

Shannon diversity (A), taxonomic richness (B), and Pielou's evenness (C) of the soil entomofauna across different land-use systems during the dry and rainy seasons. Points represent model-estimated means, and error bars indicate 95% confidence intervals. Different letters indicate significant differences among land-use systems within each seasonal period for Shannon diversity and Pielou's evenness indices (Tukey test, $p < 0.05$).