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PATTERNS OF TAXONOMIC DIVERSITY OF POMPILIDAE AND MUTILLIDAE (HYMENOPTERA: POMPILOIDEA) IN AGRICULTURAL LANDSCAPES IN THE BRAZILIAN ATLANTIC FOREST OF SOUTHERN BAHIA

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Abstract: The suppression of native forests for agricultural expansion is the primary driver of biodiversity loss in tropical regions. However, agroforests have been deemed biodiversity-friendly systems due to their ability to shelter forest species, including the shade-cocoa agroforests of southern Bahia (locally known as "cabrucas"). Nonetheless, most studies in cabrucas have focused on vertebrates, whereas research on insects (including wasps) is scarce, despite their significance for ecosystem functioning. Here, we investigated the effects of (i) environmental type (cabruca or native forest), (ii) landscape forest cover (from 8.5% to 82%), and (iii) regional deforestation context (*i.e.*, high, intermediate and low levels of deforestation) on the richness and composition patterns of stinging ectoparasitoid wasp assemblages (Pompilidae and Mutillidae) in the agricultural landscapes of southern Bahia in the Brazilian Atlantic Forest. We carefully selected 30 landscapes varying in regional and landscape context and conducted wasp sampling within one cabruca and one Atlantic Forest remnant per landscape using Malaise flight interception traps. We thus performed Generalized Linear Mixed Models separately for each family to assess the influence of predictor variables on species richness. We further used the Sorensen dissimilarity index to investigate species composition dissimilarity among (i) environmental types and (ii) regional types, in addition to Permutational Multivariate Analysis of Variance, to examine the effects of landscape forest cover on species composition. In total, we collected 82 individuals belonging to 39 species considering all 60 sampling sites, resulting in reduced richness in both forest (mean ± SD = 1.10 (±1.31) and agricultural (1.23 ±1.31) environments. In contrast to our initial prediction, no variables affected patterns of species richness. Furthermore, we observed high dissimilarity in species composition between environments and regions, whereas species composition was unaffected by forest cover. Our results therefore suggest that cabrucas can act as supplementary habitats for parasitoid wasps but cannot replace native forests.

Keywords: agroforest; biodiversity; landscape ecology; stinging ectoparasitoid wasps.

INTRODUCTION

The accelerated loss of biodiversity is directly linked to the increasing deforestation of tropical forests, driven especially by the high demand for food supplies and the consequent conversion of forests into agricultural lands (Chaudhary *et al.* 2016). Indeed, natural ecosystems have increasingly been transformed into human-modified agricultural landscapes (Foley *et al.* 2011, Lanz *et al.* 2018), thereby threatening the persistence of native species (Milla *et al.* 2015). However, species may exhibit varying responses to land-cover types even within a biological group, being either more sensitive or tolerant to such changes (Hirayama & Ushimaru 2022). Thus, identifying the diversity patterns of forest species in agricultural landscapes is essential for informing discussions on the most effective production strategies to optimize biodiversity conservation.

Although agriculture is considered the primary cause of biodiversity loss (Dudley & Alexander 2017), certain systems can maintain a large fraction of the native biota and are therefore considered "biodiversity-friendly" systems (Montagnini 2020). Good examples include traditional coffee (*Coffea* spp.) and cocoa (*Theobroma cacao* L.) agroforests (De Beenhouwer *et al.* 2013), given that emergent trees are maintained to provide shade for cultivated plants, thereby retaining wildlife species. However, the ability of these systems to harbour fauna and flora may vary both due to local conditions and the landscape context. For example, cocoa agroforests located near forests or in landscapes with high forest cover can provide habitat can provide suitable habitat for a greater number of bird (Cabral *et al.* 2021) and mammal species (Ferreira *et al.* 2020a) and act as supplementary habitat for animals that tolerate a certain level of disturbance, such as ants and bats (Dahlquist *et al.* 2007, Schroth *et al.* 2015). Thus, this system can conciliate agricultural production with the maintenance of several native forest species, presenting high conservation value compared to other agricultural systems (De Beenhouwer *et al.* 2013).

Traditional cocoa agroforests established in southern Bahia (Brazil) since the 18th century, locally known as "cabrucas", stand out from other cultivation types, as cocoa trees are planted under the canopy of large emergent trees from the Atlantic Forest biome, which thus provide shelter and/or food resources to a wide range of wildlife species (Faria *et al.* 2006, Cassano *et al.* 2009, Sambuichi *et al.* 2012). In addition to the economic significance of cultivation in the area, the maintenance of forest cover, under which most cocoa is produced, benefits the delivery of ecosystem services such as biodiversity conservation, carbon stock retention, and local hydrological cycles (Cassano *et al.* 2009, Schroth *et al.* 2015). Moreover, studies have demonstrated that cabrucas effectively curb high levels of deforestation in the Atlantic Forest (Aguiar & Pires 2019, Mapbiomas 2023). Considering that the Atlantic Forest presents a high degree of endemism and degradation, classifying this biome as a global biodiversity hotspot on Earth (Myers *et al.* 2000), cabrucas have become a key land-use system for maintaining assemblages of native species, including birds, bats, and medium-sized mammals (Faria *et al.* 2006, Ferreira *et al.* 2020a). However, few studies have been conducted on invertebrates, including insects (but see Ferreira *et al.* 2024), which, despite being diverse and highly relevant for ecosystem functioning, remain poorly studied in these systems.

Insects represent the most diverse animal group on the planet (Noriega *et al.* 2018), with direct benefits to agricultural productivity (Losey & Vaughan 2006). However, as far as we know, ecological studies about insects in cabrucas are limited to beetles (Novais *et al.* 2017), social ans parasitoid wasps and bees (Sperber *et al.* 2004, Ferreira *et al.* 2024), overlooking certain taxa that could directly benefit agricultural production, such as stinging ectoparasitoid wasps (Insecta, Hymenoptera, Pompilidae and Mutillidae). These wasps play an important role in regulating the trophic chain in natural and agricultural systems (Brock *et al.* 2021) and comprise families exhibiting a wide variety of species in the Atlantic Forest (Santos *et al.* 2014). However, despite the recognized importance of these insects, the ability of cocoa agroforests to safeguard high diversity of species of the families Pompilidae and Mutillidae is still unclear.

Here, we examined the patterns of taxonomic diversity of stinging ectoparasitoid wasps (Mutillidae and Pompilidae) in 30 cabrucas and 30 Atlantic Forest remnants inserted in contrasted landscapes in southern Bahia, Brazil. Specifically, we investigated the effects of (i) environment type (*i.e.*, cabruca or forest), (ii) forest cover and (iii) region (*i.e.*, highly forested, moderately forested, and severely deforested) on the richness and composition patterns of stinging ectoparasitoid wasp assemblages. We predicted that (i) the richness and composition of stinging parasitoid wasps would be similar between cabrucas and forests, in addition to the low beta diversity among these environments, given the structural vegetation similarity between both environments. However, we expected that (ii) species richness would increase and species composition would exhibit greater similarity as the amount of forest cover increases at the landscape scale, as a consequence of the greater habitat availability for wasps (Ferreira *et al.* 2020b), and (iii) the moderately forested region would exhibit greater richness (Collins & Glenn 1997), since regions with intermediate levels of disturbance may harbour species associated with both forested and disturbed environments (Lepczyk *et al.* 2008). Finally, we expected to observe greater beta diversity between more contrasting regions (*i.e.*, highly forested and severely deforested regions) as a result of species loss in the severely deforested regions.

MATERIALS AND METHODS

Study area

The study was conducted within the southern region of Bahia, Brazil (Figure 1), which is located in the Atlantic Forest biome, one of the world's biodiversity hotspots (Matavelli 2022). The climate of the study area is characterized as hot and humid, type Af in the Köppen classification, with an average annual temperature of 25°C (Thomas 1998). For many years, this region has been heavily influenced by cocoa cultivation in cabruca agroforestry systems, which has led to this crop gaining high economic and cultural value.

This research was conducted in 30 pairs of cabrucas and Atlantic Forest remnants (Figure 1). The sites sampled within the same landscape had an average distance of 384 m (± 181 m standard deviation), whereas the minimum distance between landscapes was 2 km. Specifically, the landscapes were evenly distributed across three contrasting regions (*i.e.*, 10 pairs per region) in terms of deforestation context: Una (highly forested), Ilhéus (moderately forested and characterized by the dominance of cabrucas), and Belmonte (severely deforested and highly dominated by pastures and *Eucalyptus* sp. plantations). In each region, we selected landscapes containing both native forest (from different successional stages) and cabruca embedded within a gradient of forest cover. To achieve this aim, we used a combination of satellite images and land-use classifications provided by two freely available Brazilian initiatives, Mapbiomas Collection 7 (MapBiomas Brazil 2023), which classifies different land uses but does not distinguish areas of cabruca from forest, and Mapbiomas Cacau, which identifies shaded-cocoa areas in the studied region. From the combination of both mappings, we extracted and quantified only the area of forest remnants. For this purpose, we overlapped both mappings and subtracted the shaded cocoa areas provided by MapBiomas Cacau to obtain only the amount of forest cover from MapBiomas Collection 7. Thus, we selected 10 landscapes in each region in which the forest cover ranged from 8.5 to 82% (Table S1), considering a radius of 1 km from the centroid between the cabruca and the forest remnant. This landscape radius was used since it enables non-overlapping between landscapes and accounts for the dispersal abilities of the target groups.

Collection of wasps

We collected wasps in 60 sampling sites (*i.e.*, 30 pairwise cabruca-forest remnants) from December 2022 to February 2023, using Malaise traps containing 95% alcohol in the collection container. We deployed three traps at each sampling site, which remained open continuously for 72 hours, totalling six traps per landscape. Both environments within the same landscape were simultaneously surveyed. Collections were carried out in accordance with the collection license and authorization (SISBIO–83493–1) issued by the *Instituto Chico Mendes de Conservação da Biodiversidade*. All specimens were identified by P.R.B. and E.F.S., who are recognized specialists in Mutillidae and Pompilidae, respectively. Specimens were deposited at the Coleção de Invertebrados from the Instituto Nacional de Pesquisas da Amazônia, Manaus, Amazonas, Brazil, and Museu de Biologia Professor Melo Leitão, Instituto Nacional da Mata Atlântica, Santa Teresa, Espírito Santo, Brazil. The

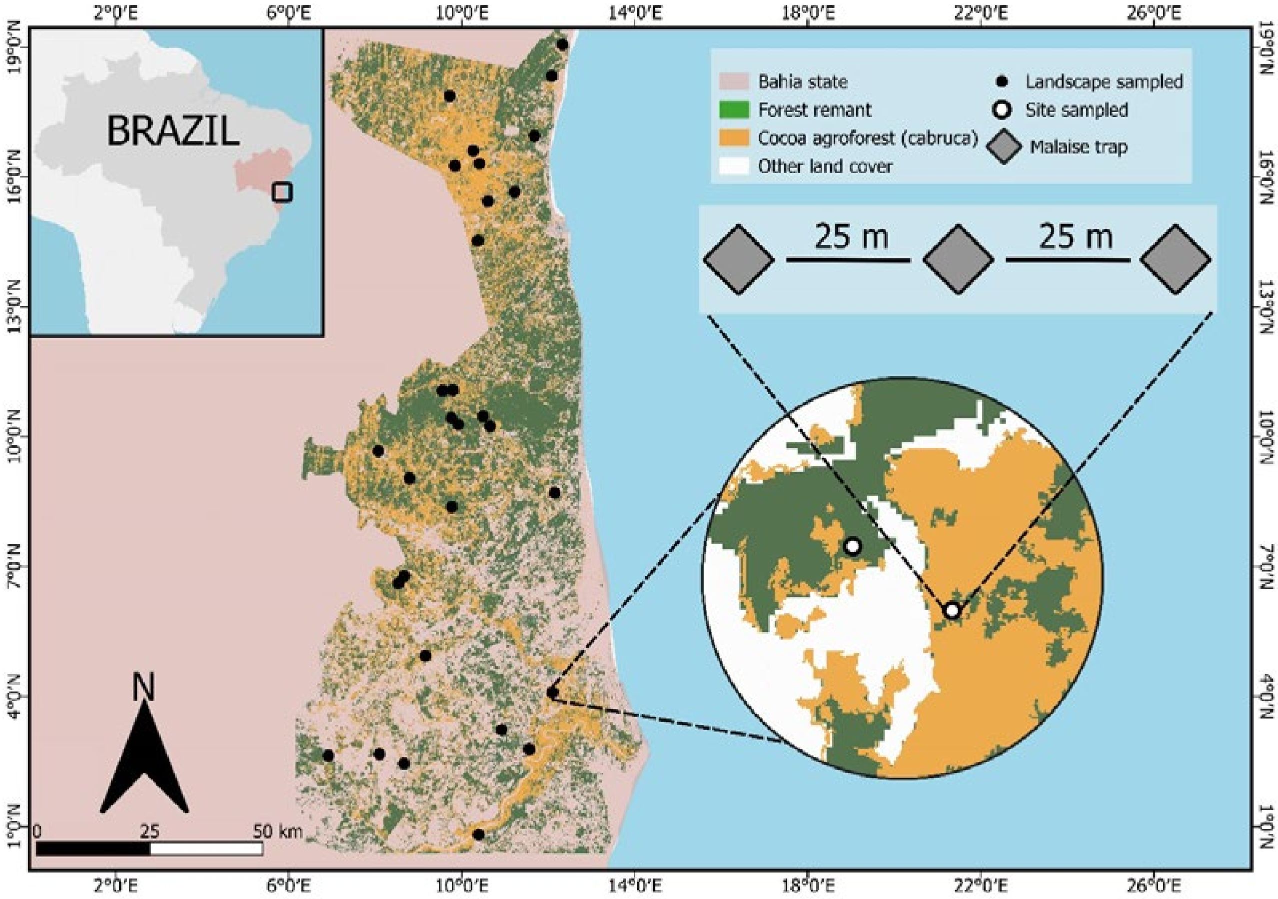

Figure 1. Map of the study area showing the distribution of the 30 landscapes (black circles) in southern Bahia, Brazil. We illustrated the sampling design within one surveyed landscape, indicating the pairwise sampled environments (cabruca and forest), and the three Malaise traps (grey diamonds) deployed in each environment.

Hymenoptera collection at IBILCE-UNESP will serve as the official repository for Pompilidae specimens.

Data analysis

All analyses were conducted separately for Mutillidae and Pompilidae. To investigate the effects of predictor variables on species richness, we subsequently performed Generalized Linear Mixed Models (GLMMs) with Poisson distribution built from the *glmmTMB* package (Brooks *et al.* 2017). We evaluated the models based on the interpretation of the coefficients and their associated p-values (using a significance threshold of $p < 0.05$). We used the type of environment (cabruca or forest), the type of region (moderately forested, highly forested, and severely deforested), the amount of landscape forest cover (in percentage) within a 1 km radius as fixed-effect variables, and the landscape (comprising the cabruca and forest from the same locality) as a random factor. The residuals of the models were tested for overdispersion and homoscedasticity using the *DHARMa* package (Hartig 2022) and attended the models' assumptions. We also used this same package to evaluate the spatial autocorrelation of the residuals using the *testSpatialAutocorrelation* function. No spatial autocorrelation was detected for either taxon (Mutillidae: $p = 0.55$; Pompilidae: $p = 0.68$).

To assess the dissimilarity of species composition between environments and regions, we calculated the total dissimilarity (Sørensen index) using the *betapart* package (Baselga *et al.* 2023). For the dissimilarity calculations, we grouped the samples to generate a single beta diversity value for each group. This approach was necessary to deal with data limitations due to the high number of singletons. We subsequently conducted beta diversity partitioning to quantify the extent to which dissimilarity was explained by turnover (using the Simpson index) and nestedness (species loss). To investigate the effect of landscape forest cover on species composition, we performed a Permutational Multivariate Analysis of Variance (PERMANOVA) using a Bray-curtis dissimilarity index and considering the landscape forest cover as the predictor variable. For this purpose, we used the vegan package (Oksanen *et al.* 2022). We considered results with p–values less than 0.05 to be significant. All analyses were conducted using R software (R Core Team 2023).

RESULTS

Overall, we collected 82 individuals representing the families Mutillidae and Pompilidae, including 39 species and 21 genera (Supplementary Material). Most species were singletons, with 77% of Mutillidae and 43% of Pompilidae being represented by a single individual (Figures 2 and 3). We identified 13 Mutillidae morphospecies and six genera, with *Ephuta* Say, *Pseudomethoca* Ashmead, and *Timulla* Ashmead being the most abundant genera with 8, 4, and 4 individuals, respectively (Figure 2). Compared with Mutillidae, Pompilidae was more abundant and presented greater frequency and species richness. We identified 26 Pompilidae species/morphospecies from 15 genera, with *Notocyphus* Smith and *Ageniella* Banks being the most abundant genera, with 18 and 17 individuals, respectively (Figure 3).

In total, cabrucas and forests showed an average richness (± standard deviation) of 1.23 (±1.30) and 1.10 (±1.29) stinging ectoparasitoid wasps, respectively. A total of 18 morphospecies were exclusive to cabrucas, 15 were exclusive to forest remnants, and only six morphospecies were shared between the two environments. The average richness values of the regions classified as severely deforested, moderately forested and highly forested were 0.75 (±0.91), 1.60 (±1.46), and 1.15 (±1.34), respectively (Figure 4).

When investigating the effects of habitat type, region, and forest cover on species richness, our models indicated that none of the included variables significantly explained the number of species for both Mutillidae and Pompilidae (Table

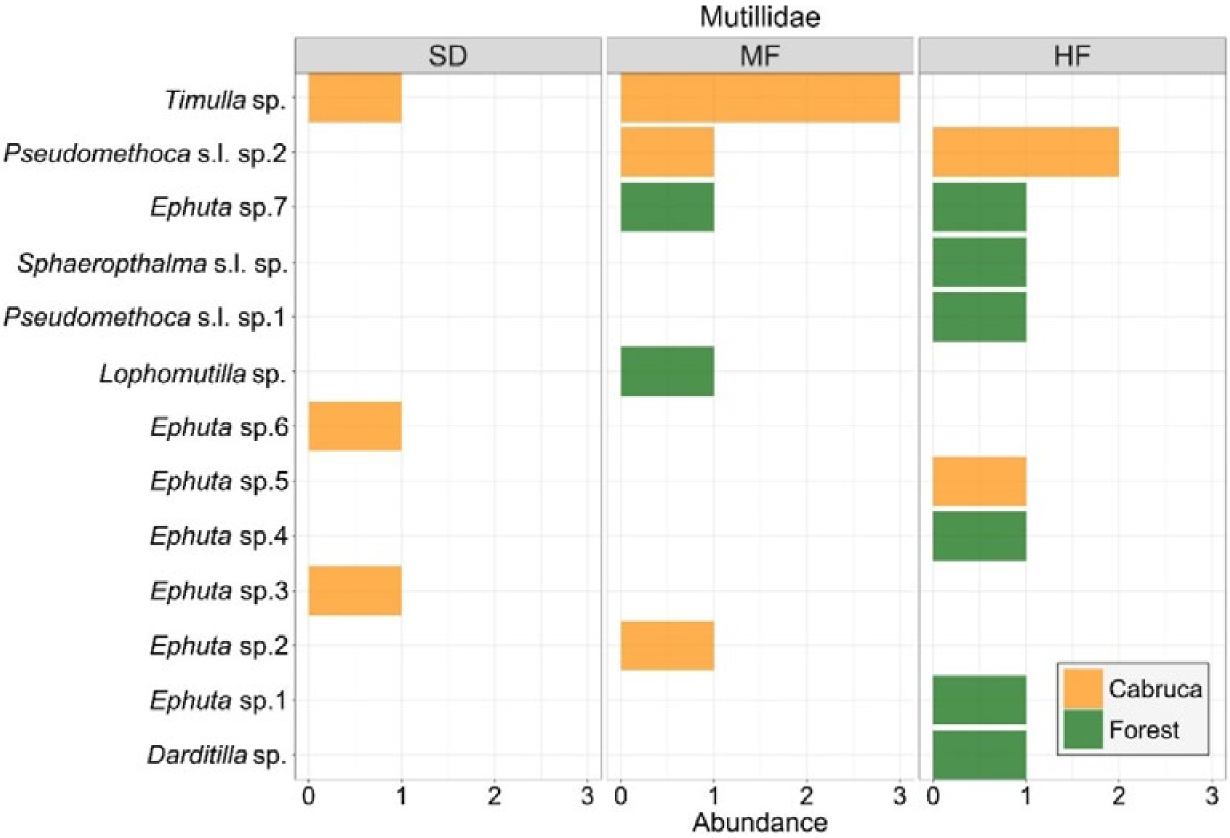

Figure 2. Species composition of the family Mutillidae in the sampled cabrucas (orange) and forest remnants (green) across three contrasted regions of southern Bahia, Brazil: SD = severely deforested; MF = moderately forested; HF = highly forested.

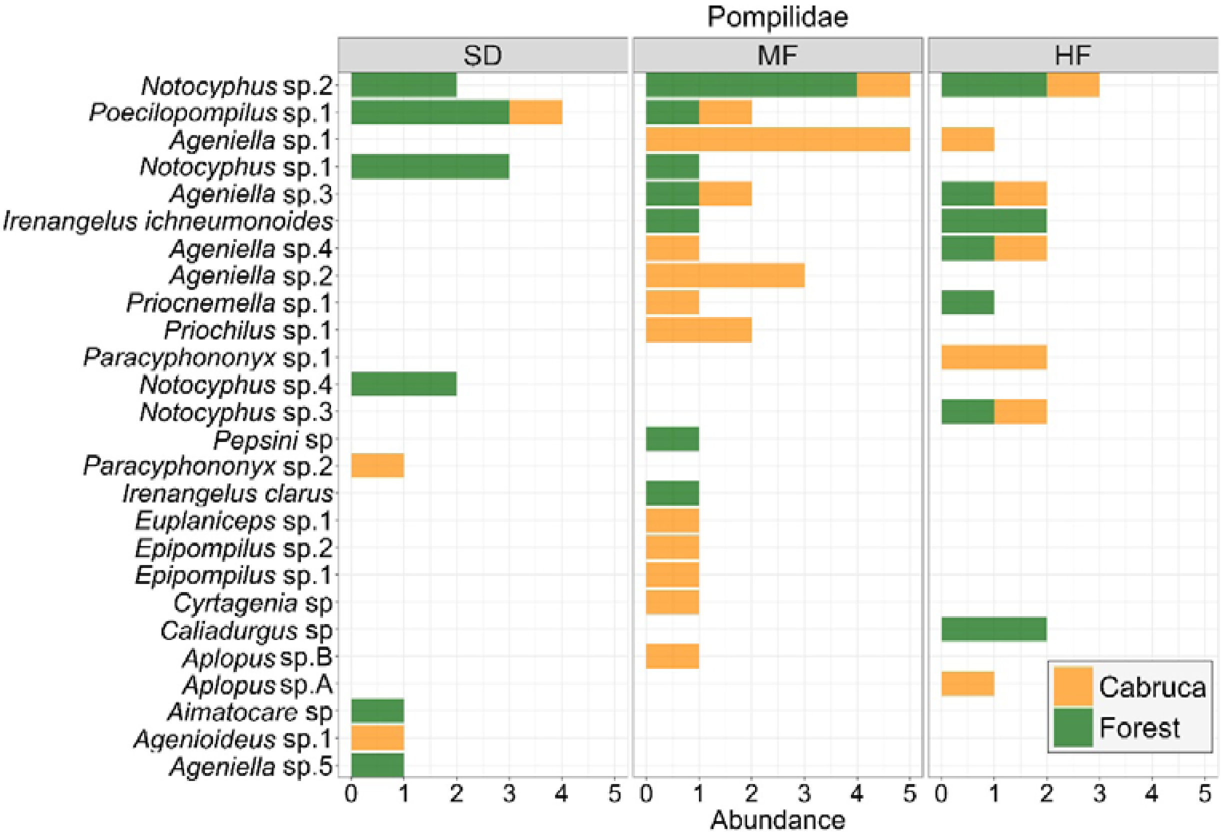

Figure 3. Species composition of the family Pompilidae in the sampled cabrucas (orange) and forest remnants (green) across three contrasted regions of southern Bahia, Brazil: SD = severely deforested; MF = moderately forested; HF = highly forested.

1). Regarding species composition, we observed a high dissimilarity between the cabruca and forest environments, with 100% dissimilarity for Mutillidae and 62% for Pompilidae (Table 2). The dissimilarity in Mutillidae composition was entirely explained by species turnover, whereas for Pompilidae, 92% was explained by species turnover, and only 8% was explained by nestedness (Table 2). As expected, the highest dissimilarity was observed between the severely deforested and highly forested regions (Mutillidae: total dissimilarity = 100%; Pompilidae = 89%), followed by severely deforested vs. moderately forested (Mutillidae = 75%; Pompilidae = 77%) and between moderately forested and highly forested (Mutillidae = 69%; Pompilidae = 56%). The patterns of regional dissimilarity were similar for both families across the three regions, with dissimilarity predominantly explained by species turnover (Table 2). Finally, PERMANOVA indicated that the amount of forest at the landscape scale did not explain the species composition of either Mutillidae ($R^2 = 0.08$; $F = 0.87$; $p = 0.58$) or Pompilidae ($R^2 = 0.03$; $F = 0.89$; $p = 0.57$).

DISCUSSION

To the best of our knowledge, this is the first study to investigate the effects of landscape and regional context on the diversity patterns of stinging ectoparasitoid wasps in neotropical agricultural landscapes. Our study revealed that cocoa agroforests in Southern Bahia are able to retain a similar number of species to native habitat remnants, likely indicating resource availability for stinging parasitoid wasps in these systems. Given that cabrucas retain many tree species (Cassano *et al.* 2009), the structural similarity between cabrucas and forest fragments may favour the occurrence of other arthropods, especially potential prey for these wasps. In addition, while various insect groups are sensitive to anthropogenic activities (Thomazini & Thomazini 2000), primarily because of their direct involvement in inter- and intra-specific ecological relationships (Myers 1987), our findings indicate that at least some species of parasitoid wasps can utilize this agroforestry system. Likewise, similarity in species richness between cabrucas and forests

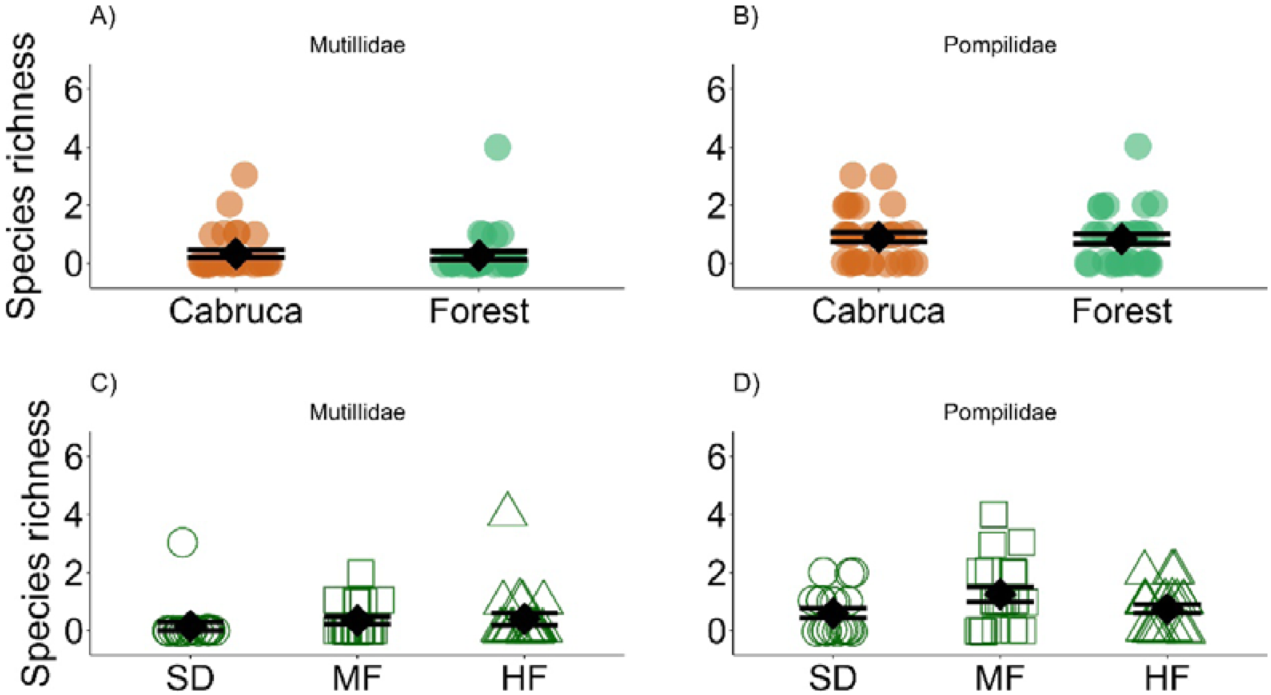

Figure 4. Species richness sampled within 60 contrasted landscapes in southern Bahia, Brazil, considering A) Mutillidae wasps among the cabruca and forest environments; B) Pompilidae wasps in the cabruca and forest environments; C) Mutillidae wasps across different regions; D) Pompilidae wasps across different regions. The diamonds and bars indicate the means and standard deviations of species richness. SD = severely deforested. MF = moderately forested. HF = Highly forested.

Table 1. Result of the Generalised Linear Mixed Model explaining the effects of predictor variables on stinging ectoparasitoid wasp species (Mutillidae and Pompilidae) in agricultural landscapes of southern Bahia, Brazil.

Taxon	Independent variable	Estimate (fixed effect)	P value
Mutillidae	Habitat type	-0.22	0.64
	Region: Moderately forested	0.01	0.99
	Region: Severely deforested	-1.05	0.33
	Forest cover	0.01	0.80
Pompilidae	Habitat type	-0.08	0.78
	Region: Moderately forested	0.52	0.11
	Region: Severely deforested	-0.18	0.67
	Forest cover	0.00	0.76

was also observed for other taxa, such as mammals (Ferreira *et al.* 2020a), other groups of parasitoid wasps (Hymenoptera-Parasitica and Chrysidoidea) (Sperber *et al.* 2004), bees and social wasps (Ferreira *et al.* 2024). Additionally, we emphasize that the sampling effort used in both environments was standardised, and that the patterns observed in both environments were similar. These findings suggest that cabrucas are supplementary habitats for certain wasp species, indicating high environmental quality and conservation value and therefore reinforcing the concept that cabrucas are biodiversity-friendly systems.

Although we collected only 39 species, the overall richness of Mutillidae in our study (13 spp.) was similar to that reported in other studies that used multiple collection methods (Perillo *et al.* 2020, Wenceslau *et al.* 2022). This similarity may also be associated with the fact that certain species of wasps may be more tolerant to intermediate

Table 2. Total (beta diversity) and partitioned (nestedness and turnover) dissimilarity values of stinging parasitoid wasps between different habitat types (cabruca and forest) and regions (severely deforested, moderately forested and highly forested) in agricultural landscapes of southern Bahia, Brazil. Dissimilarity values equal to 1 and 0 represent total dissimilarity and total similarity, respectively.

Taxon	Pairwise	Total dissimilarity	Turnover	Nestedness
Mutillidae	Cabruca x forest	1.00	1.00	0.00
Mutillidae	Moderately forested x severely deforested	0.75	0.67	0.08
Mutillidae	Highly forested x severely deforested	1.00	1.00	0.00
Mutillidae	Highly forested x moderately forested	0.69	0.6	0.09
Pompilidae	Cabruca x Forest	0.62	0.57	0.05
Pompilidae	Moderately forested x severely deforested	0.76	0.63	0.13
Pompilidae	Highly forested x severely deforested	0.89	0.88	0.01
Pompilidae	Highly forested x moderately forested	0.56	0.40	0.16

levels of human disturbances (Bos *et al.* 2007), especially Pompilidae and Mutillidae. For example, Paiva *et al.* (2020) observed that both the richness and abundance of Pompilidae and Mutillidae were significantly greater in conventional pasture monocultures than in silvopastoral systems, which tend to be fewer hostile environments. However, when the order Hymenoptera was considered as a whole, an opposite pattern was observed, with the silvopastoral system exhibiting greater species abundance and richness. These findings suggest that Pompilidae and Mutillidae wasps tend to be less sensitive to habitat modification. In particular, Pompilidae wasps may benefit from different habitats within their flight range for food resource acquisition or nesting site utilisation (Szczepko *et al.* 2012), especially species that exhibit greater dispersal ability, as they can explore a larger area and consequently be found in different land-use types (Piano *et al.* 2023).

Although species richness was similar among the different environments investigated, species composition differed, particularly for Mutillidae. For example, Vieira *et al.* (2015) demonstrated that more open and warmer areas promote greater evenness within the Mutillidae community, likely comprising species from both open and forested areas. Generally, forest edges are known to be fewer stable habitats (Laurance *et al.* 2002), yet generalist species may be favoured in these areas. Aranda & Graciolli (2015) further demonstrated that drier areas, coupled with host availability, can also influence the composition of the Mutillidae community. However, although Mutillidae wasp diversity is often greater at forest edges than at forest-interior, some species are closely associated with the core areas of forest fragments, indicating differences in life history and resource acquisition (Vieira *et al.* 2015). Thus, although Mutillidae are considered wasps with great environmental plasticity (Alvarenga *et al.* 2017), our results suggest that this cannot be applied to all species. Nevertheless, cabrucas may contribute to increase species richness at regional scales, as we revealed that some species were not recorded in forests. In addition, the role of forests in conserving the taxonomic diversity of Mutillidae and Pompilidae is indispensable, as many species are restricted to forest remnants, such as species of *Irenangelus* Schultz that are specialized kleptoparasites on spider wasps nesting in pre-existing cavities (Da Rocha-Filho & Augusto 2021). Therefore, anthropogenic landscapes composed by cabrucas and forests could contribute to the maintenance of wasp diversity in the threatened southern Brazilian Atlantic Forest.

In contrast to our initial predictions, the regional deforestation context failed to explain the richness patterns of stinging parasitoid wasps in our study.

However, the region indeed influenced patterns of species composition. As anticipated, higher beta diversity was observed at the sampling sites between highly forested and severely deforested regions for both Mutillidae and Pompilidae. In addition to the marked deforestation level among the three regions, their land-use covers are also strongly divergent. The highly forested and moderately forested regions are characterised by the dominance of land-use types capable of fostering biodiversity, *i.e.*, forest and cabruca, respectively. In contrast, the severely deforested region is characterised by the dominance of hostile land covers (*i.e.*, pasture and eucalyptus monoculture) that can act as significant environmental filters (Cabral *et al.* 2021). However, it is important to highlight that the high dissimilarity observed in species composition can also be attributed to the high number of singletons identified in our study, a pattern previously documented in other tropical studies focused on insects (Novotný & Basset 2000, Nascimento & Dominguez 2009). For example, Auko & Silvestre (2013) revealed that 58% of the 61 sampled species of wasps were identified as singletons in a protected area of southern Brazil. Similarly, Aranda & Aoki (2018) attributed the low similarity to the quantity of singletons and doubletons, which accounted for 48% of the wasps species found in the Brazilian Pantanal. According to those studies, 77% of the 13 morphospecies of Mutillidae that we collected were singletons, resulting in high beta diversity, which was mainly explained by species turnover. Although Pompilidae species were more prevalent than Mutillidae, 42.9% of the collected species were single individuals, which also resulted in high beta diversity and species turnover. Hence, the singleton pattern observed in our study can be explained by the solitary nature of both Pompilidae and Mutillidae.

In contrast to our initial predictions, landscape forest cover failed to explain patterns of species richness and composition. Although forest cover has been a strong predictor of species richness in ecological studies (Morante-Filho *et al.* 2021), we presume that cabrucas are likely compensating for the reduction in forest cover in more deforested landscapes. Given their structural similarity to forests, cabrucas can potentially serve as supplementary habitats for these insects, thus safeguarding wasp species in the region. The reduction in forest cover at the landscape scale, therefore, does not necessarily represent a reduction in the amount of available habitat for these wasps. In this case, cabruca areas could contribute to mitigating the negative effects of native habitat loss at the landscape scale (Ferreira *et al.* 2024).

Our study provides valuable information on the ecology and distribution of parasitoid wasps in cocoa agroforests and Atlantic Forest remnants; however, we acknowledge some limitations. First, although we recorded a species richness comparable to studies that employed a greater sampling effort, the high number of singletons is an indication that our collections possibly underestimated the species richness of Mutillidae and Pompilidae. Their solitary behaviour and low density may result in biases in their capture. In particular, the pronounced sexual dimorphism of Mutillidae adds a layer of complexity, as Malaise traps, which are effective in capturing males due to their winged nature, are less effective in capturing females, which are apterous and require active search methods. However, Vieira *et al.* (2017) demonstrated that Malaise traps were more effective at capturing individuals of Mutillidae than Pan traps were. Second, we would like to point out that comparisons of species composition were generally made between types of environments and between regions. We therefore recommend that these results be interpreted with caution and that future studies employ a greater sampling effort, for example, by combining different collection methods and a greater exposure time and number of traps. Nevertheless, despite these limitations, we provide relevant contributions for further studies and research on parasitoid wasps, offering insights for a better understanding of their taxonomic diversity.

Overall, our findings demonstrate that cabrucas are indeed capable of sheltering stinging parasitoid wasp species richness similar to that of native forests, thus reinforcing the value of traditional cocoa agroforests in southern Bahia for the conservation of stinging parasitoid wasps. However, the species composition was highly (Pompilidae) or completely different (Mutillidae) between the cabruca and forest environments, suggesting that species may differ in their sensitivity to land use modification in agricultural landscapes (Cassano *et al.* 2009). These results underscore the importance of land-use practices that minimise negative impacts on species diversity, aligning agricultural production with biodiversity conservation. Although cabrucas can be considered biodiversity-friendly systems and contribute to mitigating the negative effects of land-use changes in southern Bahia, they cannot substitute native forests. The preservation of these natural habitats is irreplaceable and essential for maintaining biological diversity and the ecological processes that sustain ecosystems (Ferreira *et al.* 2020a, Araújo-Santos *et al.* 2021).

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SUPPLEMENTARY MATERIAL

Appendix 1. Forest cover and geographic location of 30 cocoa agroforestry sites (cabruca) and 30 Atlantic Forest remnant sites (forest) in southern Bahia, Brazil.

Appendix 2. Abundance of Mutillidae and Pompilidae in 30 cocoa agroforestry sites (cabruca) and 30 Atlantic Forest remnant sites (forest) in southern Bahia, Brazil.

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