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ORIGINAL RESEARCH

Successional agroforestry systems as land use that promote the restoration and conservation of ant assemblages in the Amazon

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Abstract
Land-use changes, driven by the expansion of agriculture and livestock farming, are one of the main drivers of biodiversity loss in the Amazon region. In this context, Succesional Agroforestry Systems - SAFs, emerge as a potential alternative to reconcile agricultural production with biodiversity conservation and restoration. This study assessed the impact of different land-use types on ant diversity and the composition of habitat-use guilds in areas of primary forest, pastures, shifting cultivation, and SAFs at different ages. The results indicate that primary forests consistently exhibited the highest alpha, beta, and gamma diversity. The community composition also shifted along the land-use gradient, with disturbed areas showing a higher relative representation of generalist and open-area species, while forest specialists were proportionally more represented in primary forests. Old SAFs displayed diversity values and guild composition that were intermediate between primary forests and more intensively managed systems whereas young SAFs more closely resembled pastures and shifting cultivation areas. These findings highlight the importance of SAF age in shaping biodiversity recovery trajectories, suggesting that mature agroforestry systems have the potential to promote the recovery of biodiversity in human-modified landscapes. This study underscores the importance of long-term agroforestry management strategies to promote conservation and ecological restoration, especially in regions of high biodiversity value, such as the Amazon.

Keywords Habitat-use guild · Forest recovery · Human-modified landscapes · Land-use change

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Introduction

In the Amazon, the main driver of land-use change is the conversion of forests into agricultural lands and pastures (Fearnside 2005). These transformations have led to the suppression and fragmentation of vast forest areas (Jaureguiberry et al. 2022), significantly altering the original habitat in terms of abiotic conditions and resource availability - such as temperature, humidity, and soil cover (Imazon 2012; Araújo et al. 2011) - as well as biodiversity (Menezes and Schmidt 2020; Costa and Schmidt 2022) and ecosystem functions (Fontenele and Schmidt 2021; Nunes et al. 2022). However, not all agricultural systems affect biodiversity in the same way. Depending on the intensity and management practices, different land-use types can have distinct impacts on species composition and ecological processes. Intensive systems often result in a low-quality matrix (Arroyo-Rodríguez et al. 2020), which may trigger unexpected ecosystem transitions and further amplify climate change (Flores et al. 2024).

Land-use alternatives that resemble natural habitats, reconciling economic income and biodiversity conservation, have been proposed (Tscharntke et al. 2021). In this context, successional agroforestry systems (SAFs) emerge as a promising solution to address this issue (Franke et al. 2000; Arroyo-Rodríguez et al. 2020). SAFs are managed to promote natural secondary succession, aiming to mimic the structure, diversity, and ecological interactions of natural forests (Young 2024). Recent evidence shows that agroforestry systems can also act as important refuges for insects, including pollinators, across environmental gradients, thus reinforcing their potential role in biodiversity conservation (Kingazi et al. 2025).

Agroecology and agroforestry techniques are combined to the establishment of successional agroforestry systems, promoting a transition to forest restoration, which accelerates secondary succession and leads to the development of a vertically stratified forest. This structural stratification increases habitat heterogeneity and resource availability, while the producing crops in the initial phase to minimize restoration costs and actively involve farmers in restoration activities (Vieira et al. 2009). Additionally, they have the potential to slow down or reverse soil degradation, enhance fertility, capture carbon, and ensure livelihoods by providing both ecological and economic benefits (Braga et al. 2019).

In Acre, in the Reserva Extrativista Chico Mendes (RESEX-CM) covers the Acre River basin, which is considered the most deforested region in the southwestern Brazilian Amazon. Although the reserve acts as a protection against deforestation and preserves large areas of primary forests (Milien et al. 2021), deforestation still penetrates its boundaries (Mascarenhas et al. 2018), as much of the landscape is also composed of secondary forests, pastures, shifting cultivation (slash-and-burn), and successional agroforestry systems, which occur in smaller proportions compared to the other land uses. This heterogeneous landscape configuration creates a clear gradient of land-use intensity, making RESEX-CM an ideal setting to assess how different land uses and different successional stages affect species diversity and composition patterns.

To assess the effects of land-use changes on biodiversity, the use of bioindicators is necessary (McGeoch 1998; Newbold et al. 2015). Ants have been used as bioindicators (Underwood and Fisher 2006), as they perform key functions in ecosystems (Rocha et al. 2024) such as biological control, seed dispersal, ecosystem engineering, and nutrient cycling (Del Toro et al. 2012), and exhibit a predictable response of their community parameters to human impacts (Agosti et al. 2000; Philpott et al. 2010), specifically those that forage at ground (Schmidt et al. 2013), reinforcing their value as indicators of ecosystem functioning and environmental change.

In general, ant diversity is affected by the conversion of natural habitats into agricultural, forestry, and livestock areas (Philpott 2010). As a result, these anthropized areas exhibit fewer ant species, with a small number of species dominating the assemblages (Costa and Schmidt 2022). Additionally, the response of ant species varies according to their habitat-use guilds (i.e., open or forest habitat specialists and habitat generalists, which can live in both habitats) (Andersen 2019). Ant species grouped according to habitat-use guilds respond differently to human-driven environmental changes (Martins et al. 2022). Species associated with forest environments are generally the most vulnerable, often experiencing pronounced declines in richness, abundance, and biomass when native habitats are altered or converted (Sales and Schmidt 2023; Dutra et al. 2024). By contrast, taxa with broader ecological tolerances, including generalists and species typical of open habitats, frequently become more prevalent in modified landscapes, particularly where forest cover has been substantially reduced (Martins et al. 2022). Such opposing responses align with the "winner–loser" paradigm (McKinney and Lockwood 1999; Filgueiras et al. 2021), which posits that anthropogenic disturbance selectively filters communities, negatively affecting forest-dependent species while promoting a narrower group of disturbance-tolerant or open-area taxa (Paolucci et al. 2017).

In this study, we evaluated the potential contribution of successional agroforestry systems to biodiversity conservation in the southwestern Brazilian Amazon, using patterns of ant diversity as ecological indicators. Specifically, we hypothesize that young successional agroforestry systems will show lower gamma and alpha (number of species at different spatial scale) and beta diversity (differences in species composition), as well as the predominance of open-area specialist and generalist species, similar to pastures and shifting cultivation. In contrast, we hypothesize that old successional agroforestry systems will exhibit higher gamma, alpha, and beta diversity, and the predominance of forest specialist species, similar to primary forest areas. Our expectations are based on the fact that the greater structural complexity of the vegetation and heterogeneity of resources with advancing successional age will favor ant species associated with the forest and greater spatial rotation within the communities.

Materials and methods

Study area

We conducted the study in the Reserva Extrativista Chico Mendes (RESEX-CM), located in the state of Acre, southwestern Brazilian Amazon (10° 06' 11"10° 58' 39" S and 67° 56' 13" 69° 48' 00" W). The RESEX-CM covers an area of approximately 970,550 ha, consisting of open ombrophilous forest (73%) and dense ombrophilous forest (27%), spanning parts of the municipalities of Assis Brasil, Brasiléia, Capixaba, Xapuri, Sena Madureira, Epitaciolândia, and Rio Branco (BRASIL 2006).

The climate of the region is tropical humid, with an annual average temperature of approximately 27 °C. The highest precipitation occurs between December and March, with January being the month with the highest average (297 mm). The dry season is long, spanning from May to August, with the driest period averaging 43 mm of precipitation (Alvares et al. 2013).

The ant samplings were carried out in the municipalities of Brasileia and Epitaciolândia (Fig. 1). The collections were carried out in September 2023, a transitional period between the dry and rainy seasons in the state of Acre (Duarte and Mascarenhas 2007).

Land-use types

To assess the effect of different land uses on ant assemblages, we conducted our samplings in pastures (i.e., areas with a history of deforestation and disturbance, characterized by open canopy and livestock use), shifting cultivation (i.e., open canopy, simplified vegetation structure, and recent or ongoing land-use activities), young successional agroforestry systems - young SAFs (i.e., systems with one year of implementation), and old successional agroforestry systems - old SAFs (i.e., systems between nine and 29 years of implementation) and primary forest areas (i.e., areas with no history of deforestation or agricultural use, characterized by well-developed vertical stratification and closed canopy) (Fig. 2).

Both successional agroforestry systems (young and old) at the initial phase have the same cropping design, which is the consortium of trees with several kinds of crops, such as banana, cassava, corn, pineple, etc. The young SAFs were implemented in 2022 by the non-governmental organization - NGO SOS Amazônia, providing inputs and technical assistance for residents to implement the planting of half a hectare through the project "Faça Florescer Floresta" (SOS AMAZÔNIA 2022). The old SAFs were implemented through the initiative of the local residents between 1993 and 2014.

Finally, as we selected markdely distinct land-use types, and chosse very similar replicates within each land-use types, we did not account vegetation parameters (e.g., canopy cover, tree density, etc.) along the land-use types and consequentely did not considered them in the statistical models (see Statistical Analyses). We opted for that because there is a strong collinearity between land-use types and vegetation variables (Solar et al. 2015; Kuzevic et al. 2026).

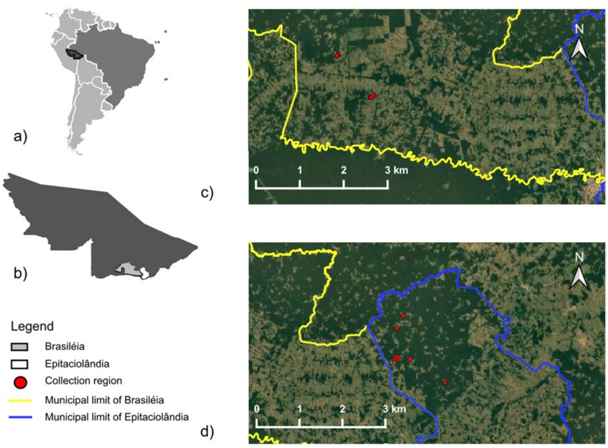

Fig. 1 Location of the sampling areas in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. (**a**) Location of Brazil in relation to South America. (**b**) State of Acre; the municipality colored in gray is Brasiléia, and the one colored in white is Epitaciolândia. (**c**) Red dots show the project collection regions in the municipality of Brasiléia; yellow lines show the municipal boundaries. (**d**) Red dots show the project collection regions in the municipality of Epitaciolândia; blue lines show the municipal boundaries

Fig. 2 Land-use types where ant samplings were carried out in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. **A** - pasture area; **B** - shifting cultivation; **C** - primary forest; **D** - old successional agroforestry systems; **E** - young successional agroforestry systems

Sampling design

Ant collections were carried out in six replicates of each land use, resulting in a total of 30 sampling units. Replicates were spatially independent and separated by distances sufficient to ensure independence, varying according to land-use configuration. In each replicate, a 250 m transect was established, with 10 sampling points spaced 25 m apart. At each sampling point, ants were collected using pitfall traps placed on the soil surface (Bestelmeyer et al. 2000). The pitfall traps consisted of 200 ml plastic containers filled with 150 ml of a killing solution made of water, glycerol (5%), and salt (0.9%) (Schmidt and Solar 2010), which killed and preserved the ants. The traps were left in the field for 48 h. The ants collected in the traps were preserved in 90% alcohol for later sorting and mounting in the Laboratório de Ecologia de Formigas da Universidade Federal do Acre (UFAC).

Pitfall traps efficiently sample epigeic ant assemblages actively foraging on the soil surface and across the litter–soil interface, including both ground-nesting and arboreal species during foraging activity, and are widely used for comparative diversity studies across land-use gradients (Bestelmeyer et al. 2000; Schmidt and Solar 2010). This method has proven particularly effective for detecting changes in community composition, dominance patterns, and habitat-use guilds across land-use gradients (Agosti et al. 2000; Philpott et al. 2010).

Ant species identification

We identified the ants to the genus level using identification keys from Feitosa and Dias (2024) and Baccaro et al. (2015). Species identification was initially conducted by comparing the morphospecies with specimens from the ant collection at the Laboratório de Ecologia de Insetos da Universidade Federal do Acre (UFAC).

Unidentified morphospecies were transported to the Laboratório de Sistemática e Biologia de Formigas da Universidade Federal do Paraná (UFPR) for species identification and confirmation by ant taxonomists. The reference specimens for this study were deposited in the collections of UFAC and UFPR.

Habitat-use guilds

All ants identified to the species level were classified into three habitat-use guilds (i.e., forest specialists, generalists, and open-area specialists) (Dutra et al. 2024). To determine the guild of each species, we used the Brazilian Ant Habitat-use Guilds (BAH) (BAH 2023) application, which provides the classification of approximately 80% of the Brazilian ant fauna into habitat-use guilds. The BAH uses a database of habitat-use guilds based on the methodology contained in Dutra et al. (2024) that calculate the habitat preference of ants through an online database.

Statistics analysis

First, to assess the effects of which land uses on ant species diversity, we employed gamma diversity (γ), which is the total number of ant species sampled in each replicate of land uses. Alpha diversity (α) was obtained as the mean number of species present across the ten points of each transect in a replicate. Beta diversity (β) between the sampling points of each transect was calculated using a presence-absence matrix, which allowed the computation of the *Sørensen* dissimilarity index. This index considers the number of species shared between the samples and the number of species exclusive to each one. The *Sørensen* dissimilarity index ranges from 0 to 1, with values close to 0 indicating that the samples share many species, and values close to 1 indicating that the samples represent distinct set of species. The index was obtained using the *beta.multi* function from the *betapart* package (Baselga et al. 2013).

To test our hypothesis, we constructed three Generalized Linear Models (GLMs), each with land-use type as the predictor variable and the response variable for the first model was γ diversity, modeled with a Poisson error distribution. The response variable for the second model was α diversity, modeled with a normal error distribution. Finally, the third model used β diversity as the response variable, applying a binomial error distribution adjusted with a quasibinomial distribution (Crawley 2013). Finally, in all tests described above, we applied ANOVA to access the significance of differences among land use types. The significancy of land-use means that at least one lad-use type has alpha, gamma or beta diversity signficatively different to the others land-use types. The R packages used to run the analyses descibed above were lme4 (Bates et al. 2007; Douglas et al. 2015), *car (*Fox and Weisberg 2019) and *ggplot2* (Wickham 2016) to construct the graphics.

Thus, we proceeded a model simplification to verify each land-uses could be joined in a single levels. We did it sorting the land-use types by average of gamma, alpha, and beta diversity and joined the levels with similar avarage of these metrics. Thus, we created a new model with less levels (land-use types) and then compare with the initial model (with all land-use types), if there is non-significant difference, we opted to the simplest model (with less types of land-use) (Crawley 2013). We proceded it until to arrive in the simplest model for each diversity metric (i.e. alpha, beta and gamma).

To identify the predominant ant habitat-use guild in each land-use type, we calculated the percentage of each guild relative to the total species richness in each land-use replicate. Thus, we used GLM, where the percentage was the response variable and land-use types (primary forest, old SAFs, young SAFs, shifting cultivation, and pasture) and habitat-use guilds (forest specialists, generalists, and open-area specialists) were the explanatory variables. Finally, we included the interaction between land-use type and habitat-use guild. We assumed a binomial error distribution due to the percentage nature of the response variable and if necessary we adjusted to quasibinomial error distribution (Crawley 2013) and applied to ANOVA to access the significance of the explanatoies variables.

For all models, we used diagnostic functions such as *rdiagnostic* from the RT4Bio package (Junior et al. 2015), which checks the distribution of residuals and other fit indicators. We conducted all analyses using R 2024.04.2 (https://www.r-project.org/). Specific packag es and functions relevant to the statistical analyses described above were used accordingly.

Results

Ant fauna

A total of 265 ants records were obtained, of which 176 (66.41%) were identified to the species level, and 89 (33.58%) were classified as morphospecies or grouped into broader taxonomic categories. The ants were distributed across 56 genera, belonging to ten subfamilies. The subfamily Myrmicinae had the highest number of genera (24 genera), followed by Ponerinae and Dorylinae, each with seven genera. Formicinae had six genera, Dolichoderinae had five, Ectatomminae had four, and Amblyoponinae, Paraponerinae, Proceratiinae, and Pseudomyrmecinae each one had one genus (Supplementary Material, Table S1).

Of the 176 ants identified to the species level, 166 species were classified according to their habitat-use guild using the BAH application, while six species were classified using the methodology reported by Dutra et al. (2024). The classification of only two species (*Camponotus compositor* Santschi, 1922 and *Hylomyrma dolichops* Kempf, 1973) was not possible, as there was insufficient data to apply the method reported in Dutra et al. (2024).

A total of 21 new ant species records were found for the state of Acre (Table 1, occurring across the different land-use types.

Gamma, alpha, and beta diversity

Gamma diversity diffred among the land-use types ($F_{4, 25} = 183.22$; $p < 0.001$). The gamma diversity of primary forest (mean 68.00) was higher than the other land-use types. The old (mean 40.50) and young (mean 32.00) SAFs showed respectively the second and third larg-

Table 1 Ant species with new occurrence records for the state of Acre. Land uses: F - Primary Forest, OS - Old successional agroforestry system, YS - young successional agroforestry system, P - Pasture, R - Shifting cultivation. NF - Not found. Habitats-use guilds: for.spe - forest specialists, generalist - generalists, open-habitat - open-area specialists

Taxon	Land-use					Habitat-use guilds
	F	OS	YS	*P*	*R*	
Dolichoderus rufescens Mann, 1912	1	0	1	0	0	for.spe
Dolichoderus abruptus (Smith, 1858)	0	1	0	0	0	open-habitat
Cylindromyrmex striatus Mayr, 1870	0	1	0	0	0	for.spe
Brachymyrmex cordemoyi Forel, 1895	1	1	1	1	1	generalist
Brachymyrmex termitophilus Forel, 1895	0	0	1	1	0	open-habitat
Brachymyrmex pictus Mayr, 1887	1	1	1	0	0	for.spe
Brachymyrmex degener Emery, 1906	1	0	0	0	0	generalist
Camponotus sanctaefidei convexinodis Wheeler, 1934	1	0	0	0	0	NF
Camponotus substitutus Forel, 1899	1	0	1	1	1	generalist
Camponotus excisus Mayr, 1870	1	0	0	0	0	for.spe
Camponotus burtoni Mann, 1916	1	0	0	0	0	for.spe
Camponotus compositor Santschi, 1922	1	0	1	1	1	NF
Acromyrmex rugosus (Smith, 1858)	0	1	0	0	0	generalist
Carebara anophthalma (Emery, 1906)	1	0	0	0	0	for.spe
Mycetarotes acutus Mayhé-Nunes, 1995	1	0	0	0	0	open-habitat
Mycetophylax lectus (Forel, 1911)	1	0	0	0	1	open-habitat
Strumigenys urrhobia (Bolton, 2000)	1	0	0	0	0	for.spe
Anochetus neglectus Emery, 1894	0	1	0	0	0	generalist
Platythyrea punctata (Smith, 1858)	0	1	0	0	0	for.spe
Probolomyrmex brujitae Agosti, 1995	0	1	0	0	0	for.spe
Pseudomyrmex tenuissimus (Emery, 1906)	0	1	0	0	0	generalist

est gamma diversity. The most intensive land-use types (i.e. pasture and shifting cultivation) presented the smallest gamma diversity (mean-pasture: 23.33; mean-shifting cultivation: 26.83), which were similar and were joined in a single level by model simplification (Fig. 3).

Alpha diversity differed among the various land-use types ($F_{4,\ 25}$ = 13.34; $p<0.001$) (Fig. 4). Differences among land-use types were identified through model simplification, in which land-use levels with statistically similar mean values were progressively grouped based on non-significant model comparisons. Primary forest presented the higher alpha diversity (mean 11.30) (Fig. 4). The alpha diversity of old SAFs (mean 7.55), young SAFs (mean 8.21) and shifting cultivation (mean 7.75 presented similar similar values. Thus, these land-uses were joined at a single level (Fig. 4) by model simplification. Finally, pastures exhibited the lowest alpha diversity (mean 6.75) (Fig. 4).

Consistent with our expectations, beta diversity also varied across land-use types ($\chi^2_{(4,25)}=16.11$, $p<0.01$). More intensive land use types (pasture and shifting cultivation) showed lower β diversity (i.e., higher similarity among ant assemblages across sampling points) compared to less intensive use-types (primary forest and old SAFs) (Fig. 5). The beta diversity of pastures (mean 0.79) and shifting cultivation (mean 0.79) presented similar values, then, was possible joined them in a single level by model simplification (Fig. 5). Both SAFs presented higher beta diversity (mean-old: 0.882; mean-young: 0.82) than more intensive land-use types (i.e. pasture and shifting cultivation), but still lower than primary forest (mean 0.90) (Fig. 5).

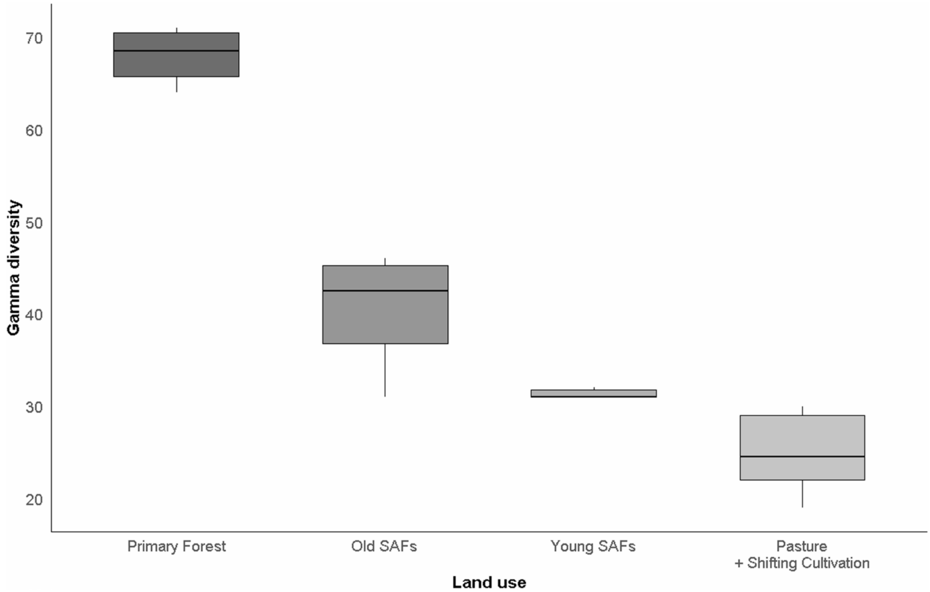

Fig. 3 Gamma diversity across the land-use types in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. Land use types: Primary Forest areas; Old SAFs - old successional agroforestry systems; Young SAFs - young successional agroforestry systems; Pasture + Shifting Cultivation - merging group composed by pasture areas and shifting cultivation

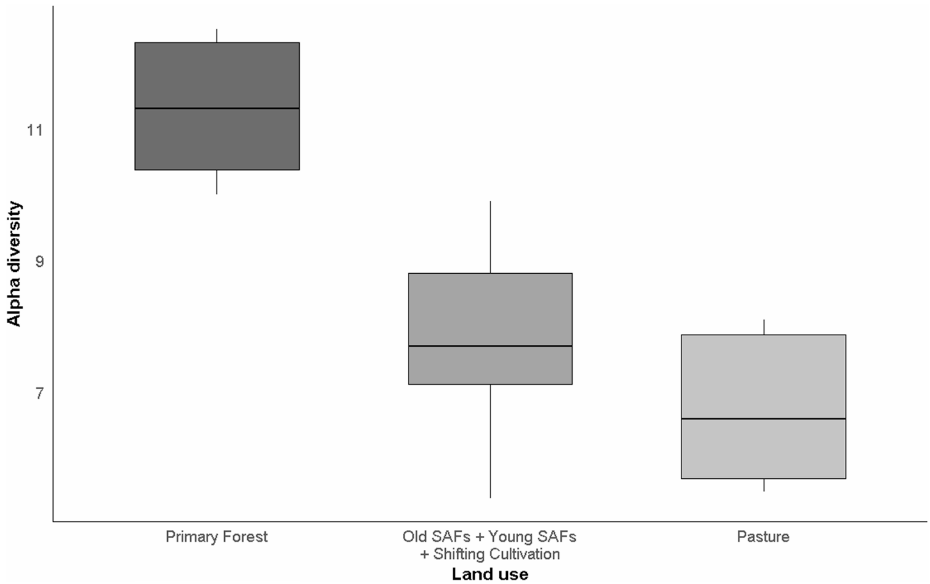

Fig. 4 Alpha diversity across the land-use types in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. Land use types: prim_for - primary forest areas; Old SAFs + Young SAFs + Shifting cultivation - merging group composed by old successional agroforestry systems and young successional agroforestry systems and shifting cultivation; pasture - pasture areas

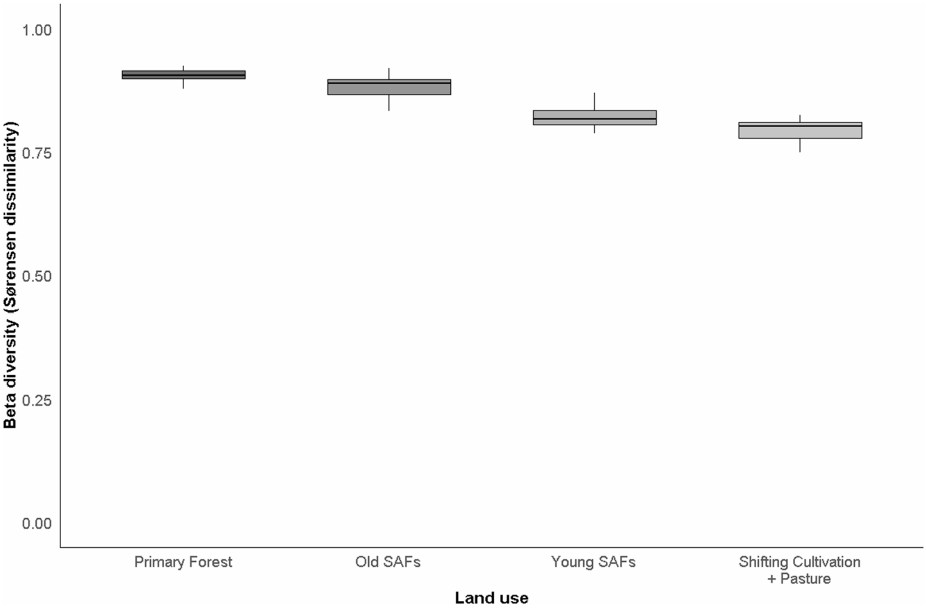

Fig. 5 Beta diversity across the land use types in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. Land use types: Primary Forest areas; Old SAFs - old successional agroforestry systems; Young SAFs - young successional agroforestry systems; Shifting Cultivation + Pasture - merging group composed by pasture areas and shifting cultivation

Habitat-use guilds

Corroborating our expectation, the percentage of species richness in habitat-use guilds did not vary across land use types ($\chi^2_{(85,4)} = 23.63$; $p = 1$), but this was different among habitat-use guilds $\chi^2_{(83,2)} = 13.43$; $p < 0.001$) and the interection between land-use types and habitat-use guilds was signficant ($\chi^2_{(75,8)} = 1.58$; $p < 0.001$). This means that ant assemblages in areas of more intensive land use (i.e., pastures and shifting cultivation) were relatively composed of more generalist ants and open-area specialists, whereas primary forest (less intensive land use) was relatively more composed of forest specialists (Fig. 6).

The ant assemblages of young SAFs were more relatively composed by generalist ants and open-areas specialists, similar to the ant assemblages from more intensive land uses (i.e., pastures and shifting cultivation) (Fig. 6). In turn, the ant assemblages of old SAFs, although presented a higher proportion of forest specialist than open-area specialists, it was followed closed by generalist (Fig. 6).

Discussion

Our results show that ant aseemblages of Old SAFs, although with lower diversity metrics (i.e. alpha, gamma and beta), show guild compositions approaching those of primary forests, but at this stage, forest specialist and generalist presentesd almost the same percentage of species richness. In it turns, young SAFs resemble the more intensive land uses

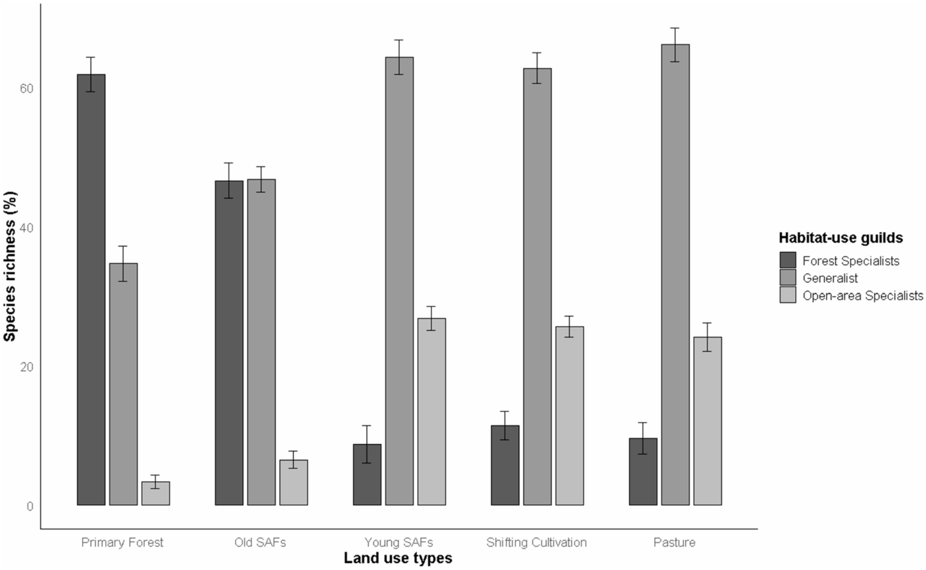

Fig. 6 Percentage of ant species richness in habitat-use guilds through out different land-use types in the municipalities of Brasileia and Epitaciolândia, Acre state, southwestern Brazilian Amazon. Habitat-uses guilds: Forest Specialists, Generalists, and Open-area Specialists. Land use types: Primary Forest, Old SAFs - Old Successional Agroforestry Systems, Young SAFs - Young Successional Agroforestry Systems, Shifting Cultivation, and Pasture areas

(i.e., pastures and shifting cultivation). In the sections below, we provide explanations for these results and present implications for biodiversity conservation in human-modified landscapes.

Ant fauna

In our study, the new records for the state of Acre are particularly interesting because they appear in even in intensive land-use types (i.e. pasture, shifting cultivation, young successional agroforestry systems) such as *Brachymyrmex cordemoyi* Forel, 1895, a generalist species, was recorded in all land-use types in this study and *Brachymyrmex termitophilus* Forel, 1895 and *Camponotus substitutus* Forel, 1899, only in intensive land-use types. This reiforce the lack of ant sampling in the southwestern Amazon (Schmidt et al. 2025).

In addition to foraging strategies, the presence of these species can be explained by the type of habitat they occupy, whether as generalists or specialists of open habitats. Species from these guilds are able to withstand different ecological filters. The fact that our study resulted in 21 new records is highly expressive and improve the ant species record to Acre for 455, highlighting the southwestern Amazon as a frontier on ant sampling in the Neotropical region (Schmidt et al. 2025; Dias and Feitosa 2024). This discovery further emphasizes the region's importance for biodiversity and underscores its potential to yield more insights into the richness of ant species in this part of the world.

The conversion to more intensive land-uses resulted in the loss of certain functional groups of ants. For example, predatory species such as those from the genera *Strumigenys* and *Gnamptogenys* were predominantly found in areas with lower land-use intensity (e.g., primary forest and old SAFs). These species typically forage in the leaf litter and build their nests in these habitats (Baccaro et al. 2015), which may explain the decline in their populations in pasture and shifting cultivation areas due to environmental changes.

In contrast, species from the genera *Brachymyrmex*, *Pheidole* and *Solenopsis* benefitted from the conversion of forests to pasture and shifting cultivation. This is evidenced by the characteristics of these intensive land-uses, which resemble open habitats (Vasconcelos et al. 2018; Fontenele and Schmidt 2021). These species are largely considered generalists and/or adapted to open habitats (Dutra et al. 2024).

Gamma, alpha and beta diversity

Regarding gamma diversity, our results show that primary forest harbors the highest values followed by old SAFs. This indicates that, beyond maintaining high local diversity (alpha diversity) and species turnover (beta diversity) (Costa and Schmidt 2022), these environments support a broader regional species pool. In contrast, more intensive land-use types (i.e. pasture and shifting cultivation), exhibited significantly lower gamma diversity, highlighting their selective ecological role on the regional ant fauna, which only species adapted to open habitat are more prompt to survy (Dutra et al. 2024) (see also our Fig. 6). Old SAFs presented the second highest gamma diversity, which allow it to be a friendly land-use for ant diversity conservation in tropical human-modified landscapes (Hoenle et al. 2022), but the fact that forest specialists and generalist presented almost the same percentage of species richness indicates that more time of forest recover is necessary to the sucessional agroforestry systems sampled achived similar level biotic complexity and biodiversaity than primary forests.

These patterns are consistent with what has been observed across the Neotropics. According to Wilker et al. (2024), the conversion of forest to pasture, an example of an intensive land-use change leads to strong declines in ant diversity due to the simplification of vegetation structure and environmental conditions. Andersen (2019) further explains that such disturbances act as strong environmental filters, excluding disturbance-sensitive and specialist species while favoring disturbance-tolerant generalists. As a result, habitat homogenization leads to the exclusion of unique species and reduced regional richness (gamma diversity).

We found out that all human-induced land-uses presented a lower alpha diversity than primary forest (Fig. 4) which corroborates the findings of Wilker et al. (2023). However, considering only alpha diversity is not possible differentiate the ant assemblages among the human-induced land-uses (i.e., old and young sucessional agroforestry systems and shifttin cultivation), reinforcing the necessity of the use of other diversity metrics, such as beta diversity (Costa and Schmidt 2022) and the use of habitat-use guilds (Dutra et al. 2024).

Beta diversity, on the other hand, seems to be more sensitive to land-use changes. Even with a more subtle change (Escobar-Ramírez et al. 2020) or with an intense change, we can find differences in β values in ant assemblages, which become evident according to the type of land-use. In our study, areas with more intensive land use (i.e., pasture) exhibited low beta diversity values. On the other hand, in areas with less intensive land use (i.e., primary forest), the high beta diversity values are intrinsically linked to a more restricted distribution of species in these environments and to environmental heterogeneity (Ribas et al. 2003).

The biotic and abiotic constraints of a habitat determine the functional traits that will be useful for ant species survival (Hoffmann and Andersen 2003; Philpott et al. 2010; Oliveira et al. 2017, 2019; Ribeiro-Neto et al. 2023) and ultimately their distribution (Heino et al. 2015). Thus, the homogenity of resources and conditions in more intensive land-use (Fearnside 2005; Imazon 2012; Araújo et al. 2011) could favor ant species overdisperse within these habitats leading to low beta diversity among the assemblages. In turn, in less intensive land-use, the heterogenity of resource and conditions could impose more restriction to ant species distribution, leading to high values of beta diversity (Costa and Schmidt 2022).

Habitat-use guilds

The use of habitat-use guilds have provided more clarity on ant composition change (Dutra et al. 2024), bearing in mind that ant species within these guilds respond differently according to their various tolerances to habitat openness (Andersen 2019) and consequently according winner–loser framework (McKinney and Lockwood 1999; Filgueiras et al. 2021), anthropogenic disturbances disproportionately disadvantage forest specialists, while favoring a limited subset of generalist and open-habitat species (Paolucci et al. 2017; Martins et al. 2022). Furthermore, these guilds often exhibit specialized aspects of morphology, ecology, or behavior (Gibb et al. 2015), and their richness throughout secondary succession tends to change differetly (Schmidt et al. 2013; Marques et al. 2017; Neves et al. 2021; Sousa-Souto et al. 2016; Bombi-Haedo et al. 2025).

Dutra et al. (2024) has reported that ant assemblages of forest habitat are predominantly made up by forest specialist and in turn, ant assemblage of pasture generalists and open-habitat specialist are dominant. This highlights that canopy cover has a direct effect on the slection of habitat-use ant guilds and thus the response of ants to human-induced disturbances is essentialy indirect because their respond to changes on vegetation strucuture that was affected by these disturbance (Andersen 2019).

Studies have documented multiple relationships between ants and agroforestry systems, including how ant communities influence ecosystem services and disservices, how ant species richness and community composition correlate with vegetation structure (Bisseleua et al. 2009, 2017) and how ant assemblages recover during secondary succession following agricultural disturbance (Bombi-Haedo et al. 2025). According to Khoo and Ho (1992), ant species can yet act as biological control agents in agroecosystems, reducing the presence of undesirable pests. Furthermore, studies highlight the importance of ants in agroecosystems due to their roles in regulating arthropod populations, influencing plant performance, and contributing to key ecosystem processes such as pest suppression and trophic interactions (de la Fuente and Marquis 1999; Roberts et al. 2000; Klein et al. 2003). In addition, ants provide intermediate ecosystem services, such as the natural control of pests and plant diseases through predation, competition, and interactions (Philpott and Armbrecht 2006; Zovi et al. 2008). These studies have demonstrated the contribution of SAFs to conservation (Brown et al. 2006) and their importance in conservation and reforestation plans aimed to protect ant diversity. Agricultural areas that are vegetatively complex, with high diversity, density, and height, are able to maintain biodiversity levels similar to those of native forests (Moguel and Toledo 1999), and regenerating forests become taxonomically, functionally, and phylogenetically similar to mature forests (Barros et al. 2021).

In our study, even cosidering its limitations (i.e. single-stratum, single-method design) the ant habitat-use guilds in areas of old SAFs are approching those of primary forest areas, which suggests that this similarity between the areas is due to shared habitat characteristics.

However, the fact that generalist has a similar percentage than forest specialists in old SAFs shows that this land-use is not equivalent to a forest in biodiversity, but is a much beter land-use than pasture and shifting cultivation for Amazon biome. On the other hand, young SAFs resembled pasture and shifting cultivation areas.

Finally, our findgins instigate a key quenstion: which point during SAFs development the replacment among the ant habitat-use guilds occur? Although there are studies that track the recovery of ant assemblages and changes in vegetation along chronosequences (Lawes et al. 2017; Hoenle et al. 2022), the is a lack of studies on SAFs context regrading to track the vegetation recover where this guild replacment occur and the necessary time for that. The investigation of that (theroretically or/and emperically) is extremelly useful for the use of ant assemblages as clear and predicatable indicator on monitorig programs (Dale and Beyeler 2001).

Conclusion

Our study showed that the time of sucession of the SAFs has a direct impact on ant composition, with areas of Old SAFs supported ground-foraging ant assemblages and guild compositions approaching those of primary forests, dominated by forest specialists. In contrast, young SAFs displayed a pattern more similar to that of intensively used land areas, such as pastures and shifting cultivation, with a predominance of generalist ants and open-areas specialists. These results suggest that ecological succession in SAFs may be a gradual process, where system maturity is key to achieving a species diversity closer to that observed in native forests.

The SAFs is a key factor for biodiversity and composition of ant habitat-use guilds. This raises important questions about the time needed for SAFs to develop and become effective in restoring the diversity of forest ant specialists. Further studies are needed to more accurately assess the temporal aspects of this process, investigating how long it takes for an SAFs to achieve vegetation cover that favors the predominance of specialized forest species. Such studies could provide valuable information for the management of SAFs as tools for ecological restoration, highlighting the importance of considering the age, development stage and management history of successional agroforestry systems in biodiversity conservation strategies.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent for publication All authors approve the publication of this manuscript.

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Conflict of interest All the authors declare that don't have known financial interests or personal relationships that could have to influence the work reported in this paper.

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References

Agosti D, Majer JD, Alonso L, Schultz T (2000) Ants: standard methods for measuring and monitoring biodiversity. Smithsonian Institution Press, Washington. https://doi.org/10.1086/343974

Alvares CA, Stape JL, Sentelhas PC, de Moraes Gonçalves JL, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507

Andersen AN (2019) Responses of ant communities to disturbance: five principles for understanding the disturbance dynamics of a globally dominant faunal group. J Anim Ecol 88(3):350–362. https://doi.org/10.1111/1365-2656.12907

Araújo EA, Ker JC, Mendonça ES, Silva IR, Oliveira EK (2011) Impacto da conversão florestal – pastagem nos estoques e na dinâmica do carbono e substâncias húmicas do solo no bioma Amazônico. Acta Amazon 41:103–114. https://doi.org/10.1590/S0044-59672011000100012

Arroyo-Rodríguez V, Fahrig L, Tabarelli M, Watling JI, Tischendorf L, Benchimol M et al (2020) Designing optimal human-modified landscapes for forest biodiversity conservation. Ecol Lett. https://doi.org/10.1111/ele.13535

Baccaro FB, Feitosa RM, Fernández F et al (2015) Guia para os gêneros de formigas do Brasil. Editora INPA, Manaus, p 388

BAH! – Brazilian Ant Habitat-use guilds [Mobile application software] (2023) (Version 1.0). Rio Branco: Laboratório de Ecologia de Formigas – UFAC

Barros MF, Ribeiro EMS, Vanderlei RS, de Paula AS, Silva AB, Wirth R, Cianciaruso MV, Tabarelli M (2021) Resprouting drives successional pathways and the resilience of Caatinga dry forest in human-modified landscapes. For Ecol Manage 482:118881. https://doi.org/10.1016/j.foreco.2020.118881

Baselga A, Orme D, Villeger S, De Bortoli J et al (2013) Betapart: Partitioning beta diversity into turnover and nestedness components version 1.3. R package

Bates D, Sarkar D, Bates MD, Matrix L (2007) The lme4 Package. R Package Version 2:74

Bestelmeyer BT, Agosti D, Alonso LE, Brandão CRF, W.L., et al (2000) Field techniques for the study of ground-living ants: An overview, description, and evaluation. In: Agosti D, Majer JD, de Alonso LT, Schultz T (eds) Ants: Standard methods for measuring and monitoring biodiversity. Smithsonian Institution, Washington, p. 280, pp 122–144

Bisseleua DHB, Missoup AD, Vidal S (2009) Biodiversity conservation, ecosystem functioning, and economic incentives under cocoa agroforestry intensification. Conserv Biol 23(5):1176–1184. https://doi.org/10.1111/j.1523-1739.2009.01220.x

Bisseleua DHB, Begoude D, Tonnang H, Vidal S (2017) Ant-mediated ecosystem services and disservices on marketable yield in cocoa agroforestry systems. Agriculture. Ecosystems & Environment 247:409–417. https://doi.org/10.1016/j.agee.2017.07.004

Bombi-Haedo K, Oliveira FM, Arnan X, Ribeiro-Neto JD, Leal IR (2025) Ant community recovery in regenerating Caatinga dry forest following slash-and-burn agriculture. J Arid Environ 227:105298. https://doi.org/10.1016/j.jaridenv.2024.105298

Braga D, Pellicciottii A, Gonçalves R (2019) Sistemas Agroflorestais indicados para o Acre: Catálogo. Governo do Estado do Acre, EMA

BRASIL (2006) Ministério do Meio Ambiente/Instituto Brasileiro de Meio Ambiente e dos Recursos Naturais Renováveis. Plano de Manejo da Reserva Extrativista Chico Mendes. Brasília

Brown GG, Römbke J, Höfer H, Verhaagh MANERED, Sautter KD, Santana DDQ (2006) Biodiversity and function of soil animals in Brazilian agroforestry systems. Sistemas Agroflorestais: Bases Científicas para o desenvolvimento sustentável. UENF, Campos dos Goytacazes, pp 217–242

Costa MMSD, Schmidt FA (2022) Gamma, alpha, and beta diversity of ant assemblages response to a gradient of forest cover in human-modified landscape in Brazilian Amazon. Biotropica 54(2):515–524. https://doi.org/10.1111/btp.13073

Crawley MJ (2013) The R Book, 2nd edn. Chichester

Dale VH, Beyeler SC (2001) Challenges in the development and use of ecological indicators. Ecol Indic 1:3–10

de la Fuente MAS, Marquis RJ (1999) The role of ant-tended extrafloral nectaries in the protection and benefit of a neotropical rainforest tree. Oecologia 118:192–202. https://doi.org/10.1007/s004420050718

Del Toro I, Ribbons R, Pelini S (2012) The little things that run the world revisited: a review of ant-mediated ecosystem services and disservices (Hymenoptera: Formicidae). Myrmecol News 17:133–146

Dias AM, Feitosa RM (2024) Frontier ants (Hymenoptera: Formicidae) unveiled: exploring the remarkable diversity of the Brazilian Far West. Biota Neotrop 24(4):e20241686. https://doi.org/10.1590/1676-0611-BN-2024-1686

Douglas B, Martin M, Ben B, Steve W (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67(1):1–48. https://doi.org/10.18637/jss.v067.i01

Duarte AF, Mascarenhas MDM (2007) Manifestações do bioclima do Acre sobre a saúde humana no contexto socioeconômico da Amazônia. Amazon Cienc Desenvolv 3(5):149–162
Dutra DBS, Feitosa RM, Jory TT et al (2024) Ant habitat-use guilds response to forest-pasture shifting in the southwestern Amazon. J Insect Conserv 28:305–313. https://doi.org/10.1007/s10841-023-00544-1
Escobar-Ramírez S, Tscharntke T, Armbrecht I, Torres W, Grass I (2020) Decrease in β-diversity, but not in α-diversity, of ants in intensively managed coffee plantations. Insect Conserv Divers 13(5):445–455. https://doi.org/10.1111/icad.12417
Fearnside PM (2005) Deforestation in Brazilian Amazonia: history, rates, and consequences. Conserv Biol 19(3):680–688. https://doi.org/10.1111/j.1523-1739.2005.00697.x
Feitosa RM, Dias AM (2024) An illustrated guide for the identification of ant subfamilies and genera in Brazil. Insect Syst Evol 55(5):451–571. https://doi.org/10.1163/1876312X-bja10062
Filgueiras BKC, Peres CA, Melo FPL, Leal IR, Tabarelli M (2021) Winner–loser species replacements in human-modified landscapes. Trends Ecol Evol 36(6):545–555. https://doi.org/10.1016/j.tree.2021.02.00610.1016/j.tree.2021.02.006
Flores BM, Montoya E, Sakschewski B, Nascimento N, Staal A, Betts RA et al (2024) Critical transitions in the Amazon forest system. Nature 626(7999):555–564. https://doi.org/10.1038/s41586-023-06970-0
Fontenele LK, Schmidt FA (2021) Forest pasture shifting alters the assemblages of seed removing ants in southwestern Brazilian Amazon. J Insect Conserv. https://doi.org/10.1007/s10841-021-00295-x
Fox J, Weisberg S (2019) An R Companion to Applied Regression, Third edition. Sage, Thousand Oaks CA
Franke IL, Lunz AMP, Amaral EF (2000) Metodologia para planejamento, implantação e monitoramento de sistemas agroflorestais: um processo participativo., 49 ed. Embrapa, Rio Branco
Gibb H, Stoklosa J, Warton DI, Brown AM, Andrew NR, Cunningham SA (2015) Does morphology predict trophic position and habitat use of ant species and assemblages? Oecologia 177:519–531. https://doi.org/10.1007/s00442-014-3101-9
Heino J, Melo AS, Bini LM (2015) Reconceptualising the beta diversity-environmental heterogeneity relationship in running water systems. Freshw Biol 60(2):223–235. https://doi.org/10.1111/fwb.12502
Hoenle PO et al (2022) Rapid ant community reassembly in a N eotropical forest: recovery dynamics and land-use legacy. Ecol Appl 32(4):e2559. https://doi.org/10.1002/eap.2559
Hoffmann BD, Andersen AN (2003) Responses of ants to disturbance in Australia with particular reference to functional groups. Austral Ecol 28:444–464. https://doi.org/10.1046/j.1442-9993.2003.01301.x
Imazon (2012) A atividade madeireira na Amazônia brasileira: produção, receita e mercados. Serviço Florestal brasileiro, Instituto do homem e meio ambiente. Imazon, Bélem
Jaureguiberry P, Titeux N, Wiemers M, Bowler DE, Coscieme L, Golden AS (2022) The direct drivers of recent global anthropogenic biodiversity loss. Sci Adv. https://doi.org/10.1126/sciadv.abm9982
Junior et al (2015) RT4Bio - R Tools for Biologists. https://doi.org/10.13140/RG.2.1.4532.2966
Khoo B, Ho CT (1992) The influence of *Dolichoderus thoracicus* (Hymenoptera: Formicidae) on losses due to *Helopeltis thievora* (Heteroptera: miridae), black pod disease, and mammalian pests in cocoa in Malaysia. Bull Entomol Res 82:485–491. https://doi.org/10.1017/S0007485300042553
Kingazi N, Temu RA, Sirima A et al (2025) Agroforestry as a refuge for insect pollinators: seasonal and elevational insights from Northern Tanzania. J Insect Conserv 29:50. https://doi.org/10.1007/s10841-025-00688-2
Klein AM, Steffan-Dewenter I, Tscharntke T (2003) Fruit set of highland coffee increases with the diversity of pollinating bees. Proc Res Soc Lond Ser B 270:955–961. https://doi.org/10.1098/rspb.2002.2306
Kuzevic S, Bobikova D, Kuzevicova Z (2026) Assessment of long-term land cover and vegetation trends using NDVI and CORINE data: a case study from Slovakia. Sustainability 18(2):663. https://doi.org/10.3390/su18020663
Lawes MJ, Moore AM, Andersen AN, Preece ND, Franklin DC (2017) Ants as ecological indicators of rainforest restoration: community convergence and the development of an ant forest indicator index in the Australian wet tropics. Ecol Evol 7(20):8442–8455. https://doi.org/10.1002/ece3.2992
Marques TG, Espírito-Santo MM, Neves F, Schoereder JH (2017) Ant assemblage structure in a secondary tropical dry forest: the role of ecological succession and seasonality. Sociobiology 64:261–275. https://doi.org/10.13102/sociobiology.v64i3.1276
Martins IS, Ortega JCG, Guerra V, Costa MMS, Martello F, Schmidt FA (2022) Ant taxonomic and functional beta-diversity respond differently to changes in forest cover and spatial distance. Basic Appl Ecol 60:89–102. https://doi.org/10.1016/j.baae.2022.02.008
Mascarenhas FDS, Brown IF, Silva SD (2018) Deforestation and forest fires transforming the reality of the Chico Mendes Extractive Reserve. Desenvolvimento e Meio Ambiente 48:236–262
McGeoch MA (1998) The selection, testing and application of terrestrial insects as bioindicators. Biol Rev Camb Philos Soc 73(2):181–201. https://doi.org/10.1017/S000632319700515X
McKinney ML, Lockwood JL (1999) Biotic homogenization: a few winners replacing many losers in the next mass extinction. Trends Ecol Evol 14:450–453. https://doi.org/10.1016/S0169-5347(99)01679-1

Menezes ASO, Schmidt FA (2020) Mechanisms of species coexistence and functional diversity of ant assemblages in forest and pasture habitats in southwestern Brazilian Amazon. Sociobiology 67(1):33–40. https://doi.org/10.13102/sociobiology.v67i1.4552

Milien EJ, Rocha KS, Brown IF, Perz SG (2021) Roads, deforestation and the mitigating effect of the Chico Mendes extractive reserve in the southwestern Amazon. Trees, Forests and People 3:100056. https://doi.org/10.1016/j.tfp.2020.100056

Moguel P, Toledo VM (1999) Biodiversity conservation in traditional coffee systems of Mexico. Conserv Biol 13:11–21. https://doi.org/10.1046/j.1523-1739.1999.97153.x

Neves F, Antoniazzi R, Camarota F, Pacelhe FT, Powell S (2021) Spatiotemporal dynamics of the ant community in a dry forest differ by vertical strata but not by successional stage. Biotropica 53:372–383. https://doi.org/10.1111/btp.12918

Newbold T et al (2015) Global effects of land use on local terrestrial biodiversity. Nature. https://doi.org/10.1038/nature14324

Nunes CA, Berenguer E, França F, Ferreira J, Lees AC, Louzada J, Barlow J (2022) Linking land-use and land-cover transitions to their ecological impact in the Amazon. National Academy of Sciences, v. 119(27). https://doi.org/10.1073/pnas.2202310119

Oliveira FMP, Ribeiro-Neto JD, Andersen AN, Leal IR (2017) Chronic anthropogenic disturbance as a secondary driver of ant community structure: interactions with soil type in Brazilian Caatinga. Environ Conserv 44:115–123. https://doi.org/10.1017/S0376892916000291

Oliveira FMP, Andersen AN, Arnan X, Ribeiro-Neto JD, Arcoverde GB, Leal IR (2019) Effects of increasing aridity and chronic anthropogenic disturbance on seed dispersal by ants in Brazilian Caatinga. J Anim Ecol 88:870–880. https://doi.org/10.1111/1365-2656.12979

Paolucci LN, Schoereder JH, Brando PM, Andersen AN (2017) Fire-induced forest transition to derived savannas: cascading effects on ant communities. Biol Conserv 214:295–302. https://doi.org/10.1016/j.biocon.2017.08.020

Philpott SM, Perfecto I, Ambrecht I, Parr CL (2010) Ant diversity and function in disturbed and changing habitats. In: Lach L, Parr C, Abbott K (eds) Ant ecology. Oxford University Press, New York, pp 137–157

Philpott D (2010) Revolutions in sovereignty: how ideas shaped modern international relations. Princeton University Press

Philpott SM, Armbrecht I (2006) Biodiversity in tropical agroforests and the ecological role of ants and ant diversity in predatory function. Ecol Entomol 31(4):369–377. https://doi.org/10.1111/j.1365-2311.2006.00793.x

R Core Team (2024) R: A language and environment for statistical computing

Ribas CR, Schoereder JH, Pic M, Soares SM (2003) Tree heterogeneity, resource availability, and larger scale processes regulating arboreal ant species richness. Austral Ecol 28(3):305–314. https://doi.org/10.1046/j.1442-9993.2003.01290.x

Ribeiro-Neto JD, Oliveira FMP, Arcoverde GB, Tabarelli M, Leal IR, Arnan X (2023) Aridity and chronic anthropogenic disturbances cause a taxonomic, functional, and phylogenetic homogenization of ant communities in a Caatinga dry forest. Biol Conserv 284:110151. https://doi.org/10.1016/j.biocon.2023.110151

Roberts DL, Cooper RJ, Petit LJ (2000) Use of premontane moist forest and shade coffee agroecosystems by army ants in western Panama. Conserv Biol 14:192–199. https://doi.org/10.1046/j.1523-1739.2000.98522.x

Rocha FP, Bogar TA, Ibañez Weemaels A, Hu J, Liang M, Park C, Lee RH, Khan SA, Han S, Ng YL, Guénard B (2024) Two sides of the same coin? Ants are ecosystem engineers and providers of ecosystem services. Myrmecol News 34:129–157. https://doi.org/10.25849/myrmecol.news_034:129

Sales FM, Schmidt FA (2023) Nesting stratum and habitat affinity matter in ant assemblage response to forest-pasture shifting. Entomo Bras 16(2):1983–0572. https://doi.org/10.12741/ebrasilis.v16.e1024

Schmidt FA, Solar RRC (2010) Hypogaeic pitfall traps: methodological advances and remarks to improve the sampling of a hidden ant fauna. Insectes Soc 57:261–266. https://doi.org/10.1007/s00040-010-0078-1

Schmidt FA, Ribas CR, Schoereder JH (2013) How predictable is the response of ant assemblages to natural forest recovery? Implications for their use as bioindicators. Ecol Indic 24:158–166. https://doi.org/10.1016/j.ecolind.2012.05.031

Schmidt FA et al (2025) The western frontier of Brazilian ant diversity: contribution of rede bia to knowledge on ant diversity in the southwestern Amazon. In: Brazilian myrmecology: exploring the world's richest ant fauna, v. 1,20, pp.465–478. https://doi.org/10.37885/250920263

Solar RRDC et al (2015) How pervasive is biotic homogenization in human-modified tropical forest landscapes? Ecol Lett 18(10):1108–1118. https://doi.org/10.1111/ele.12494

SOS AMAZONIA (2022) Relatório de Atividades 2022. Disponível em https://sosamazonia.org.br/tpost/bt2ad27hk1-sos-amaznia-apresenta-relatrio-de-ativid

Sousa-Souto L, Figueiredo P, Ambrogi B, Oliveira A, Ribeiro GT, Neves F (2016) Composition and richness of arboreal ants in fragments of brazilian Caatinga: effects of secondary succession. Sociobiology 63:762–769. https://doi.org/10.13102/sociobiology.v63i2.909

Tscharntke T, Grass I, Wanger TC, Westphal C, Batáry P (2021) Beyond organic farming–harnessing biodiversity-friendly landscapes. Trends Ecol Evol 36(10):919–930. https://doi.org/10.1016/j.tree.2021.06.010

Underwood EC, Fisher BL (2006) The role of ants in conservation monitoring: if, when, and how. Biol Conserv 132(2):166–182. https://doi.org/10.1016/j.biocon.2006.03.022

Vasconcelos HL et al (2018) Neotropical savanna ants show a reversed latitudinal gradient of species richness, with climatic drivers reflecting the forest origin of the fauna. J Biogeogr 11. https://doi.org/10.1111/jbi.13113

Vieira DL, Holl KD, Peneireiro FM (2009) Agro-successional restoration as a strategy to facilitate tropical forest recovery. Restor Ecol 17(4):451–459. https://doi.org/10.1111/j.1526-100X.2009.00570.x

Wickham H (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York

Wilker I, Lasmar CJ, Schmidt FA, da Costa MMS et al (2023) Land-use change in the Amazon decreases ant diversity but increases ant-mediated predation. Insect Conserv Divers 16(3):379–392. https://doi.org/10.1111/icad.12632

Wilker I, Queiroz et al (2024) A systematic review of the land use change effects on ant diversity in Neotropics. Biological Conservation, 299, 110778. https://doi.org/10.1016/j.biocon.2024.110778

Young KJ (2024) Mimicking Nature: A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands. In: Montagnini F (ed) Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Advances in Agroforestry, vol 14. Springer, Cham

Zovi D, Stastny M, Battisti A, Larsson S (2008) Ecological costs on local adaptation of an insect herbivore imposed by host plants and enemies. Ecology 89(5):1388–1398. https://doi.org/10.1890/07-0883.1

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