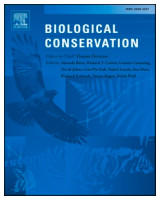
Biological Conservation 299 (2024) 110778

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon



Review

A systematic review of the land use change effects on ant diversity in Neotropics

Icaro Wilker [a,b,*], Antônio C.M. Queiroz [a], Carla R. Ribas [a,c], Maria Santina C. Morini [d], Chaim J. Lasmar [a], Fernando A. Schmidt [e], Rodrigo M. Feitosa [f], Anselmo Nogueira [g], Fabrício B. Baccaro [h], Mônica A. Ulysséa [i], Thiago Izzo [j], Lucas N. Paolucci [k], Yves P. Quinet [l], André B. Vargas [m], Ana Y. Harada [n], Tathiana G. Sobrinho [o], Tatianne G. Marques [p], Jorge L.P. Souza [q,r], Kleber Del-Claro [s], Denise Lange [t], Jean C. Santos [u], Rogério R. Silva [v], Renata B.F. Campos [w], Emília Z. Albuquerque [x], Ananza M. Rabello [y], Ricardo R.C. Solar [z], Stela A. Soares [aa], Karine S. Carvalho [ab], Aline B. Moraes [ac], Helena M. Torezan-Silingardi [s], Larissa Nahas [s], Iracenir Andrade dos Santos [ad,ae], Cinthia B. Costa-Milanez [af], Flávia A. Esteves [ag], Tiago Frizzo [ah], Wesley daRocha [ai], Felipe Martello [aj], Eduardo Diehl-Fleig [ak,l]

[a] *Programa de Pós-graduação em Ecologia Aplicada, Departamento de Ecologia e Conservação, Instituto de Ciências Naturais, Universidade Federal de Lavras, Lavras, Minas Gerais, Brazil*
[b] *School of Biosciences, Cardiff University, Cardiff, UK*
[c] *Departamento de Biologia, Programa de Pós-Graduação em Biodiversidade, Universidade Federal Rural de Pernambuco, Recife, Brazil*
[d] *Laboratório de Mirmecologia do Alto Tietê, Núcleo de Ciências Ambientais, Universidade de Mogi das Cruzes, Mogi das Cruzes, Brazil*
[e] *Laboratório de Ecologia de Formigas, Centro de Ciências Biológicas e da Natureza, Universidade Federal do Acre, Rio Branco, Brazil*
[f] *Departamento de Zoologia, Laboratório de Sistemática e Biologia de Formigas, Universidade Federal do Paraná, Curitiba, Brazil*
[g] *Laboratório de Interações Planta-Animal, Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, São Bernardo do Campo, Brazil*
[h] *Departamento de Biologia, Universidade Federal do Amazonas, Manaus, Brazil*
[i] *Museu Paraense Emílio Goeldi, Belém, Brazil*
[j] *Departamento de Botânica e Ecologia, Laboratório de Ecologia de Comunidades, Universidade Federal do Mato Grosso, Cuiabá, Brazil*
[k] *Departamento de Biologia Geral, Universidade Federal de Viçosa, Viçosa, Brazil*
[l] *Departamento de Biologia, Laboratório de Entomologia, Universidade Estadual do Ceará, Fortaleza, Brazil*
[m] *Centro Universitário de Volta Redonda – UniFOA, Volta Redonda, Brazil*
[n] *Coordenação em Zoologia, Museu Paraense Emilio Goeldi, Belém, Brazil*
[o] *Departamento de Ciências Agrárias e Biológicas, Laboratório de Sistemática e Ecologia de Insetos, Universidade Federal do Espírito Santo, Campus São Mateus, São Mateus, Brazil*
[p] *Laboratório de Ecologia Aplicada, Instituto Federal do Norte de Minas Gerais, Campus Salinas, Salinas, Brazil*
[q] *Universidade Federal de Ouro Preto - UFOP, Ouro Preto, Minas Gerais, Brazil*
[r] *Programa de Pós-Graduação em Zoologia, Universidade Federal Do Amazonas (UFAM), Manaus, Amazonas, Brazil*
[s] *Laboratório de Ecologia Comportamental e de Interações, Instituto de Biologia, Universidade Federal de Uberlândia, Uberlândia, Brazil*
[t] *Universidade Tecnológica Federal do Paraná, Campus Santa Helena, Santa Helena, Brazil*
[u] *Departamento de Ecologia, Laboratório de Ecologia & Biodiversidade, Universidade Federal de Sergipe, São Cristóvão, Brazil*
[v] *Coordenação de Ciências da Terra e Ecologia, Museu Paraense Emílio Goeldi, Belém, Brazil*
[w] *Laboratório de Ecologia, ambiente e território, PPG Gestão Integrada do Território, Universidade Vale do Rio Doce, Governador Valadares, Brazil*
[x] *National Museum of Natural History, AntLab, Smithsonian Institution, Washington, DC, USA*
[y] *Instituto de Ciências Humanas, Faculdade de Educação do Campo, Universidade Federal do Sul e Sudeste do Pará, Marabá, Brazil*
[z] *Departamento de Genética, Ecologia e Evolução, Centro de Síntese Ecológica e Conservação, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil*
[aa] *Secretaria Estadual de Educação de Mato Grosso do Sul, Campo Grande, Brazil*
[ab] *Departamento de Ciências Naturais, Universidade Estadual do Sudoeste da Bahia, Campus Vitória da Conquista, Vitória da Conquista, Brazil*
[ac] *Prefeitura Municipal de Novo Hamburgo, Novo Hamburgo, Brazil*
[ad] *Laboratório de Conservação e Biodiversidade Labjoy, Instituto de Formação Interdisciplinar e Intercultural, Universidade Federal do Oeste do Pará, Santarém, PA, Brazil*
[ae] *Programa de Pós-Graduação em Recursos Naturais da Amazônia, Universidade Federal do Oeste do Pará (UFOPA), Santarém, PA, Brazil*

* Correspondence author at: Programa de Pós-graduação em Ecologia Aplicada, Departamento de Ecologia e Conservação, Instituto de Ciências Naturais, Universidade Federal de Lavras, Lavras, Minas Gerais, Brazil.
E-mail addresses: gonzagaicaro@gmail.com, icaro.carvalho2@estudante.ufla.br (I. Wilker).

https://doi.org/10.1016/j.biocon.2024.110778
Received 18 June 2024; Received in revised form 22 August 2024; Accepted 24 August 2024
Available online 12 September 2024
0006-3207/© 2024 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

[af] Departamento de Biologia, Instituto de Ciências Exatas e Biológicas, Universidade Federal de Ouro Preto, Ouro Preto, Brazil
[ag] Department of Entomology, Institute for Biodiversity Science & Sustainability, California Academy of Sciences, San Francisco, USA
[ah] Departamento de Ecologia, Instituto de Ciências Biológicas, Universidade de Brasília, Campus Darcy Ribeiro, Brasília, Brazil
[ai] Laboratório de Ecologia de Insetos, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil
[aj] University of Oxford, Environmental Change Institute, School of Geography and the Environment, Oxford, UK
[ak] São Leopoldo, Rio Grande do Sul, Brazil

ARTICLE INFO

Original content: Land use change effects on ant diversity in Neotropics.xlsx (Original data)

Keywords:
Formicidae
Brazil
Meta-analysis
Biodiversity
Biomes

ABSTRACT

Land use changes represent one of the leading causes of terrestrial biodiversity loss, particularly in tropical ecosystems. In Brazil, a country that encompasses six distinct biomes and one of the world's highest ant diversities, the increasing land use changes are having detrimental effects on biodiversity. Our aim in this study was to summarize the impact of land use changes on ants in Brazil through a systematic review. We adhered to the PRISMA Eco-Evo methodology and conducted a qualitative review of studies, as well as a meta-analysis focusing on ant species richness and abundance. Especially, we observe a more pronounced negative effect in more contrasting conversions, such as from tropical forest to open anthropogenic land uses. We associate the decrease in richness with drastic changes in the vegetation structure. Consequently, this leads to extreme temperature variations, reduced humidity, and a decline in both the variety and quantity of food resources and nesting sites. Our findings provide a foundation for the conservation and management of anthropogenic land uses in human-impacted regions. More specifically, we highlight that future management plans should aim for anthropogenic land uses that more closely resemble the original natural vegetation, to maintain conditions and increase resource availability for biodiversity in the new habitats. Additionally, avoiding intensive management practices, such as the use of fertilizers and pesticides in agricultural systems, can also support the conservation of entomofauna in terms of species richness and abundance, and potentially benefit ecosystem services.

1. Introduction

Land use changes, like the conversion of natural habitats into anthropogenic land uses, significantly drive the decline in global biodiversity, potentially hampering ecosystem functioning (de Chazal and Rounsevell, 2009; Newbold et al., 2015, 2019). While these changes occur worldwide, they have more pronounced impacts in tropical regions (Magnusson et al., 2018; Nunes et al., 2022; Sala et al., 2000), which is of concern because tropical areas host the highest terrestrial biodiversity (Antonelli et al., 2018; Gardner et al., 2009). In tropical ecosystems, land use changes often create strong contrasts between natural habitats and altered anthropogenic land use, primarily due to the expansion of the agricultural frontier (Gibbs et al., 2010; Song et al., 2018). For example, in the Brazilian Amazon biome, most conversions involve conversion from forest to soy monoculture and extensive pasture, representing open land uses that significantly differ from the original habitat (FAO, 2016; Nunes et al., 2022; Parente et al., 2021). Anthropogenic land uses, such as agricultural crops and pastures, typically exhibit low environmental heterogeneity, leading to reduced resource quantity and diversity, and more severe alterations to local conditions (Priyadarshana et al., 2024; Stein and Kreft, 2015). In addition, the use of synthetic pesticides can increase the negative effects of land use on several species (Sánchez-Bayo and Wyckhuys, 2019). Similarly, agricultural practices such as the use of fertilizers can alter nutrient deposition (e.g., salinization), impacting species richness and ecosystem processes (Hopmans et al., 2021; Lasmar et al., 2021a). Thus, these impacts on habitat structure and quality result in a substantial loss of specialist species and an increase in generalist ones (Filgueiras et al., 2021; Martins et al., 2022; Tabarelli et al., 2012).

The adverse impacts of land use changes on biodiversity have been extensively researched across various terrestrial organisms, encompassing vertebrates (Newbold, 2018), plants (Laliberté et al., 2010), soil microbiomes (Díaz-Vallejo et al., 2021), and arthropods (Attwood et al., 2008). Among arthropods, ants are regarded as excellent model organisms for investigating the consequences of land use changes in tropical regions (Andersen et al., 2002; Ribas et al., 2012). This recognition is due to their high species richness (Feitosa et al., 2022) and their significant ecological roles, including seed dispersal, bioturbation, and predation (Folgarait, 1998; Lach et al., 2010). Ants exhibit a high sensitivity to anthropogenic land uses (e.g., Queiroz et al., 2020; Rabello et al., 2018; Wilker et al., 2023).

Within the Neotropical Region, Brazil encompasses an extensive spatial expanse that includes six biomes: Amazon (tropical forest), Atlantic Forest (tropical forest), Caatinga (xeric shrubland), Cerrado (savannah), Pampa (grassland), and Pantanal (flooded grasslands). Furthermore, within the same biome, multiple vegetation types can coexist. For example, in the Cerrado biome, comprising forested vegetation (cerradão or woodland savannah), savannah, and open vegetation (grasslands). However, despite the high biodiversity found in these biomes, they undergo significant land use changes, with the Cerrado and the Atlantic Forest biomes considered global biodiversity hotspots (Trew and Maclean, 2021). Indeed, currently all Brazilian biomes are under severe threat due to land use changes (Magnusson et al., 2018; Projeto MapBiomas, 2022).

While some general patterns have indicated that anthropogenic impacts can reduce ant assemblage diversity (e.g., fire effects: Vasconcelos et al., 2017) and ecosystem functions, such as the reduced removal of diaspores by ants (Bona et al., 2023), the intensity of these impacts is largely determined by their association with habitat openness (Andersen, 2019). Therefore, ant assemblages from closed-forested vegetation types are more sensitive to the impacts promoted by the establishment of pastures and agricultural land uses (Costa and Schmidt, 2022; Lasmar et al., 2021b; Queiroz et al., 2020) than ant assemblages in open vegetation types (e.g., grasslands; Queiroz et al., 2020). Furthermore, ant assemblages from closed-forested vegetation types require more time to recover from anthropogenic impacts than those from open vegetation types (Casimiro et al., 2019). Considering Brazil's significance in global ant diversity (Feitosa et al., 2022; Schmidt et al., 2022) and the escalating threats faced by its biodiversity, such as agricultural frontiers and mining projects (Pereira et al., 2020), the country serves as an excellent model for studying the effects of land use changes on biodiversity.

Thus, we conducted a systematic review, including both a qualitative review and a meta-analysis, with the aim of assessing the impact of land use changes on ant assemblages in Brazil. We conducted a qualitative review examining studies that evaluated the effects of land use changes on ants in Brazil, identifying knowledge gaps and proposing new

[1] In Memoriam.

approaches for future studies. We also conducted a meta-analysis to determine if the negative effects on species richness and abundance of ants resulting from land use change are associated with the biome and land use change type. Specifically, we predict that (i) the negative impacts of land use changes in species richness and abundance will be more significant in tropical forest biomes (e.g., Amazon and Atlantic Forest) compared to grassland biomes (e.g., Pampa and Pantanal), and (ii) these negative effects in species richness and abundance will be more pronounced in cases of intense conversion, such as the conversion from forests habitat to pasture or mining anthropogenic land uses.

2. Methods

2.1. Data collection

We followed the PRISMA-EcoEvo methodology (O'Dea et al., 2021). First, we conducted a search for studies on the effects of land use change on ants in Brazil using the Ants of Brazil Project database (Feitosa et al., 2022; Schmidt et al., 2022). We also performed a preliminary search (naïve search) for relevant studies in the "Web of Science databases - Main Collection (Clarivate Analytics)" (www.webofscience.com), "Scopus" (www.scopus.com), and "SciELO.ORG" (www.scielo.org). Initially, we carried out a preliminary search using pertinent keywords related to the topic (Grames et al., 2019). To achieve this, we categorized the keywords into four sections, following the PICO/PECO model (population, intervention/exposure, comparator, outcome; Haddaway et al., 2016). The "Population" section pertained to the specific population under study (e.g., Ants), the "Intervention/Exposure" section referred to various exposure or environmental factors (e.g., Land use), the "Comparator" section related to what the exposure would be compared to (e.g., Biomes), and the "Outcome" encompassed the measured variables (e.g., Diversity). The naïve search conducted in November 2023. The titles, abstracts, and keywords of these studies were exported, and additional keywords were identified using the "litsearchr" package (Grames et al., 2019), within the R software (R Core Team, 2021). In the analysis of the new keywords, we included the term 'species composition' as an outcome and performed a subsequent search. In addition to the search using English terms, we also conducted searches in Portuguese and Spanish in the same databases (see Appendix A: Keywords). The new search returned 3488 studies in Web of Science, 1573 in Scopus, and 16 in SciELO.ORG. We also included an additional 72 studies from the Ants of Brazil Project, bringing the total to 5149.

2.2. Exclusion and inclusion criteria

We removed duplicate studies and conducted a screening of titles, abstracts, and full articles. Our inclusion criteria focused on studies that specifically assessed the impact of land use changes on ant assemblages in Brazil. We applied exclusion criteria, including: (1) studies conducted outside Brazil; (2) studies unrelated to ant communities or assemblages; (3) studies not addressing the effects of land use changes; (4) studies lacking a comparison between natural habitat and anthropogenic land use. We also excluded non-case studies (e.g., reviews) and studies dealing with anthropogenic disturbances not related to land use categorization (e.g., chronic disturbances like logging or non-timber forest product extraction). Furthermore, we omitted studies focusing on ecological succession (e.g., succession or restoration) and those where it was impossible to separate the impact on ant assemblages from other evaluated organisms (e.g., macrofauna). Out of the initial pool of 5149 studies, 128 remained for the qualitative review (Fig. 1A), and 42 were eligible for the meta-analysis. Detailed information is available in Appendix B (PRISMA-EcoEvo). A list of data sources used in the study is provided in the Appendix A: Data sources.

2.3. Qualitative review

From the 128 studies, we extracted qualitative data including the study ID (citation), publication year, language, journal, impact factor, biome, sampling season, vegetation type, anthropogenic land use, sampling methods, sampled strata (epigeic, leaf-litter, subterranean, and arboreal), and response variable, such as species richness and abundance. We are counting votes for qualitative data from the studies and assessed whether land use affects species compositions. Species composition refers to the differences in the identity of ant species

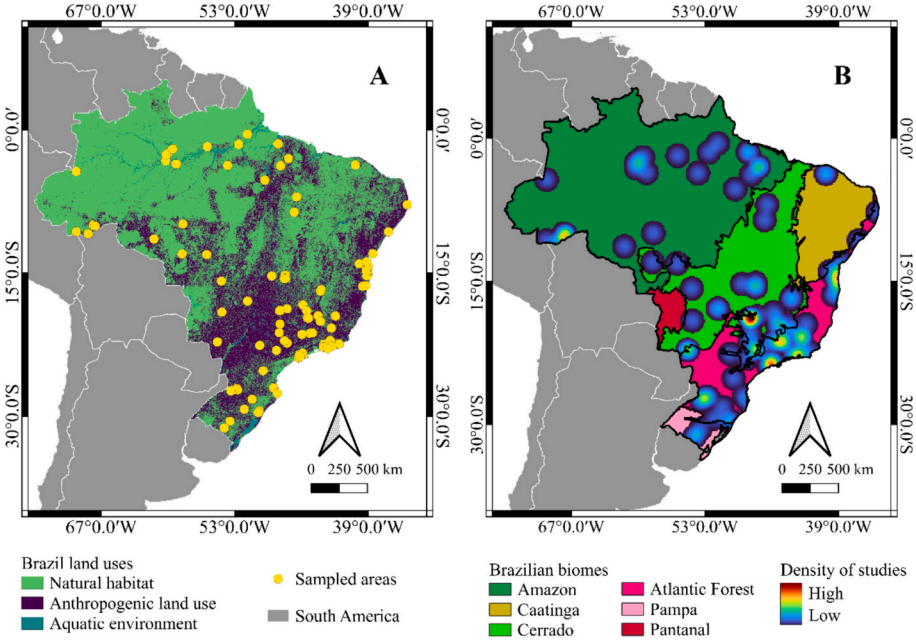


Fig. 1. Study sites extracted from the 128 studies concerning the effects of land use changes on ants in Brazil. The panel A indicates the concentration of study sites in regions with a high degree of land use changes, and panel B indicates the concentration of studies in the Brazilian biomes Atlantic Forest and Cerrado.
The figure was generated using QGIS version 3.32 (QGIS.org, 2023) and adapted from the land use and land cover map for the year 2021 provided by MapBiomas (Projeto MapBiomas, 2022) and biome data from Instituto Brasileiro de Geografia e Estatística (IBGE, 2019).

between natural habitats and anthropogenic land uses, extracted from analyses such as PERMANOVA (Permutational Multivariate Analysis of Variance) and ANOSIM (Analysis of Similarities) (Anderson, 2001; Clarke, 1993; Warton et al., 2012).

2.4. Extracting and calculating effect sizes

For the meta-analysis, we gathered data on the most frequently assessed response variable, including species richness and abundance. Species richness was reported in studies as either observed species richness or estimators (e.g., Chao1, Chao2, Jackknife1, individual-based rarefaction, and sample-based rarefaction). Abundance was reported in studies as number of ant workers and species frequency. For these response variables, we collected mean values, sample size, and dispersion metrics such as variance, standard deviation, standard error, and 95 % confidence intervals. We extracted these data from the text, tables, and figures of the studies. When the data was solely presented in figures, we utilized WebPlotDigitizer version 4.6 to extract the mean and dispersion metrics (www.automeris.io/WebPlotDigitizer/). We standardized all the dispersion metrics into standard deviation. We also obtained data regarding vegetation type and anthropogenic land uses. Vegetation types were classified into various categories, encompassing forest types such as primary and secondary forests, riparian forests, and woodland savannah, as well as grassland, “restinga”, savannah, “vereda”, mangrove, and “canga”. The anthropogenic land use data were classified into agriculture and pasture categories when these two anthropogenic uses were sampled jointly, annual agriculture (e.g., soybean plantation), perennial agriculture (e.g., coffee plantation), mining, pasture, silviculture (e.g., *Eucalyptus* spp. plantation), and urbanization.

We analyzed a total of 42 studies and 212 comparisons for the meta-analysis, which were categorized according to the response variable: species richness (studies: $n = 36$; comparisons: $n = 171$) and abundance (studies: $n = 14$; comparisons: $n = 41$). For this, we determined an effect size that could be summarized across all studies. The effect size is a metric that quantifies the relationship between two entities, capturing the direction and magnitude of this relationship (Harrer et al., 2021). In our case, the effect size indicated the effects of land use change on the richness and abundance of ants. To calculate the effect size (Hedges' g), we used the standardized mean difference (SMD) metric corrected for small sample sizes (J-corrected form; Goulet-Pelletier and Cousineau, 2018; Hedges, 1981) and utilized the “escalc” function of the “metafor” R package (Viechtbauer, 2010). A negative Hedges' g indicates an adverse effect of a given response variable resulting from the land use change, while a positive value indicates the opposite. The zero value represents the absence of an effect size. We only analyzed comparisons involving three or more elements. For instance, we excluded the conversion from “canga” to mining because we found only one comparison in this case.

2.5. Meta-analysis

We analyzed nine multilevel linear (mixed-effects) models using the “rma.mv” function from the “metafor” R package (Viechtbauer, 2010). In all models, we used the study ID as a random variable due to the non-independence of the effect sizes found in the same study. We constructed three general models with no fixed moderators (only with the random variable): one with all effect sizes for the general model ($n = 212$), one for species richness (n = 171), and one for abundance (n = 41). Additionally, we established six models with moderators to test our two predictions, both for richness and abundance. To test our prediction that (i) the negative impacts of land use changes in species richness and abundance will be more significant in tropical forest biomes, we created two models with the biome as the moderator. To test our prediction that (ii) the negative impacts of land use changes in species richness and abundance will be more pronounced in cases of intense conversion, we built two models with the land use conversion type as the moderator.

For each model, we assessed Cochran's Q. In these statics, using the chi-square distribution with n-1 degrees of freedom, significant results ($p < 0.05$) indicate heterogeneity, suggesting substantial variability among the effect sizes. We evaluated both total heterogeneity (Q_T) and moderator heterogeneity (Q_W). Additionally, we examined publication bias through funnel plots. Publication bias refers to the tendency to publish studies with significant results (Rosenthal, 1979), which can introduce bias into the effect sizes available for meta-analyses. Identifying publication bias is a critical aspect of meta-analyses, as it facilitates the validation of these findings through additional investigations (Nakagawa and Santos, 2012). The figures were generated using the R package “ggplot2” (Wickham, 2016).

3. Results

3.1. Qualitative review

The first study found was published in 1995, and since then, there has been a growth trend over the years, with a peak of 12 studies in 2013 and 2018. Most of the studies evaluated were published in English (101 studies; 79 %) and Portuguese (26 studies; 20 %). Studies were published in 71 journals, with Sociobiology (13 studies; 10 %) and Neotropical Entomology (10 studies; 08 %) having the highest publication numbers. Of the journals with impact factors, the values ranged from 0.271 to 13.211, with a mean ($\bar{x}$) and standard deviation ($\pm$SD) of 4.126 and 2.671, respectively. The most sampled biomes included the Atlantic Forest (53 studies; 41 %), Cerrado (29 studies; 23 %), and Amazon (28 studies; 22 %) (Fig. 1B).

Most studies sampled ants during both the dry and rainy seasons (45 studies; 35 %) or solely in the rainy season (45 studies; 35 %). In line with the trend of the most frequently sampled biomes, the vegetation types most studied were forests (106 studies; 83 %) and savannahs (25 studies; 19 %). The most studied anthropogenic land uses were pasture (51 studies; 40 %), silviculture (46 studies; 36 %), and annual agriculture (41 studies; 32 %). Pitfall traps (68 studies; 53 %) were the most used sampling method, and the most studied habitat stratum was the epigeic stratum (82 studies; 64 %). Most studies assessed the effects on species richness (114 studies; 89 %), diversity indices (65 studies; 51 %), species composition (64 studies; 50 %), and abundance (62 studies; 48 %). Of the 64 studies that evaluated species composition, 56 studies (87 %) reported differences in composition between ant assemblages from natural habitats and those from anthropogenic land uses. In addition, few studies have evaluated ecosystem functions and functional groups, making it impossible to find general patterns among them. For qualitative review graphs, see Appendix A, Figs. A.1–A.14.

3.2. Meta-analysis

We identified a detrimental impact on ants due to land use change (E++ = −0.763, CI = −1.079 to −0.447, df = 211; where E++ represents Hedges' g (effect size), CI represents confidence interval, and df represents degrees of freedom). Furthermore, we observed that the land use change reduces ant species richness (E++ = −0.962, CI = −1.286 to −0.638, df = 170; Fig. 2), but we did not detect any significant impact on ant abundance (E++ = −0.188, CI = −0.803 to 0.427, df = 40; Fig. 2).

For our first prediction, we found that land use changes lead to a more pronounced decrease in ant species richness in the Amazon, Atlantic Forest, and Cerrado biomes (Fig. 3, Table A.1). However, no significant impact was observed on ant abundance (Fig. 3, Table A.1). For our second prediction, we observed that land use changes, mainly from forests and savannahs to open anthropogenic land uses, resulted in a reduction in ant species richness and ant abundance (Fig. 4, Table A.2).

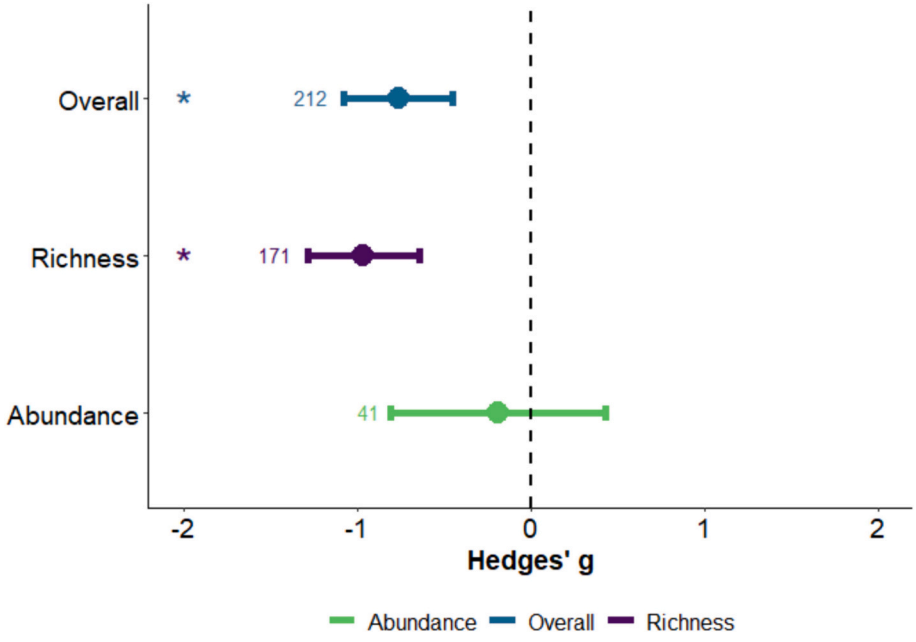


Fig. 2. Negative impacts were observed on ant species richness due to land use changes, but we did not find an effect for abundance. The numbers adjacent to the confidence interval denote the quantity of effect sizes analyzed. The data points represent the estimated mean effect size (Hedges' g), and the bars indicate the 95 % confidence interval. The asterisk indicates a significant result.

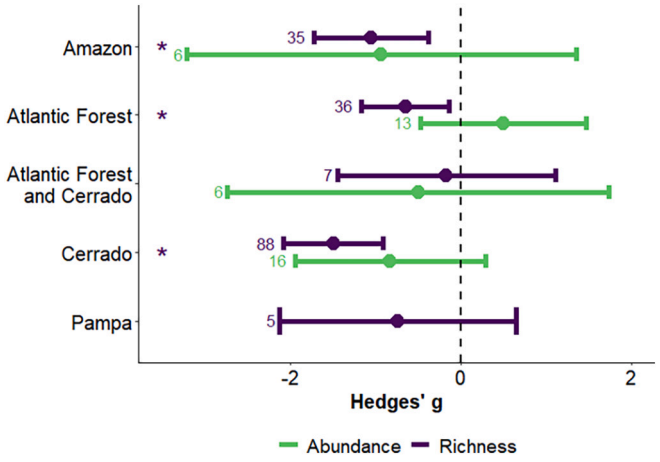


Fig. 3. Negative effects of land use changes (biome moderator) on ant species richness, but we did not find an effect for abundance. The "Atlantic Forest and Cerrado" indicates the presence of effect sizes for both biomes in the study. Biomes that are not shown in the figures lacked effect sizes for inclusion in the meta-analysis. The numbers adjacent to the confidence interval denote the quantity of effect sizes analyzed. The data points represent the estimated mean effect size (Hedges' g), and the bars indicate the 95 % confidence interval. The asterisk indicates a significant result.

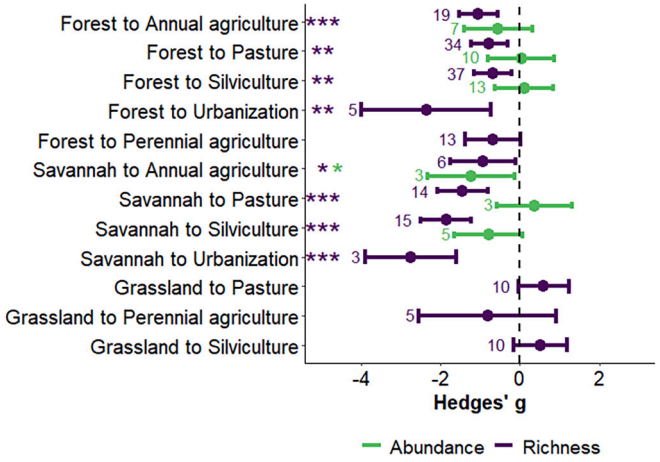


Fig. 4. Negative and null effects of land use (conversion type moderator) changes on ant species richness and abundance. Points represent the estimated mean effect size (Hedges' g), and the lines represent the 95 % confidence interval. Numbers next to the confidence interval indicate the number of effect sizes analyzed. The asterisk indicates a significant result.

3.3. Heterogeneity and publication bias

We found high heterogeneity in the overall model without moderators ($Q_T = 1591.202$, $p < 0.001$, df = 211). For species richness, we also observed high heterogeneity ($Q_T = 1467.317$, $p < 0.001$, df = 170), which was partially explained by biome ($Q_W = 41.915$, $p < 0.001$, df = 5) and conversion type ($Q_W = 117.463$, $p < 0.001$, df = 12). For abundance, we similarly found high heterogeneity ($Q_T = 102.095$, $p < 0.001$, df = 40), which was not explained by biome ($Q_W = 3.971$, $p = 0.409$, df = 4), but yes for the conversion type ($Q_W = 17.532$, $p = 0.007$, df = 6).

We evaluated publication bias using funnel plots, which revealed asymmetry and the presence of bias in the articles evaluated, indicating that studies with smaller samples (larger standardized error) tend to be published if the result found is negative (Appendix A, Figs. A.15–A.17).

4. Discussion

Here, we synthesized the negative and neutral effects of land use changes on ants in Brazil, a significant part of the Neotropical space. In general, land use changes decrease ant diversity, mainly ant richness. Additionally, this decrease in richness is more pronounced in tropical forests and tropical savannahs. More specifically, the more significant changes in land use, such as the conversion from closed tropical forests to open agricultural systems, excluded a larger proportion of ants, decreasing richness and altering species compositions. These patterns

highlight the negative impact of land use changes in tropical ecosystems, where the primary land use changes are often from closed habitats to open anthropogenic habitats, as we found. On the other hand, we only found a negative effect of conversion from savannah to annual agriculture on ant abundance. This may have occurred due to the management of these areas, due use of synthetic fertilizers and pesticides, causing negative effects on the diversity of entomofauna. Moreover, few studies have assessed the effects of land use changes on ecosystem functions and interactions. As a result, despite the decrease in species richness in anthropogenic land uses, the different effects on ecosystem functioning remain unknown. Thus, our results suggest that, to conserve most of the species' diversity, it may be important to implement management plans aimed at maintaining habitat similarity in anthropogenic land uses similar to the original habitats, also avoiding use of pesticides in agriculture systems.

Studies about land use change effects on ants in Brazil have focus on the three major Brazilian biomes and primary land use conversions, aiming to grasp ant diversity responses in these prevalent changes. However, certain biomes, vegetation types, and land uses lack adequate research and documentation, necessitating further exploration, like Caatinga (xeric shrublands), Pantanal (flooded grasslands), and mining activities. Most of the sampling was carried out within the epigeic strata (epigeic and leaf-litter). This was primarily accomplished using pitfall traps and mini-Winkler extractors, as they provide the highest ant diversity and foraging activity (Lasmar et al., 2021a, 2023). Pitfall traps are cost-effective and simple sampling methods, applicable across diverse vegetation types and human-altered land uses (Schmidt et al., 2022). Furthermore, most samples were collected during both the rainy and dry seasons, or only during the rainy season, when ant diversity is higher (Queiroz et al., 2023). Our results show that although the sampling effort maximize ant diversity and activity, moreover the focus relies on the most common land use changes in Brazil. However, there is still a need for more studies in other biomes, vegetation types, and anthropogenic land uses, as the effects of land use changes may differ in these cases.

We observed marked species richness loss likely attributable to the presence of ecological filters (Diamond et al., 2012; Ribas et al., 2003). When forested and savannah vegetation types are transformed into open anthropogenic land uses, there is a change in conditions, such as greater temperature variation and decreased humidity, as well as a decrease in the quantity and diversity of food and nesting resources (da Silva et al., 2022; Mathieu et al., 2005; Pacheco and Vasconcelos, 2007). This change tends to favour only a few more resilient and generalist ant species, allowing them to increase their numbers if they were already present in natural habitats or invade these anthropogenic land uses (Andersen, 2019; McKinney and Lockwood, 1999). When the vegetation structure is still maintained, as in the case of converting forest to silviculture, there can still be ecological filters. Even though the conditions remain similar (e.g., high forest cover), a significant portion of the resources is lost with the conversion to monoculture (Simberloff et al., 2010). For ant abundance, we only found a negative effect of the conversion from savannah to annual agriculture. This could be due to land use management, such as the use of fertilizers and insecticides, which are usual procedures in conventional agriculture in Brazil (Dalle Laste et al., 2019). Insecticides are the second-largest driver of entomofauna loss, behind land use change (Sánchez-Bayo and Wyckhuys, 2019). Therefore, maintaining the similarity of the original habitat in anthropogenic land uses can promote the conservation of diversity. However, in some cases where the higher vegetation structure is maintained, diversity can still decrease, highlighting the importance of plant diversity for resource availability in these new habitats. Additionally, avoiding intensive management practices, such as the use of fertilizers and pesticides in agricultural systems, can also promote the conservation of diversity.

We observed no effects on species richness and abundance across various biomes and land use change types. In many instances, these outcomes might be attributed to the limited number of comparisons. Furthermore, certain anthropogenic land uses maintain conditions and resource diversity like those of biomes and vegetation types, potentially bolstering ant richness and abundance, such as conversion from grassland to pasture and from forest to perennial agriculture (Bos et al., 2007; Delabie et al., 2021; Lassau and Hochuli, 2004; Queiroz et al., 2020; Solar et al., 2015; Vasconcelos et al., 2017). Additionally, in some anthropogenic land uses, the survival of generalist ants may lead to increased abundance, resulting in a no effect of land use change on overall ant abundance (Wilker et al., 2023). Moreover, these areas often exhibit a higher presence of invasive ant species (Baidya and Bagchi, 2022; Holway et al., 2002), which tend to have higher abundances (Lester and Gruber, 2016) and may also contribute to the null effect we observed in ant abundance.

Regarding the assessment of ant abundance, it is important to consider that the term “ant abundance” may not directly reflect the actual number of individuals, but rather the foraging activity. In ants, where the colony is regarded as the individual (Wilson, 1987), the present ants are part of this collective organism. Therefore, when using methods such as “ant trapping or area-based ant counting”, it is crucial to understand that this might indicate more about foraging activity than the true abundance of ants. Despite observing a decrease in species diversity, the quantity of ants engaged in foraging activities remained no effect in most of the comparisons, suggesting the necessity for further studies to comprehend the ecosystem functions and interactions of these ants in anthropogenic land uses. Moreover, colony counting as a method to evaluate ant abundance still poses a challenge in diversity studies, particularly due to difficulties in nest counting, especially in polydomous species. Only six studies opted to use species occurrence frequency per trap as a viable alternative to circumvent issues related to ant foraging and colony size (Brandão et al., 2011; Rizzotto et al., 2019). Moreover, it is important to acknowledge that our data might have certain biases, as there is a tendency to publish articles that report negative effects on ant assemblages, while smaller articles with null or positive results might go unpublished. This pattern of bias toward publishing articles that support our hypotheses is also found in other scientific fields, and the publication and citation of studies with neutral effects are encouraged (Mlinarić et al., 2017).

Contrary to responses related to taxonomic metrics, the impacts of land use changes on functional ecology and interactions remain uncertain. Outcomes for ecosystem functions are contingent upon the function type, vegetation type, and land use type. They may reveal a negative effect (e.g., reduced seed removal when changes from grassland to silviculture; Rabello et al., 2018), a positive effect (e.g., increased seed removal and insect predation when shifting from forest to pasture; Fontenele and Schmidt, 2021; Wilker et al., 2023), or null effect (e.g., unchanged seed removal when changing from savannah to pasture; Rabello et al., 2018). Thus, ecosystem functions may exhibit effects different from those found for species richness (Queiroz et al., 2021; Wilker et al., 2023). Moreover, the frequent increase in invasive ants in anthropogenic land uses (Baidya and Bagchi, 2022) has a high impact on interactions with other species, increasing competition with other ants (Neumann and Pinter-Wollman, 2022) and decreasing pollinators' activity (Unni et al., 2021). Along with the decrease in pollination and seed dispersal (Bona et al., 2023), other ant-plant interactions may also decline due to land use changes. For instance, a few ants are involved with several plant species and multiple ecosystem functions (Costa et al., 2016), which can decrease due to reduced stability caused by anthropogenic disturbance (Câmara et al., 2019) or the loss of plant resource availability (Fagundes et al., 2016). Thus, this knowledge gap regarding ecosystem functions and interactions must be addressed, given the vital role played by ants in various biomes, vegetation types, and anthropogenic land uses.

5. Conclusions

Here, we identified the negative effects of land use changes on ant diversity in Brazil, a vast Neotropical country. Although we found a greater number of studies in biomes, vegetation types, and anthropogenic land uses with a higher frequency of land use changes, we recommend more efforts in less-explored areas, such as the xeric shrublands of the Caatinga and land uses associated with mining. However, despite some biomes being underexplored, like the Pampa and Pantanal, their vegetation types can be found in more studied biomes, like the Cerrado, and can therefore serve as references for possible effects. Our meta-analysis revealed that land uses that significantly alter vegetation structure lead to a reduction in species richness, but largely maintain abundance, with a decrease in abundance occurring only in certain conversions to agriculture. From this, we emphasize the importance of management plans in areas of anthropogenic land use, maintaining habitat-specific environmental similarity (Arroyo-Rodríguez et al., 2020), supporting higher vegetation diversity to ensure resource availability and avoiding intensive use of pesticides in agricultural systems. Additionally, we suggest that future research on land use effects also focus on ecosystem functions, traits, guilds, and interactions to assess possible changes in the functioning of these new ecosystems, as well as the ecosystem services provided by species that remain in anthropogenic land uses.

CRediT authorship contribution statement

Icaro Wilker: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Antônio C.M. Queiroz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Carla R. Ribas:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Maria Santina C. Morini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Chaim J. Lasmar:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Fernando A. Schmidt:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Rodrigo M. Feitosa:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Anselmo Nogueira:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Fabrício B. Baccaro:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Mônica A. Ulysséa:** Writing – review & editing, Writing – original draft, Data curation. **Lucas N. Paolucci:** Writing – review & editing, Writing – original draft, Data curation. **Yves P. Quinet:** Writing – review & editing, Writing – original draft, Data curation. **André B. Vargas:** Writing – review & editing, Writing – original draft, Data curation. **Ana Y. Harada:** Writing – review & editing, Writing – original draft, Data curation. **Tathiana G. Sobrinho:** Writing – review & editing, Writing – original draft, Data curation. **Tatianne G. Marques:** Writing – review & editing, Writing – original draft, Data curation. **Jorge L.P. Souza:** Writing – review & editing, Writing – original draft, Data curation. **Kleber Del-Claro:** Writing – review & editing, Writing – original draft, Data curation. **Denise Lange:** Writing – review & editing, Writing – original draft, Data curation. **Jean C. Santos:** Writing – review & editing, Writing – original draft, Data curation. **Rogério R. Silva:** Writing – review & editing, Writing – original draft, Data curation. **Renata B.F. Campos:** Writing – review & editing, Writing – original draft, Data curation. **Emília Z. Albuquerque:** Writing – review & editing, Writing – original draft, Data curation. **Ananza M. Rabello:** Writing – review & editing, Writing – original draft, Data curation. **Ricardo R.C. Solar:** Writing – review & editing, Writing – original draft, Data curation. **Stela A. Soares:** Writing – review & editing, Writing – original draft, Data curation. **Karine S. Carvalho:** Writing – review & editing, Writing – original draft, Data curation. **Aline B. Moraes:** Writing – review & editing, Writing – original draft, Data curation. **Helena M. Torezan-Silingardi:** Writing – review & editing, Writing – original draft, Data curation. **Larissa Nahas:** Writing – review & editing, Writing – original draft, Data curation. **Iracenir Andrade dos Santos:** Writing – review & editing, Writing – original draft, Data curation. **Cinthia B. Costa-Milanez:** Writing – review & editing, Writing – original draft, Data curation. **Flávia A. Esteves:** Writing – review & editing, Writing – original draft, Data curation. **Tiago Frizzo:** Writing – review & editing, Writing – original draft, Data curation. **Wesley daRocha:** Writing – review & editing, Writing – original draft, Data curation. **Felipe Martello:** Writing – review & editing, Writing – original draft, Data curation. **Eduardo Diehl-Fleig:** Writing – review & editing, Writing – original draft, Data curation.

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.

Data availability

Data available from the Figshare database doi: https://doi.org/10.6084/m9.figshare.24723918.v1 (Wilker et al., 2023). A list of data sources used in the study is provided in the Data sources section.

Acknowledgements

We are most grateful for the comments and suggestions on the previous versions of the manuscript by Tatiana G. Cornelissen, Clarissa A. Rosa, Cássio A. Nunes, Raquel L. Carvalho, Débora R. Carvalho, and Paulo S. Pompeu. This study was part of IW's PhD. thesis at UFLA with an internship period at the Cardiff University. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. ACMQ received a postdoctoral fellowship from P&D GT0611 – "Descomissionamento da PCH Pandeiros: Uma experiência inédita na América do Sul" CEMIG/Programa de Pesquisa e Desenvolvimento da ANEEL. CRR was funded by Programa Pesquisador Mineiro (PPM-00736-18). CJL received a postdoctoral fellowship from CAPES (PNPD/CAPES, Finance code: 001). RMF was funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (grant 301495/2019-0). AN was funded by the by CNPq through a Pq-2 (grant 312389/2023-0) and by the São Paulo Research Foundation (FAPESP) through a Young Investigators Grant (2019/19544-7). FBB was funded by the CNPq (grant 312878/2023-5040). MAU was funded by CNPq (PCI/MPEG, grant 317262/2023-8). TI was funded by research productivity fellowship (CNPq 3312684/2021-5). JLPS was funded by the CNPq PCI/INMA (300886/2022-5). EZA was funded by Peter Buck Postdoctoral Fellowship Program at the Natural Museum of Natural History Smithsonian Institution. RRCS was funded by the CNPq (grant 308350/2022-7).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110778.

References

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

Andersen, A.N., Hoffmann, B.D., Müller, W.J., et al., 2002. Using ants as bioindicators in land management: simplifying assessment of ant community responses. J. Appl. Ecol. 39 (1), 8–17. https://doi.org/10.1046/j.1365-2664.2002.00704.x.

Anderson, M.J., 2001. A new method for non-parametric multivariate analysis of variance. Austral Ecol. 26, 32–46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x.
Antonelli, A., Zizka, A., Carvalho, F.A., et al., 2018. Amazonia is the primary source of Neotropical biodiversity. Proc. Natl. Acad. Sci. U. S. A. 115 (23), 6034–6039. https://doi.org/10.1073/pnas.1713819115.
Arroyo-Rodríguez, V., Fahrig, L., Tabarelli, M., et al., 2020. Designing optimal human-modified landscapes for forest biodiversity conservation. Ecol. Lett. 23 (9), 1404–1420. https://doi.org/10.1111/ele.13535.
Attwood, S.J., Maron, M., House, A.P.N., et al., 2008. Do arthropod assemblages display globally consistent responses to intensified agricultural land use and management? Glob. Ecol. Biogeogr. 17 (5), 585–599. https://doi.org/10.1111/j.1466-8238.2008.00399.x.
Baidya, P., Bagchi, S., 2022. Influence of human land use and invasive species on beta diversity of tropical ant assemblages. Insect Conserv. Diver. 15 (1), 73–85. https://doi.org/10.1111/icad.12536.
Bona, K., Delabie, J.H.C., Cazetta, E., 2023. Effects of anthropogenic disturbances on diaspore removal by ants: a meta-analysis. Acta Oecol. 118 https://doi.org/10.1016/j.actao.2023.103893.
Bos, M.M., Steffan-Dewenter, I., Tscharntke, T., 2007. The contribution of cacao agroforests to the conservation of lower canopy ant and beetle diversity in Indonesia. Biodivers. Conserv. 16 (8), 2429–2444. https://doi.org/10.1007/s10531-007-9196-0.
Brandão, C.R.F., Silva, R.R., Feitosa, R.M., 2011. Cerrado ground-dwelling ants (Hymenoptera: Formicidae) as indicators of edge effects. Zoologia-Curitiba 28, 379–387. https://doi.org/10.1590/S1984-46702011000300012.
Câmara, T., Leal, I.R., Blüthgen, N., 2019. Anthropogenic disturbance and rainfall variation threaten the stability of plant–ant interactions in the Brazilian Caatinga. Ecography 42 (11), 1960–1972. https://doi.org/10.1111/ecog.04531.
Casimiro, M.S., Sansevero, J.B.B., Queiroz, J.M., 2019. What can ants tell us about ecological restoration? A global meta-analysis. Ecol. Indic. 102, 593–598. https://doi.org/10.1016/j.ecolind.2019.03.018.
Clarke, K.R., 1993. Non-parametric multivariate analysis of changes in community structure. Aust. J. Ecol. 18, 117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x.
Costa, F.V., Mello, M.A., Bronstein, J.L., 2016. Few ant species play a central role linking different plant resources in a network in rupestrian grasslands. PloS One 11 (12), e0167161. https://doi.org/10.1371/journal.pone.0167161.
Costa, M.M.S.D., Schmidt, F.A., 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.
da Silva, W.B., Cajaiba, R.L., Santos, M., et al., 2022. Effectiveness of ant communities to detect anthropogenic disturbance in Neotropical forest landscapes: a case study in the Brazilian Amazon. Biodivers. Conserv. 31 (1), 211–226. https://doi.org/10.1007/s10531-021-02329-x.
Dalle Laste, K.C., Durigan, G., Andersen, A.N., 2019. Biodiversity responses to land-use and restoration in a global biodiversity hotspot: ant communities in Brazilian Cerrado. Austral Ecol. 44 (2), 313–326. https://doi.org/10.1111/aec.12676.
de Chazal, J., Rounsevell, M.D.A., 2009. Land-use and climate change within assessments of biodiversity change: a review. Glob. Environ. Change 19 (2), 306–315. https://doi.org/10.1016/j.gloenvcha.2008.09.007.
Delabie, J., Koch, E., Dodonov, P., et al., 2021. Sampling and analysis methods for ant diversity assessment. In: Santos, J.C., Fernandes, W.G. (Eds.), Measuring Arthropod Biodiversity: A Handbook of Sampling Methods. Springer International Publishing, pp. 13–54. https://doi.org/10.1007/978-3-030-53226-0_2.
Diamond, S.E., Sorger, D.M., Hulcr, J., et al., 2012. Who likes it hot? A global analysis of the climatic, ecological, and evolutionary determinants of warming tolerance in ants. Glob. Change Biol. 18 (2), 448–456. https://doi.org/10.1111/j.1365-2486.2011.02542.x.
Díaz-Vallejo, E.J., Seeley, M., Smith, A.P., et al., 2021. A meta-analysis of tropical land-use change effects on the soil microbiome: emerging patterns and knowledge gaps. Biotropica 53, 738–752. https://doi.org/10.1111/btp.12931.
Fagundes, R., Dáttilo, W., Ribeiro, S.P., 2016. Food source availability and interspecific dominance as structural mechanisms of ant-plant-hemipteran multitrophic networks. Arthropod Plant Interact. 10, 207–220. https://doi.org/10.1007/s11829-016-9428-x.
FAO, 2016. State of the World's Forests 2016. Forests and Agriculture: Land-use Challenges and Opportunities (Rome).
Feitosa, R.M., Camacho, G.P., Silva, T.S.R., et al., 2022. Ants of Brazil: an overview based on 50 years of diversity studies. Syst. Biodivers. 20 (1), 1–27. https://doi.org/10.1080/14772000.2022.2089268.
Filgueiras, B.K., Peres, C.A., Melo, F.P., et al., 2021. Winner–loser species replacements in human-modified landscapes. Trends Ecol. Evol. 36 (6), 545–555. https://doi.org/10.1016/j.tree.2021.02.006.
Folgarait, P.J., 1998. Ant biodiversity and its relationship to ecosystem functioning: a review. Biodivers. Conserv. 7, 1221–1244. https://doi.org/10.1023/A:1008891901953.
Fontenele, L.K., Schmidt, F.A., 2021. Forest-pasture shifting alters the assemblages of seed-removing ants in southwestern Brazilian Amazon. J. Insect Conserv. 25 (2), 213–220. https://doi.org/10.1007/s10841-021-00295-x.
Gardner, T.A., Barlow, J., Chazdon, R., et al., 2009. Prospects for tropical forest biodiversity in a human-modified world. Ecol. Lett. 12, 561–582. https://doi.org/10.1111/j.1461-0248.2009.01294.x.
Gibbs, H.K., Ruesch, A.S., Achard, F., et al., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc. Natl. Acad. Sci. U. S. A. 107 (38), 16732–16737. https://doi.org/10.1073/pnas.0910275107.
Goulet-Pelletier, J.C., Cousineau, D., 2018. A review of effect sizes and their confidence intervals, part I: the Cohen's d family. The Quantitative Methods for Psychology 14 (4), 242–265. https://doi.org/10.20982/tqmp.14.4.p242.
Grames, E.M., Stillman, A.N., Tingley, M.W., et al., 2019. An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks. Methods Ecol. Evol. 10 (10), 1645–1654. https://doi.org/10.1111/2041-210X.13268.
Haddaway, N.R., Bernes, C., Jonsson, B.G., et al., 2016. The benefits of systematic mapping to evidence-based environmental management. Ambio 45 (5), 613–620. https://doi.org/10.1007/s13280-016-0773-x.
Harrer, M., Cuijpers, P., Furukawa, T., et al., 2021. Doing meta-Analysis with R: A Hands-on Guide. Chapman and Hall/CRC.
Hedges, L.V., 1981. Distribution theory for Glass's estimator of effect size and related estimators. J. Educ. Stat. 6 (2), 107–128. https://doi.org/10.3102/10769986006002107.
Holway, D.A., Lach, L., Suarez, A.V., et al., 2002. The causes and consequences of ant invasions. Annu. Rev. Ecol. Syst. 33 (1), 181–233. https://doi.org/10.1146/annurev.ecolsys.33.010802.150444.
Hopmans, J.W., Qureshi, A.S., Kisekka, I., et al., 2021. Critical knowledge gaps and research priorities in global soil salinity. Adv. Agron. 169, 1–191. https://doi.org/10.1016/bs.agron.2021.03.001.
IBGE, 2019. Biomas e Sistema Costeiro-Marinho do Brasil - 1:250,000. Instituto Brasileiro de Geografia e Estatística. https://www.ibge.gov.br/geociencias/informacoes-ambientais/vegetacao/15842-biomas.html. (Accessed 28 May 2024).
Lach, L., Parr, C., Abbott, K., 2010. Ant Ecology. Oxford University Press.
Laliberté, E., Wells, J.A., Declerck, F., et al., 2010. Land-use intensification reduces functional redundancy and response diversity in plant communities. Ecol. Lett. 13 (1), 76–86. https://doi.org/10.1111/j.1461-0248.2009.01403.x.
Lasmar, C.J., Bishop, T.R., Parr, C.L., et al., 2021a. Geographical variation in ant foraging activity and resource use is driven by climate and net primary productivity. J. Biogeogr. 48 (6), 1448–1459. https://doi.org/10.1111/jbi.14089.
Lasmar, C.J., Queiroz, A.C., Rosa, C., et al., 2021b. Contrasting edge and pasture matrix effects on ant diversity from fragmented landscapes across multiple spatial scales. Landsc. Ecol. 36 (9), 2583–2597. https://doi.org/10.1007/s10980-021-01258-y.
Lasmar, C.J., Bishop, T.R., Parr, C.L., et al., 2023. Testing the context dependence of ant nutrient preference across habitat strata and trophic levels in Neotropical biomes. Ecology 104 (4), e3975. https://doi.org/10.1002/ecy.3975.
Lassau, S.A., Hochuli, D.F., 2004. Effects of habitat complexity on ant assemblages. Ecography 27 (2), 157–164. https://doi.org/10.1111/j.0906-7590.2004.03675.x.
Lester, P.J., Gruber, M.A.M., 2016. Booms, busts and population collapses in invasive ants. Biol. Invasions 18 (11), 3091–3101. https://doi.org/10.1007/s10530-016-1214-2.
Magnusson, W.E., Grelle, C.E., Marques, M.C., et al., 2018. Effects of Brazil's political crisis on the science needed for biodiversity conservation. Front. Ecol. Evol. 6, 163. https://doi.org/10.3389/fevo.2018.00163.
Martins, I.S., Ortega, J.C.G., Guerra, V., et al., 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.
Mathieu, J., Rossi, J.P., Mora, P., et al., 2005. Recovery of soil macrofauna communities after forest clearance in Eastern Amazonia, Brazil. Conserv. Biol. 19 (5), 1598–1605. https://doi.org/10.1111/j.1523-1739.2005.00200.x.
McKinney, M.L., Lockwood, J.L., 1999. Biotic homogenization: a few winners replacing many losers in the next mass extinction. Trends Ecol. Evol. 14 (11), 450–453. https://doi.org/10.1016/S0169-5347(99)01679-1.
Mlinarić, A., Horvat, M., Šupak Smolčić, V., 2017. Dealing with the positive publication bias: why you should really publish your negative results. Biochem. Med. 3, 447–452. https://doi.org/10.11613/BM.2017.030201.
Nakagawa, S., Santos, E.S.A., 2012. Methodological issues and advances in biological meta-analysis. Evol. Ecol. 26, 1253–1274. https://doi.org/10.1007/s10682-012-9555-5.
Neumann, K., Pinter-Wollman, N., 2022. The effect of resource availability on interspecific competition between a native and an invasive ant. Philos. Trans. R. Soc. B 377 (1851), 20210146. https://doi.org/10.1098/rstb.2021.0146.
Newbold, T., 2018. Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. P. Roy. Soc. B-Biol. Sci. 285 (1881) https://doi.org/10.1098/rspb.2018.0792.
Newbold, T., Hudson, L.N., Hill, S.L.L., et al., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520 (7545), 45–50. https://doi.org/10.1038/nature14324.
Newbold, T., Adams, G.L., Robles, G.A., et al., 2019. Climate and land-use change homogenise terrestrial biodiversity, with consequences for ecosystem functioning and human well-being. Emerg. Top. Life Sci. 3 (2), 207–219. https://doi.org/10.1042/ETLS20180135.
Nunes, C.A., Berenguer, E., França, F., et al., 2022. Linking land-use and land-cover transitions to their ecological impact in the Amazon. Proc. Natl. Acad. Sci. U. S. A. 119 (27), e2202310119 https://doi.org/10.1073/pnas.2202310119.
O'Dea, R.E., Lagisz, M., Jennions, M.D., et al., 2021. Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. Biol. Rev. 96 (5), 1695–1722. https://doi.org/10.1111/brv.12721.
Pacheco, R., Vasconcelos, H.L., 2007. Invertebrate conservation in urban areas: ants in the Brazilian Cerrado. Landscape Urban Plan. 81 (3), 193–199. https://doi.org/10.1016/j.landurbplan.2006.11.004.
Parente, L., Nogueira, S., Baumann, L., et al., 2021. Quality assessment of the PRODES Cerrado deforestation data. Remote Sens. Appl. Soc. Environ. 21, 100444 https://doi.org/10.1016/j.rsase.2020.100444.

Pereira, E.J.A.L., de Santana Ribeiro, L.C., da Silva Freitas, L.F., et al., 2020. Brazilian policy and agribusiness damage the Amazon rainforest. Land Use Policy 92. https://doi.org/10.1016/j.landusepol.2020.104491.

Priyadarshana, T.S., Martin, E.A., Sirami, C., et al., 2024. Crop and landscape heterogeneity increase biodiversity in agricultural landscapes: a global review and meta-analysis. Ecol. Lett. 27 (3), e14412 https://doi.org/10.1111/ele.14412.

Projeto MapBiomas, 2022. Coleção 7 da Série Anual de Mapas de Uso e Cobertura da Terra do Brasil. https://storage.googleapis.com/mapbiomas-public/brasil/collection-7/lclu/coverage/brasil_coverage_2021.tif (accessed 28 May 2024).

QGIS.org, 2023. QGIS Geographic Information System. QGIS Association. http://www.qgis.org. (Accessed 28 May 2024).

Queiroz, A.C.M., Rabello, A.M., Braga, D.L., et al., 2020. Cerrado vegetation types determine how land use impacts ant biodiversity. Biodivers. Conserv. 29 (6), 2017–2034. https://doi.org/10.1007/s10531-017-1379-8.

Queiroz, A.C.M., Rabello, A.M., Lasmar, C.J., et al., 2021. Diaspore removal by ants does not reflect the same patterns of ant assemblages in mining and rehabilitation areas. Neotrop. Entomol. 50, 335–348. https://doi.org/10.1007/s13744-021-00861-7.

Queiroz, A.C.M., Marques, T.G., Ribas, C.R., et al., 2023. Ant diversity decreases during the dry season: a meta-analysis of the effects of seasonality on ant richness and abundance. Biotropica 55 (1), 29–39. https://doi.org/10.1111/btp.13158.

R Core Team, 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/. (Accessed 28 May 2024).

Rabello, A.M., Parr, C.L., Queiroz, A.C.M., et al., 2018. Habitat attribute similarities reduce impacts of land-use conversion on seed removal. Biotropica 50 (1), 39–49. https://doi.org/10.1111/btp.12506.

Ribas, C.R., Schoereder, J.H., Pic, M., et al., 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.

Ribas, C.R., Campos, R.B., Schmidt, F.A., et al., 2012. Ants as indicators in Brazil: a review with suggestions to improve the use of ants in environmental monitoring programs. Psyche 2012, 636749. https://doi.org/10.1155/2012/636749.

Rizzotto, A.M., Roani, A.H., Guarda, C., et al., 2019. Ant fauna in permanent preservation areas and in forest plantations in the northwestern region of Rio Grande do Sul state. Ciência Florestal 29, 1227–1240. https://doi.org/10.5902/1980509836279.

Rosenthal, R., 1979. The file drawer problem and tolerance for null results. Psychol. Bull. 86 (3), 638–641. https://doi.org/10.1037/0033-2909.86.3.638.

Sala, O.E., Stuart Chapin, F.I.I.I., Armesto, J.J., et al., 2000. Global biodiversity scenarios for the year 2100. Science 287 (5459), 1770–1774. https://doi.org/10.1126/science.287.5459.1770.

Sánchez-Bayo, F., Wyckhuys, K.A., 2019. Worldwide decline of the entomofauna: a review of its drivers. Biol. Conserv. 232, 8–27. https://doi.org/10.1016/j.biocon.2019.01.020.

Schmidt, F.A., Ribas, C.R., Feitosa, R.M., et al., 2022. Ant diversity studies in Brazil: an overview of the myrmecological research in a megadiverse country. Insect. Soc. 69 (1), 105–121. https://doi.org/10.1007/s00040-022-00848-6.

Simberloff, D., Nuñez, M.A., Ledgard, N.J., et al., 2010. Spread and impact of introduced conifers in South America: lessons from other southern hemisphere regions. Austral Ecol. 35 (5), 489–504. https://doi.org/10.1111/j.1442-9993.2009.02058.x.

Solar, R.R., Barlow, J., Ferreira, J., 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.

Song, X.P., Hansen, M.C., Stehman, S.V., et al., 2018. Global land change from 1982 to 2016. Nature 560 (7720), 639–643. https://doi.org/10.1038/s41586-018-0411-9.

Stein, A., Kreft, H., 2015. Terminology and quantification of environmental heterogeneity in species-richness research. Biol. Rev. 90 (3), 815–836. https://doi.org/10.1111/brv.12135.

Tabarelli, M., Peres, C.A., Melo, F.P., 2012. The 'few winners and many losers' paradigm revisited: emerging prospects for tropical forest biodiversity. Biol. Conserv. 155, 136–140. https://doi.org/10.1016/j.biocon.2012.06.020.

Trew, B.T., Maclean, I.M., 2021. Vulnerability of global biodiversity hotspots to climate change. Glob. Ecol. Biogeogr. 30 (4), 768–783. https://doi.org/10.1111/geb.13272.

Unni, A.P., Mir, S.H., Rajesh, T.P., 2021. Native and invasive ants affect floral visits of pollinating honey bees in pumpkin flowers (Cucurbita maxima). Sci. Rep. 11 (1), 4781. https://doi.org/10.1038/s41598-021-83902-w.

Vasconcelos, H.L., Maravalhas, J.B., Cornelissen, T., 2017. Effects of fire disturbance on ant abundance and diversity: a global meta-analysis. Biodivers. Conserv. 26, 177–188. https://doi.org/10.1007/s10531-016-1234-3.

Viechtbauer, W., 2010. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. 36, 1–48. https://doi.org/10.18637/jss.v036.i03.

Warton, D.I., Wright, T.W., Wang, Y., 2012. Distance-based multivariate analyses confound location and dispersion effects. Methods Ecol. Evol. 3, 89–101. https://doi.org/10.1111/j.2041-210X.2011.00127.x.

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

Wilker, I., Lasmar, C.J., Schmidt, F.A., et al., 2023. Land-use change in the Amazon decreases ant diversity but increases ant-mediated predation. Insect Conserv. Diver. 16 (3), 379–392. https://doi.org/10.1111/icad.12632.

Wilson, E.O., 1987. Causes of ecological success: the case of the ants. J. Anim. Ecol. 56 (1), 1–9. https://doi.org/10.2307/4795.