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REVIEW ARTICLE

Ant diversity studies in Brazil: an overview of the myrmecological research in a megadiverse country

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Abstract
Scientometric investigation and scientific production analysis are essential for science progress. Although a vast number of studies on Brazilian ant diversity have been carried out, a critical analysis of the advances in its scientific production is still missing. We compiled a comprehensive database on ant diversity papers carried out in the Brazilian territory. Our main research question is: what is the profile of ant diversity studies developed in Brazil? We sorted the studies according to the main terrestrial Brazilian biomes. We compiled 468 papers, which were published in 132 journals and encompassed a time range from 1970 to 2020. Most studies were carried out in Atlantic Forest (143), followed by Amazon Forest (111), Cerrado (106), Caatinga (38), Pantanal (14), and Pampa (4). In all biomes, ant samplings presented a much-aggregated distribution. Most studies had samplings carried out in all seasons in almost all biomes. The three most employed sampling techniques were pitfall traps, direct sampling, and attractive baits. The main subject of papers were ant assemblage diversity and ant fauna surveys. We discussed the implications of ant diversity study profiles regarding all aspects considered, the historical changes in these factors during the time range, and their possible influence on ant diversity paper publications, and provided suggestions for a more efficient use of time and financial resources for future research directions on ant diversity studies. Finally, we propose that our study can be replicated in other world regions, allowing for a comprehensive view on ant diversity research at a global scale.

Keywords Biodiversity · Brazilian biomes · Distribution · Database · Formicidae · Scientometrics

Introduction

In the last decades, the number of scientific papers on biodiversity has increased noticeably in the literature Heberling et al. (2021). Despite the importance in acquiring and synthesizing scientific knowledge for the progress of science and decision-making to achieve conservation of biodiversity, it is not an easy task (Reichman et al. 2011; Hampton et al. 2013). For instance, in megadiverse countries with large territorial extensions, many of the biodiversity data are often dispersed in different sources (e.g., museums, libraries, online repositories, and languages) (Dáttilo et al. 2020; Teixido et al. 2020). Therefore, we need to join forces to maximize the scientific value of biodiversity data in the era of big data (i.e., large growth in production and analysis of scientific knowledge) (Jarić et al. 2020).

Brazil encompasses a large geographical latitudinal and longitudinal range (latitude range ~ 28°; longitude range ~ 39°), comprising extensive heterogeneity in climate, soil, vegetation, and hydrographic basins. This significant heterogeneity has played a central role in the development of an exuberant diversity of terrestrial biomes (Arruda et al. 2017), which host the highest biodiversity in the world (Lewinsohn and Prado 2005; MMA 2021). More than 10% (1500 out of 13,850) of the ant species known in the world (Bolton 2021) can be found in Brazil, and according to a

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conservative estimation, there are approximately 1000–2000 ant species that can be described in its territory (Baccaro et al. 2015). These massive numbers place Brazil as one of the major centers of ant biodiversity in the world (Dunn et al. 2007) which make it a land of ants.

Several aspects of the biology and ecology of Brazilian ants have been studied for a long time, since the first naturalists (e.g., Mayr 1878; Emery 1888—oldest records about ant diversity studies) until now, promoting the shaping of a large and collaborative group of myrmecologists (Brandão 2015). This group has discussed the advances in ant studies, mostly carried out in Brazil, every 2 years over more than 40 years during the scientific meeting "Simpósio de Mirmecologia: An international ant meeting". This symposium has witnessed an increasing participation of foreign researchers in the last editions, making it the main international myrmecological meeting in the world (Brandão 2020).

Although a vast number of studies on Brazilian ant diversity have been carried out, a few meta-analyses have been performed on the drivers of ant diversity and abundance (e.g., fire disturbance, Vasconcelos et al. 2017) and the use of ants as bioindicators (Ribas et al. 2012) in the country. To date, a critical analysis of the advances in scientific production, considering its quantitative features and characteristics (i.e., a scientometric approach), has never been performed. A scientometric investigation on historical trends of ant diversity studies is essential to highlight the knowledge gaps on ant biodiversity in Brazil. This information is especially desirable considering the high human pressure over Brazilian biomes and the perspective of scarce financial funding of the Brazilian government for biodiversity research in the short–medium term (Bockmann et al. 2018). In 2012, 38 ant researchers created the "Formigas do Brasil" (Ants of Brazil; https://formigasdobrasil.com/) workgroup, aiming to provide a base line for the improvement of Brazilian myrmecological studies for the international scientific community. The workgroup has created a comprehensive database on ant diversity papers carried out in the Brazilian territory.

Supported by this database, the research question addressed here is as follows: what is the profile of ant diversity studies developed in Brazil? The study profile was described considering (1) general aspects—total number of papers, time range, number of journals, and number of papers per biome; (2) publication technical data—journal impact factor, language, and number of authors; and (3) geographical/methodological information—geographical distribution of ant samplings, sampling season, sampling techniques, and study type. We searched for these sets of aspects in published scientific papers to outline the historical trends in ant diversity studies developed in Brazil. Our findings can lead to more efficient use of time and financial resources in future research on ant diversity studies carried out in Brazil.

Materials and methods

Paper search

We carried out standardized searches for myrmecological papers in three literature databases, Web of Science, Scielo, and Scopus, for a time range from 1945 (oldest year of databases) to 2013 (when paper searching was done for the first time). For the updated survey, in 2020, the time range considered was 2013–2020, when we also verified the potential redundancy between papers of the two surveys regarding the year 2013. Additionally, in 2020, papers from personal datasets were included, considering the time range of 1945–2020 with another round of verification for the redundancy of papers with the previous surveys in online datasets.

We surveyed articles specifically about the ant diversity of a single Brazilian terrestrial biome: Amazon Forest, Atlantic Forest, Cerrado—Brazilian savanna, Caatinga—seasonal tropical dry forest, Pantanal—wetlands, and Pampa—subtropical grasslands (MMA 2021). Then, we carried out the paper searching using the keywords "ant + Brazil" or "formiga + Brasil" (in Portuguese), and we also included the name of each biome, in turn, in the keywords. We only selected in the database, papers that reported ant diversity studies. A wide range of ant diversity studies were considered, including fauna surveys, assemblage diversity, ecological interactions, behavior biology, sampling methods, and community assembly (see details of each type in Profile of ant diversity studies in Brazil section), and we also considered review papers on ant diversity.

Information survey

We extracted 27 different data metrics from each paper (Online Resource 1). At this step, we confirmed the adequacy of the paper to a specific biome and if there was a clear indication and description that the sampling or experiment was carried out in the biome domain. Studies that carried out sampling in more than one Brazilian biome were categorized as "multi-biome" and studies in which sampling was carried out in Brazil and another world region were categorized as "transcontinental". Finally, papers that did not fit into either location category or did not provide a clear identification of the sampling location were categorized as "non-informed". Thus, the paper sorting system resulted in nine categories regarding the information on the location where the samplings or experiments were carried out.

Considering that many researchers worked on information survey groups, some misunderstanding and

misinterpretation could happen resulting in slightly different data. Thus, we checked if there are bias in the survey and established a maximal level of bias of 15% for all datasets. To estimate the level of bias for all datasets, we randomly and proportionally chose 31 papers from each location category in the dataset to proceed with a second information survey performed by the first author. Every divergence between the second and first information surveying rounds was considered bias. The percentage of the bias was calculated in a universe of 837 combinations made up of 27 metrics and 31 papers. We observed 107 divergences between the two information surveying rounds, which indicates 12.8% bias.

Profile of ant diversity studies in Brazil

To describe the profile of ant diversity studies developed in Brazil, the 27 metrics were sorted into three categories: (1) general aspects, (2) publication technical data, and (3) geographical/methodological information. General aspects encompassed the following information: (a) total number of papers; (b) time range; (c) number of journals; (d) number of papers per biome (total and per year). Publication technical data were (e) journal impact factor (2019 as reference year); (f) language; and (g) number of authors. Geographical/methodological information included (h) geographical distribution of ant samplings, (i) sampling season, (j) sampling techniques, and (l) study type.

We counted and sorted the papers according to the location categories (see Information surveying) for all aspects cited above, except for (d) geographical distribution of ant samplings, which were extracted from the coordinates provided in each paper. In some cases, the provided coordinates were related to the sampling design (i.e., coordinates of treatments within sampling site), and in other cases, the information about geographical location was related to sampling site. We used the sampling points to calculate the kernel density estimates for the entire country. In our case, the kernel density represents the distribution of sampling effort through the country. The kernel smoothing bandwidth was scaled to its standard deviation, following the Sheather and Jones (1991) method. The biome delimitations were retrieved from the IBGE website (https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842biomas.html?=&t=o-que-e) and superimposed on the map after kernel calculations. We used GISTools (Brunsdon and Chen 2014), maptools (Bivand and Lewin-Koh 2020), rgdal (Bivand et al. 2020), and spatstat (Baddeley et al. 2015) to import and manage the shape files, run the kernel density estimation, and plot the map in R (R Core Team 2020).

Considering that ants can nest from tree canopies to underground soil layers (Blüthgen and Feldhaar 2010), which led to the development of a great diversity of sampling techniques (Dunn et al. 2010; Delabie et al. 2020), we sorted the sampling techniques reported in the studies into eight categories. The categories considered were direct sampling, direct observation, attractive baits (all kinds of attractive baits installed in all strata of the environment), pitfall traps (installed in all strata of the environment and with or without associated attractive baits), litter sampling (litter–Winkler extraction, litter–Berlese–Tullgren funnel, and litter bag), arboreal sampling (beating vegetation, sweep net, and canopy hamper), soil sampling (soil–Winkler extraction, soil–Berlese–Tullgren funnel, Tropical Soil Biology and Fertility Protocol—TSBF, and other methods for soil extraction), and other sampling techniques (Malaise trap, experimental cavities, and others not fitting in the categories described above).

In general, Brazilian biomes present a marked climatic seasonality with a highly variable extension of rainy and dry periods among them (Ab'Sáber 2012; Coutinho 2017). Considering that climatic seasonality can affect ant activity (Costa et al. 2018; Lasmar et al. 2021) and diversity (Rabello et al. 2015), we accounted the sampling season reported in ant diversity studies, which could be rainy, dry, both seasons or non-informed, when there is none explicated information regarding to sampling season.

Regarding the categories of ant diversity studies, we considered the following six categories: ant fauna surveys, papers that provide local lists of species; ant assemblage diversity, papers that report ant diversity comparisons among habitats; ant interaction, papers that report the ecological interactions among ant species and with other organisms; ant behavior, papers that report ant communication and behavioral interactions; ant sampling methods, papers that report advances and remarks on ant sampling; and ant community assembly rules, papers that report the role of abiotic and biotic factors on species community assembly. Additionally, we also account for papers that report reviews on ant diversity, which were here designed as "review papers".

Results

General aspects

Total number of papers, time range, and number of journals We compiled 468 papers, encompassing a time range of 50 years (1970–2020). All these papers were published in 132 journals, of which 63 published a single paper on Brazilian ant diversity. The journals with the most papers published on Brazilian ant diversity were Sociobiology (57 papers), Neotropical Entomology (19 papers), Biotropica (18 papers), Revista Brasileira de Entomologia (17 papers), Insectes Sociaux (15 papers), Journal of Tropical Ecology (14 papers), Biodiversity and Conservation (13 papers), Plos

One (12 papers), Austral Ecology and Brazilian Journal of Biology (11 papers each), and Biota Neotropica, Boletim do Museu Emílio Goeldi and Oecologia (10 papers each).

Number of papers per biome (total and per year) We observed that most ant diversity studies in Brazil were carried out in Atlantic Forest (143), followed by Amazon Forest (111), Cerrado (106), Caatinga (38), Pantanal (14), and Pampa (4) (Fig. 1). Moreover, 25 studies met our criteria for the multi-biome category (20 in two biomes, three in three biomes, one in four biomes, and one in all biomes—although in hospital buildings). Six papers were considered transcontinental, of which three were comparisons of ant diversity patterns between Brazil, Australia, Indonesia, and USA, and three corresponded to a review of ants in hospitals, a diaspore removal study and a description of species diversity in the genus *Sericomyrmex*. Finally, 21 papers met our criteria for the non-informed category. Otherwise, analyzing the number of papers per biome/category per year (Fig. 2), we can identify three marked periods/moments on Brazilian ant diversity publications: (1) beginning of 2000, all biomes had a conspicuous increasing in number of papers per year; (2) around 2010, research on Atlantic Forest achieved the highest number of papers/year on Brazilian ant diversity and later began to decline, with research on Pantanal showing the same trend, although with fewer papers per year. At the same period, research on ant diversity in the Amazon Forest, Caatinga, Cerrado, and Transcontinetal showed their highest increase in number of papers/year; (3) nowadays, Amazon Forest, Caatinga and Multi-biomes are the biomes/categories that present positive increasing in number of papers per year.

Publication technical data

Journal impact factor From 468 papers, 372 were published in journals with impact factors, and 103 were published in journals without impact factors. From those with impact factors, the mean score was 1.88 (max.: 8.67–min.: 0.13), the median was 1.33, and the mode was 0.69. Among the biomes/categories (Fig. 3), papers that reported ant diversity studies in Pampa achieved the highest impact factor (mean 2.35), followed by Caatinga and multi-biomes (mean 2.21), Amazon Forest (mean 2.08), transcontinental (mean 1.98), Cerrado (mean 1.95), Atlantic Forest (mean 1.58), Pantanal (mean 1.46), and non-informed (mean 1.03).

Language In general, most papers reporting ant diversity in Brazil were written in English (255, which correspond to

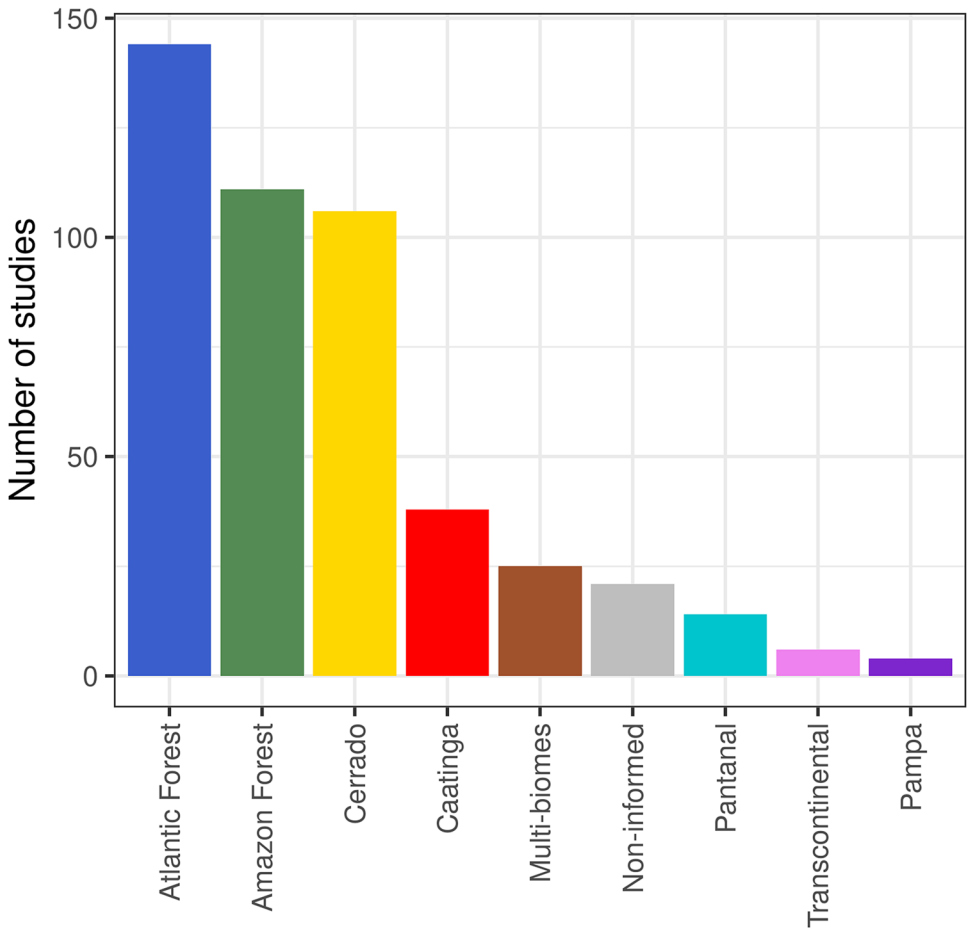

Fig. 1 Number of papers on ant diversity in Brazilian Biomes from 1970 to 2020

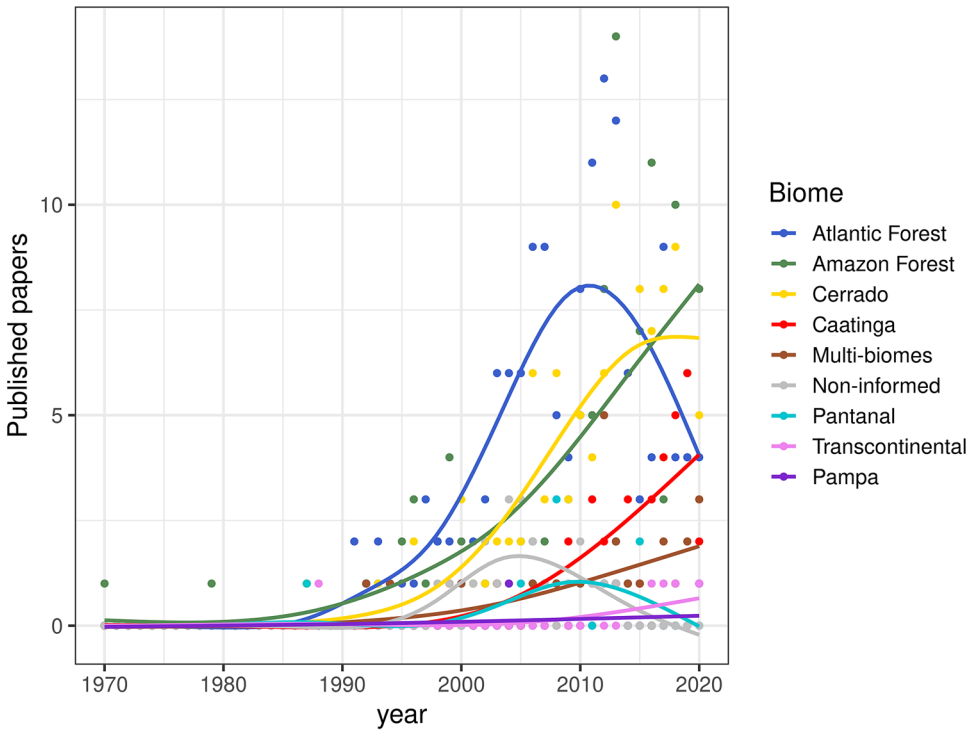

Fig. 2 Number of papers per year on ant diversity in Brazilian Biomes from 1970 to 2020

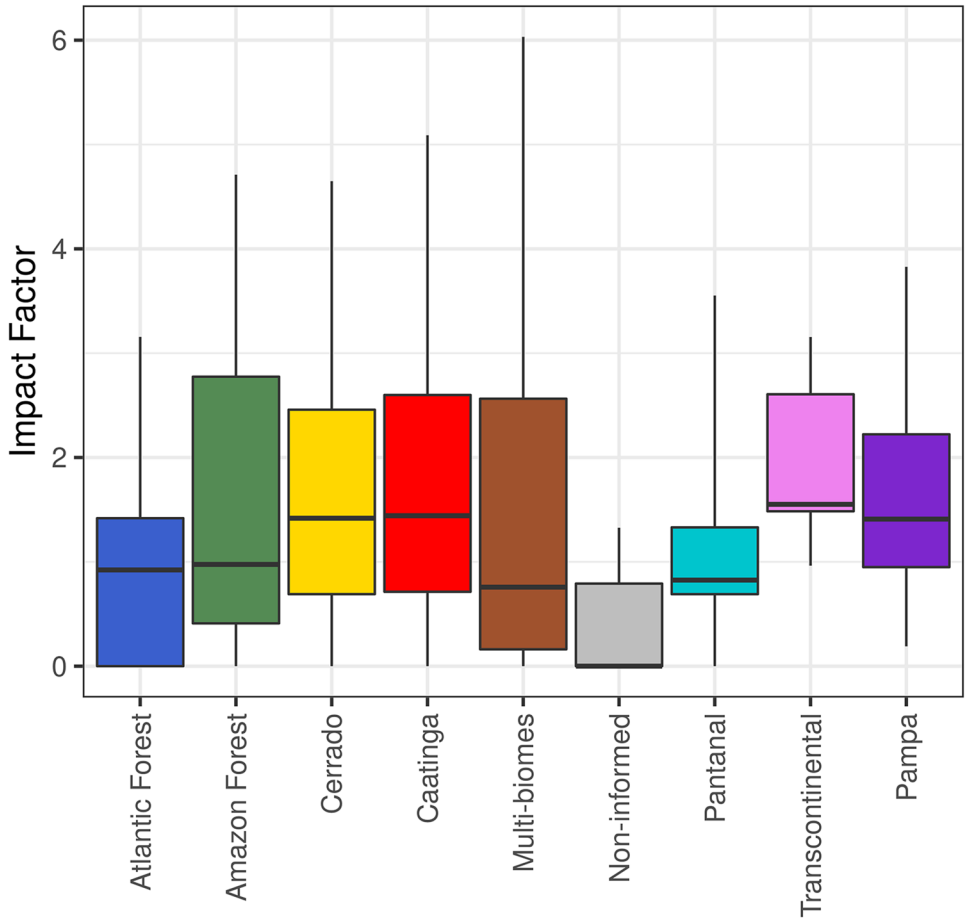

Fig. 3 Mean impact factor of papers on ant diversity in Brazilian Biomes from 1970 to 2020

54.48% of the papers in the dataset). In all biomes/categories, the number of papers written in English was higher than those in Portuguese, except for Pampa and Pantanal, where the number of papers written in English and Portuguese was the same (Fig. 4). Only a few papers were written in Spanish and restricted to two biomes, Amazon Forest and Caatinga.

Number of authors The number of authors per paper ranged from 1 to 21 (Fig. 5). The most frequent number of authors was three, which accounted for 22.86% of the papers in the dataset.

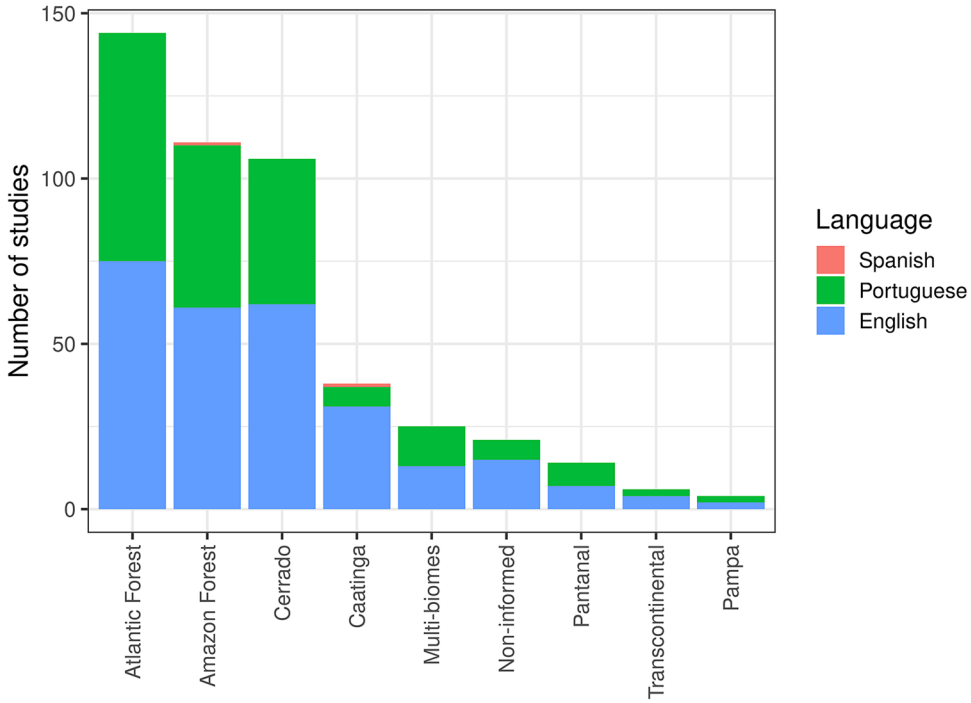

Fig. 4 Language used in papers on ant diversity in Brazilian Biomes from 1970 to 2020

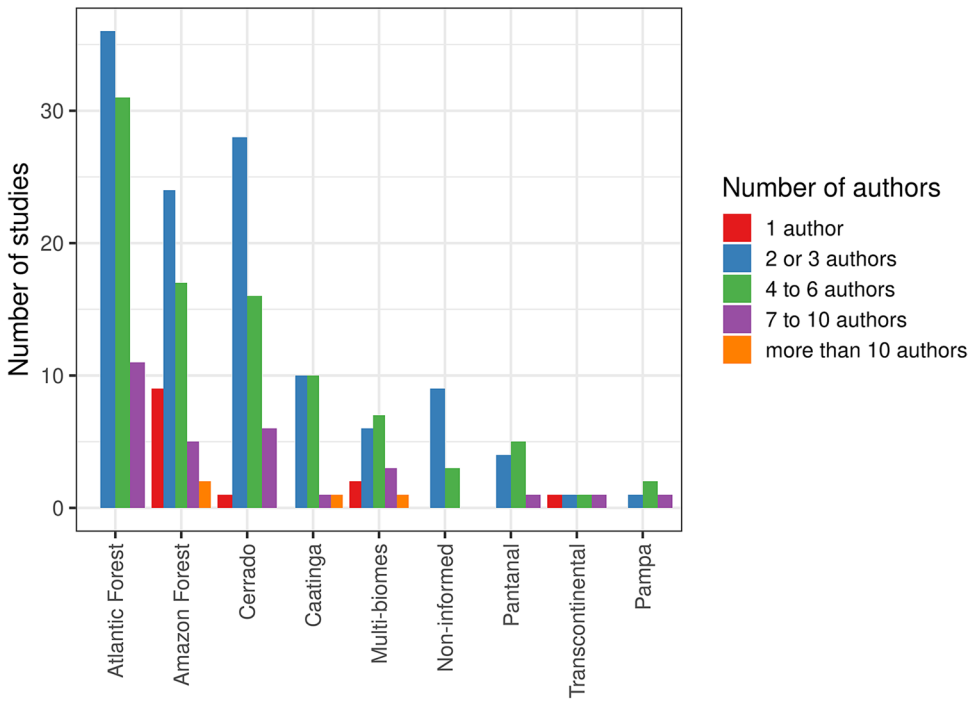

Fig. 5 Number of authors in papers on ant diversity in Brazilian Biomes from 1970 to 2020

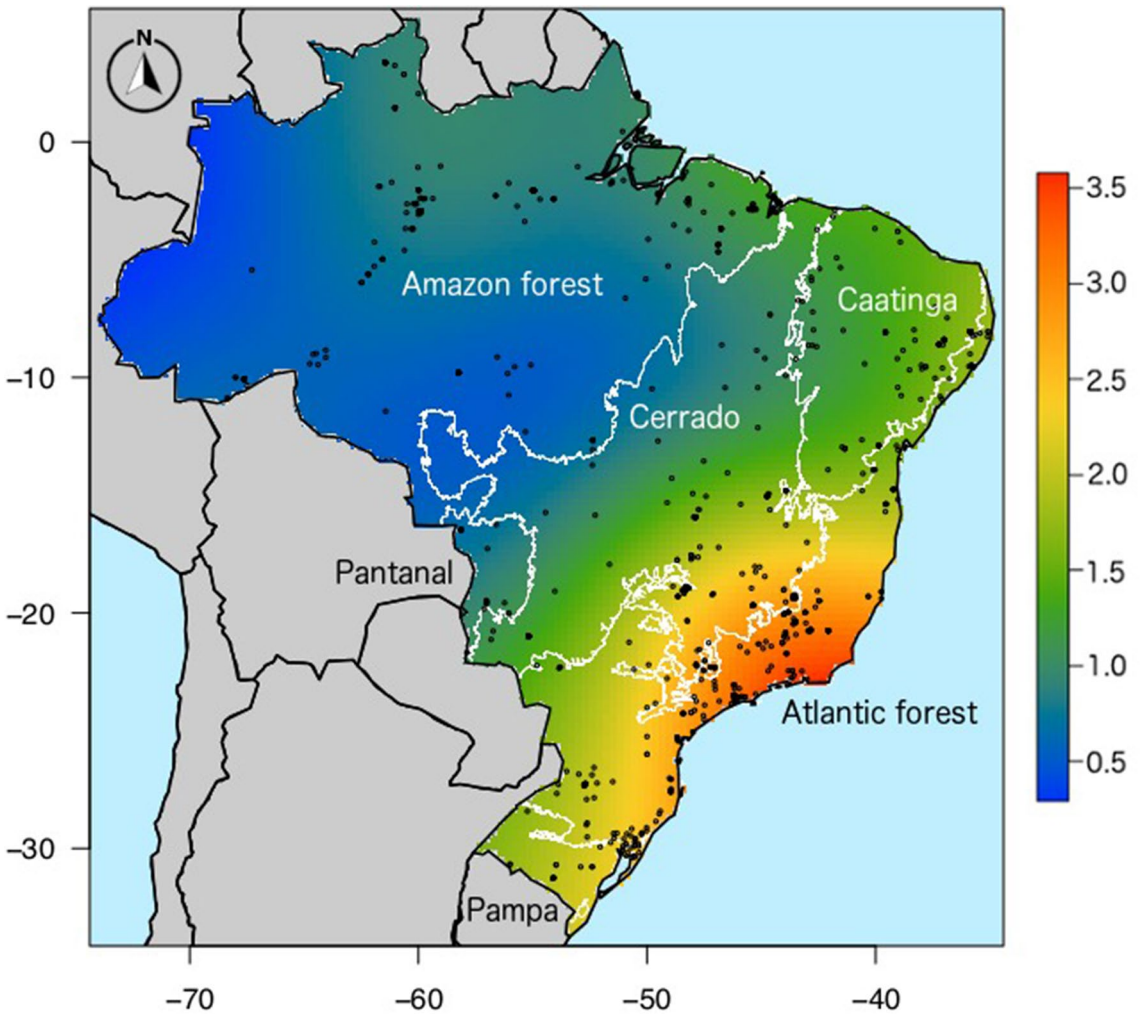

Fig. 6 Ant diversity study records throughout Brazilian biomes from 1970 to 2020. Kernel smoothing bandwidth was used to indicate the density of ant diversity studies, with warm colors in regions with high occurrence density

Geographical/methodological information

Geographical distribution of the studies Considering the density of ant sampling in the biomes, we can point out Atlantic Forest as the biome where most ant samplings have been carried out in Brazil (Fig. 6). However, the central portion of the Atlantic Forest presents a higher density of ant sampling than the northern and southern extremes. Cerrado presented a high density of ant samplings near the border with the Atlantic Forest; however, it also presented areas of medium and low densities of ant samplings in the central and northern regions, respectively. The remaining biomes presented medium (e.g., Pampa and Caatinga) and low densities of ant samplings (e.g., Amazon Forest and Pantanal).

Sampling seasons Ant sampling was carried out in all seasons (dry, rainy, or both) for all biomes/categories. However, most studies had samplings carried out in both seasons in almost all biomes/categories (Fig. 7).

Sampling techniques We accounted for 23 ant sampling techniques through all biomes/categories, which were classified into eight categories. In most biomes/categories, the three most employed sampling technique categories were pitfall traps, direct sampling, and attractive baits (Fig. 8). However, litter sampling and direct observation were also largely used in the Amazon Forest, Atlantic Forest, and Cerrado (Fig. 8).

Study types Most papers, 204 studies, reported ant assemblage diversity, followed by ant fauna surveys, 134; ant interaction, 87; ant sampling methods, 16; ant behavior, 15; ant community assembly rules, seven; and review papers, five. For the majority of biomes/categories, the main subject of the papers was ant assemblage diversity and fauna surveys (Fig. 9).

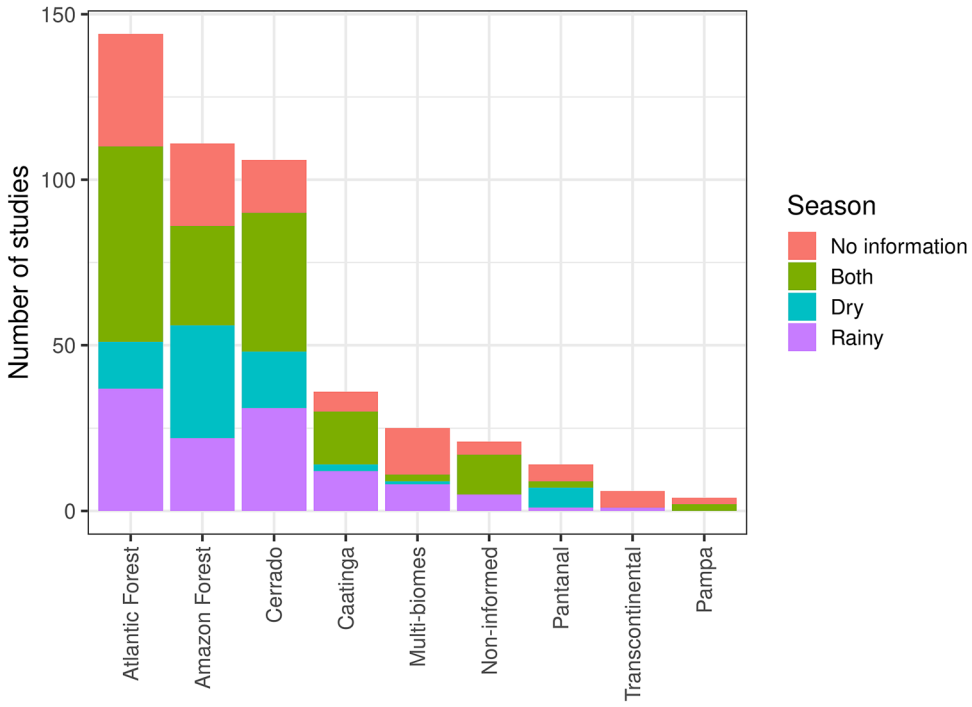

Fig. 7 Sampling season reported in papers on ant diversity in Brazilian Biomes from 1970 to 2020

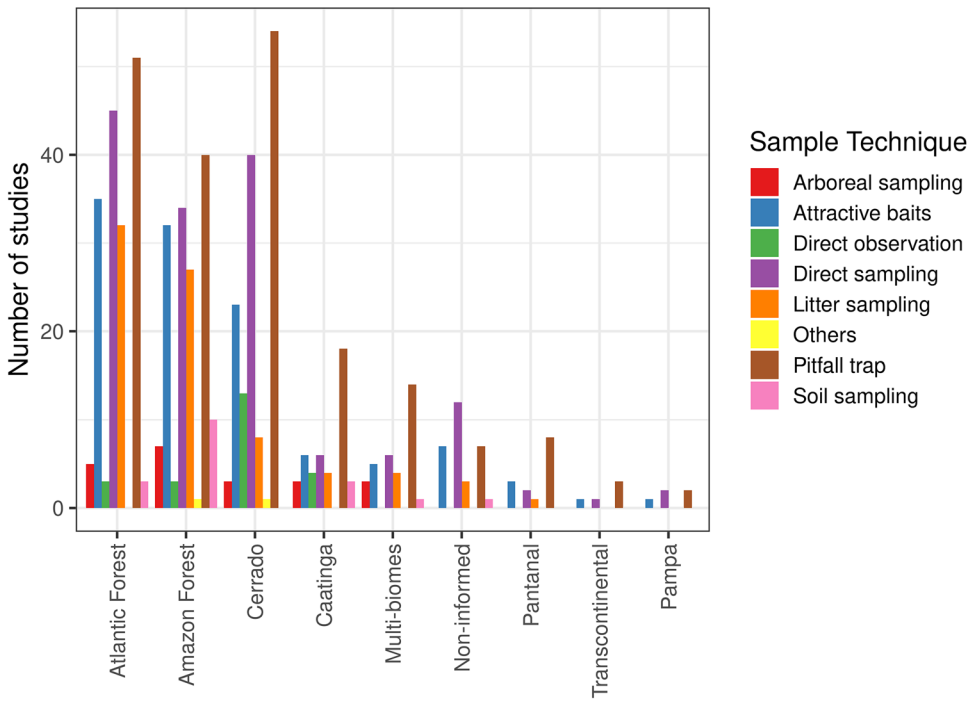

Fig. 8 Categories of sampling techniques reported in papers on ant diversity in Brazilian Biomes from 1970 to 2020

Discussion

This is the first description of historical trends and is an overview study on the ant diversity studies carried out in Brazil. Here, we first discussed the implications of ant diversity study profiles regarding the three sets of aspects considered: general, technical, and geographical/methodological. Second, considering that scientific publication is directly affected by social, economic, and policy factors, we also discuss the historical trends of these factors during the time range (1970–2020) and their possible influence on the publication of ant diversity papers. Finally, we provide suggestions for a more efficient use of time and financial

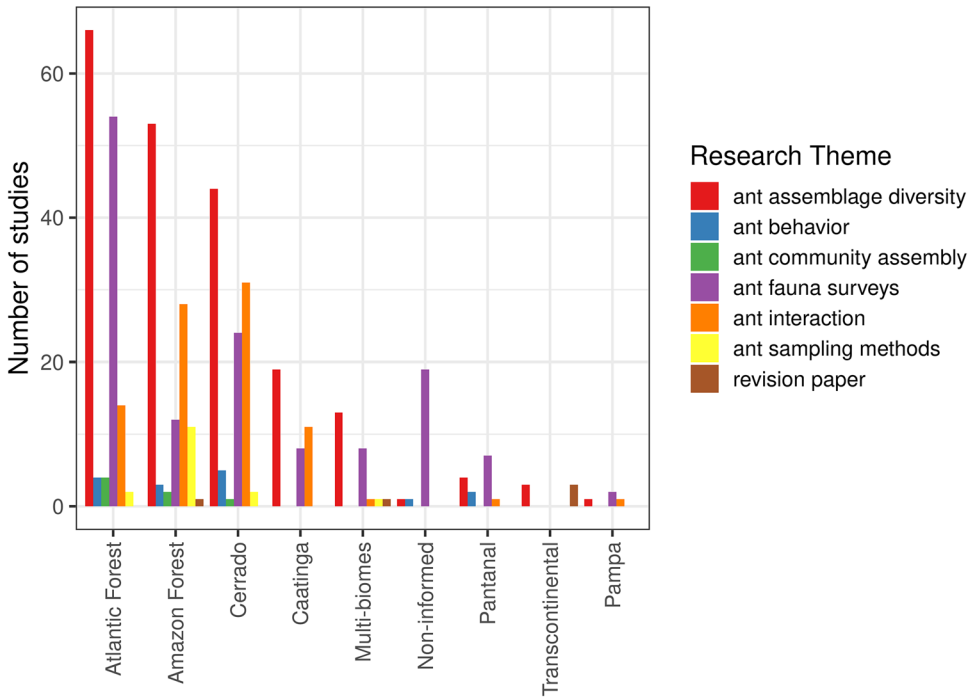

Fig. 9 Studies types reported in papers on ant diversity in Brazilian Biomes from 1970 to 2020

resources in the development of future research directions on ant diversity studies carried out in Brazil.

General aspects

Based on the total number of papers surveyed (468 papers) and the time range (50 years), we obtained a comprehensive sample of ant diversity studies carried out in Brazil. The findings of these studies are reported in a great number of journals, and many papers have been published in journals with large international audiences. Even considering that six of the top ten journals are based in Brazil, most of them are accessed by the international myrmecological community.

The relatively high number of papers published in local journals suggests that Brazilian's myrmecologists are more comfortable or confident to publish in those journals, though this strategy certainly reduces the access of international researchers to the content of the studies, especially if these articles are in Portuguese. An explanation could be the financial limitation of Brazilian researchers (Escobar 2015; Angelo 2019; Andrade 2019; Thomé and Haddad 2019) to carry on more comprehensive samplings in a continental country such Brazil. In fact, even the smaller Brazilian biomes are comparatively extensive when compared to similar ecosystems abroad. This financial limitation of Brazilian researchers could also hamper them to pay the high costs related to paper publication charge at international journals and English writing reviews usually requested. For comparison, the journal Nature, one of the most prestigious journals in the world, currently announced publications costs of €9500 for open-access papers, the equivalent of 27.4 months of salary for a Brazilian Ph.D. student. Additionally, there seems to be a recent movement for the valorization of national journals in Brazil, so that even high-impact articles written in English have been published in Brazilian periodicals.

According to the total number of papers, we identified Atlantic Forest, Amazon Forest, and Cerrado as highly studied biomes and Caatinga, Pampa, and Pantanal as poorly studied biomes. This should have a direct relation to the historical socioeconomic development of Brazil, which began in the southeastern coastal area and then moved toward to southern and northern coast and countryside in general (Marques et al. 2016). This trend has historically concentrated most of the first Brazilian universities, oldest biodiversity graduate courses, and ant researcher groups in coastal states. Moreover, the countryside of southeastern Brazil (mainly Minas Gerais state), which presents extensive areas of Atlantic Forest and Cerrado, also experienced an early and fast spreading of universities. Expressive biodiversity research centers, such as Instituto Nacional de Pesquisas da Amazônia in Manaus, Amazonas state, and Museu Paraense Emilio Goeldi in Belém, Pará state, played an important role in the position of the Amazon Forest among the highly studied biomes. The number of studies in the Amazon is highly aggregated around these research centers. Although Caatinga, Pampa, and Pantanal have also been the focus of biodiversity research, the establishment of groups focused on ant diversity is relatively recent when compared to those in southeastern Brazil and the major states of the northern

region, which could explain the small number of studies in these areas. Nevertheless, Pampa and Pantanal could achieve a higher number of papers if studies from neighboring South American countries that are also covered by these biomes were considered. However, by including studies for biomes shared with other countries, we would also artificially increase the number of studies of highly studied biomes (i.e., Amazon Forest, Atlantic Forest, and Cerrado).

Regarding the multi-biome studies, most papers reporting ant diversity in more than one biome have been carried out in biome transition sites, which demand similar financial funds and time efforts for ant diversity studies throughout all Brazilian biomes. The unique paper that reported ant diversity in all six Brazilian biomes (Castro et al. 2015) sampled ants in hospitals, which are predominantly exotic ant fauna adapted to urban sites and cannot be considered representative of the ant fauna of the Brazilian biomes. However, recently, Lasmar et al. (2021) filled this gap with a study on ant foraging activity throughout all six Brazilian biomes. Although many Brazilian myrmecologists have established partnerships with foreign ant researchers, a few Brazilian researchers have compared Brazilian ant diversity patterns with other regions in the world (e.g., Campos et al. 2011; Schmidt et al. 2017), which could explain the small number of papers classified as transcontinental. Although recent initiatives have improved the integration of South American myrmecologists (e.g., Hormigas Neotropicales initiative) (https://www.instagram.com/hormigasneotropicales/), we did not find papers reporting ant diversity studies throughout South America. Finally, the small number of papers (21) classified as "non-informed" regarding the sampled biome highlights that most Brazilian ant researchers have provided the information on the sampled biome as essential data in the study site description.

Publication technical data

We considered that papers reporting ant diversity studies in Brazil are at a medium–high-quality level related to impact factors. Even under historical financial crises, the financial support of Brazilian research agencies, such as Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES and Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq, as well as state research agencies has promoted an increase in the scientific contribution of local studies by allowing the expansion of the research designs in regard to spatial, temporal, and comparative scales. In addition, the financial support of Brazilian research agencies expanded the potential for collaboration between Brazilian and international researchers through initiatives that have promoted the training of Brazilian researchers visiting renewed and traditional institutions abroad and the establishment of broad research networks among groups from different regions of the globe. We highlight that 78% of Brazilian scientific publications on ant diversity were published in indexed journals, which demonstrates that myrmecologists in Brazil are concerned with the interests of the audience.

The great number of papers written in English indicates that ant diversity findings in English are probably a result of internships and collaboration with foreign researcher centers and personal investment by Brazilian ant researchers in English scientific writing and the increasing access to services for the translation/revision of scientific text in English. Nonetheless, appropriate English writing is an essential request for a clear understanding of international audiences. Based on our experience with publication processes, many manuscripts with Brazilian authors are asked to have the English writing reviewed by a native speaker. Moreover, the comments on English writing by referees usually lack a clear indication of the inconsistencies, which impairs proper addressing of the issues by the authors. The number of authors per paper shows that the researcher groups developing ant diversity studies in Brazil are abundant. Although we did not account for this, the authorship of most papers about Brazilian ant diversity is made up of ant researchers from different Brazilian and foreign institutions.

Geographical/methodological information

In all Brazilian biomes, ant sampling presented a highly aggregated distribution mainly near major centers of biodiversity research. The main reason for the high aggregation of ant samplings probably had its roots in historical financial limitations. These limitations are most evident in the Amazon Forest, where the costs (time and money) of accessing remote areas are very high (Magnusson et al. 2013), leading to a high number of sampling sites close to the capital cities of Manaus and Belém, where researchers can access representative sampling sites at low costs. In the Atlantic Forest and Cerrado, in addition to the cost limitations described above, the high levels of habitat loss, fragmentation, and degradation also contribute to the establishment of geographically limited and permanent sampling sites.

Additionally, most biodiversity research in Brazil comes from master and doctorate projects that have a limited time (usually 1–2 years) for sampling, species identification, and data analyses, which also contribute to the lack of sampling sites in remote areas of Brazilian biomes. Figure 6 allows us to visually identify the gaps in ant diversity studies throughout Brazilian biomes and suggests the most under-sampled or unknown areas that should be the focus of future research. However, our approach did not account for habitat loss. Therefore, models that incorporate both sampling density and habitat loss are preferable for identifying the highest priority areas for new ant surveys (Divieso et al. 2020).

The choice of sampling season seems to be related to the aims of the studies. Thus, if the main aim is an ant diversity survey, the rainy season with high humidity and temperature would be recommended in biomes with marked climatic seasonality, such as Caatinga, Cerrado, Pantanal, and countryside of Atlantic Forest. For the Amazon Forest and coastal Atlantic Forest that have low seasonality, ants can be sampled abundantly throughout the year (Levings 1983; Kaspari 2000). In the southern portion of Atlantic Forest and all Pampa, where rain is well distributed throughout the year, the seasonality of temperature is a primary driver of ant activity and should be considered in ant diversity surveys. However, for studies that aim to use the changes in diversity and ecological patterns to describe ant assemblages associated with different habitat types or under distinct levels of conservation, the sampling season has not been considered a drawback (Rabello et al. 2015), and in these cases, ant sampling was usually carried out in both sampling seasons.

The higher use of pitfall traps than other sampling techniques could be due to their convenience, low financial, and time costs (Souza et al. 2012; Brown and Matthews 2016) and flexibility in habitat installation (ranging from underground, ground, tree trunk, and canopy) (Bestelmeyer et al. 2000; Ribas et al. 2003; Schmidt and Solar 2010), which make it an appropriate technique to be used in studies that aim to compare ant diversity between sites. However, in total, 23 sampling techniques have been reported in ant diversity studies in Brazil, which shows, in our view, the concern of ant researchers in exploring all potential ant habitats to increase the chances of new species discovery and providing a better understanding of ant ecology.

The dominance of studies on ant diversity patterns and ant surveys could be attributed to their low cost (money and time); however, this hampers the development of studies that offer more intricate inferences on species interactions and community assembly. Most ant diversity studies are dedicated to describing the diversity patterns of ant assemblages, which could be due to ants promptly responding to environmental changes and, therefore, allowing researchers to make clear predictions about ant diversity patterns. In this way, in Brazil, several ant diversity studies have investigated the impact of human-induced disturbances on diversity patterns and used the results in a bioindication approach (Ribas et al. 2012).

Ant survey studies, the second most abundant ant diversity study type, aim to describe ant fauna at a specific location. We understand that to improve the relevance of this kind of study, the survey should be conducted at broader spatial scales, which could be not necessarily in an ecological context (e.g., biomes or part of them) but at political division levels (e.g., Brazilian states) (Leal 2002; Ulysséa et al. 2011; Diehl et al. 2014; Demétrio et al. 2017; Prado et al. 2019; Jory and Feitosa 2020; Schmidt et al. 2020). Many Brazilian states have more than one biome in their territory, and the provision of lists of ant species to them contributes to knowledge of local biodiversity and can be helpful to local researchers, especially students, in states that lack large reference collections or taxonomic working groups.

Ant interactions, the third most abundant ant diversity study type, are full of studies with elegant experimental designs allowing us to make inferences on the processes and patterns at play. The small number of papers on ant behavior, ant community assembly, ant sampling methods, and revision papers could be due to the difficulty of carrying out these studies (e.g., keeping ant nests in the laboratory or following ant interactions in the field for behavior research). In addition, there are other related issues, namely, the development level of ecology in Brazil (i.e., many diversity patterns have already been described for more than just ants, and dedicated efforts should be made to investigate the cause of these patterns with community assembly approaches, allowing better management of Brazilian biomes). The high diversity of sampling techniques and comparison of their efficiency (Bestelmeyer et al. 2000) make it a solved theme, although there is still space for novelties (Wong and Guenard 2017; Lopes et al. 2019). Finally, little attention has been given by ant researchers to the synthesis of several themes related to ant diversity, which are very desirable to describe what is already done and known and what needs to be filled (e.g., Ribas et al. 2012; Vasconcelos et al. 2017).

Connecting the development of ant diversity studies and the historical economic and social development of Brazil

From 1970 to 2020, Brazil experienced strong political changes (from military dictatorship to democracy reopening), several economic and political crises, and corruption scandals. In the middle of the 1990s, relative economic stability was achieved, allowing an expressive increase in Brazilian science—mainly in universities (Sguissardi 2006) in terms of both new doctorate degrees per year (15,650 doctors in 2016) and the publication of scientific articles in international journals (79,028 in 2010) (MCTIC 2017). Recently, from 2012 to 2016, Brazilian Science probably experienced the most exuberant time in terms of financial resources that, in addition to scholarships for students and grants to research projects, also had strong support for international exchange throughout the Science without Borders program. In this way, the Brazilian myrmecological community also experienced an incredible increase in the number of people working on ant diversity.

Despite these relevant advances, in the last 5 years, Brazil has struggled to keep its science programs due to frequent cuts to funding and student scholarships (Escobar

2015; Angelo 2019; Andrade 2019; Thomé and Haddad 2019) and financial resources to universities and researching institutions (Andes 2018). This is a major drawback to the individual wishes of young scientists, because there are no clear perspectives of permanent positions offered in the short–medium term, and consequently. All science fields have consequently experienced slow progress with limited people replacement and human capital flight. Specifically, losses in the biodiversity field will strongly hamper the spread of studies throughout Brazilian biomes. Additionally, withdrawal of environmental laws results in increased deforestation rates and biomes being destroyed by fires, and the disbelief in science by the Brazilian government and society in general are additional challenges (Barlow et al. 2019) which have made the conditions for the development of science in Brazil even more uncertain.

Although we present an expressive number of papers (see Fig. 1), we believe that it could be higher if the Brazilian government had applied more resources to science, mainly in the biodiversity field (basic research). Brazil currently invests only 1.2% of its gross domestic product in science and technology. The resulting drawbacks of research effort are manifested in all knowledge fields of Brazilian science, including ant research, as seen in Fig. 6 which shows that only a limited part of Brazilian territory has been contemplated by ant diversity studies. However, several efforts have been made to overcome these drawbacks, such as large ant surveys in the Amazon Forest (Vasconcelos et al. 2010), Atlantic Forest (Silva and Brandão 2010), "Cerrado" (Vasconcelos et al. 2018), and ant foraging ecology throughout all six Brazilian biomes (Lasmar et al. 2021). In recent years, several researchers have also developed vast ant surveys in different regions of Brazil and organized research networks with standard ant sampling protocols to cover all Brazilian biomes (Magnusson et al. 2013).

Conclusion and ant research needs

As an important direction for studies on Brazilian ant diversity, we recommend that researchers commit to publishing their findings in English, preferentially in well-evaluated international journals. Such a strategy could help disseminate the importance and quality of ant research in Brazil and strengthen collaborations with international research groups. This could be a way to compensate for the damage caused by the current policy for research funding in the country.

Regarding the sampling methods and the most appropriate seasons for ant surveys, Brazilian myrmecologists should follow the proposals of the great number of studies historically carried out in the different environments and biomes of Brazil. This scenario would allow for an increase in the comparison capacity between ecological patterns of Brazilian ecosystems under a comprehensive approach. In this scenario, ant researchers must keep in mind that the experimental designs applied must primarily consider the biological questions that their studies intend to answer, always based on the theoretical framework available and observing rigorous patterns of sampling standardization.

Thus, according to our results, it is noteworthy that a great part of the studies involving ant diversity in Brazil address biological questions related to diversity patterns and ant surveys. Such works have been extremely important for revealing the main diversity and taxonomic patterns in Brazilian ecosystems. Nevertheless, we could now direct our efforts to studies that aim to address the ecological drivers and processes that generate these patterns—the ant community assembly—thereby improving our ability to make predictions about the conservation and management of Brazilian natural areas and their impressive biodiversity.

Additionally, there is an urgent need to improve the area covered by ant diversity studies in Brazil due to the high levels of habitat loss, fragmentation, and degradation not only limited to Atlantic rainforest and "Cerrado" but also present in all biomes (Divieso et al. 2020). We propose three not excluding ways to approach this challenge: (1) increasing the number of ant diversity studies by projects directed to region gaps; (2) increasing ant diversity studies by the establishment of people and research centers in biodiversity gap regions; and (3) establishing research networks that provide datasets on ant diversity of Brazilian biomes.

The first approach would be somewhat like what occurred in the time of the first foreign naturalists of the XVIII and XIX centuries, when researchers from well-established research centers came to remote corners of the globe to carry out their studies (Vanzolini 1996; Kury 2001). Although this strategy should effectively contribute to improving the knowledge of biodiversity gaps, financial funding for this kind of initiative is very limited, which can seriously hamper field work campaigns. Additionally, most scientific agencies have been interested in financially supporting projects that promote the development of the local scientific capacity, which fit more with the goals of our second proposed approach.

Our second proposed approach seems to be a better method, because it is more locally oriented and based on the establishment of researchers and research groups in these places, which combines biodiversity knowledge with local development and empowerment of people's intellectual skills. Although academic-scientific regional development is more dependent on government political will than the actions of researchers, we (all myrmecologists) can provide a useful contribution to overcome the challenge of biodiversity knowledge in Brazil. A remarkably effective example is provided by the "Formigas do Brasil" workshop led by the first three authors, which is an 8-day course on systematic

ant ecology with each edition held in a different biome. Although not focused on only ants, the PPBio (Programa de Pesquisa sobre Biodiversidade—https://ppbio.inpa.gov.br) managed to install and maintain field infrastructure but also strengthened the local to regional research networks.

The establishment of research networks, the third approach, can be an efficient short–medium-term strategy in the short–medium term to overcome the financial restrictions of biodiversity research at broad spatial scales. Regarding ants, at least three initiatives have been recently developed in Brazil: (1) Ant-PELD; (2) Atlantic ants; and (3) Sinergyse. Ant-PELD is led by Rodrigo Feitosa and Marcio Pie, and this program carried out standard samplings throughout Brazilian Biomes with the support of myrmecologists that work in each biome. The Atlantic Ants project is led by Rogério R. Silva and involved the survey of all ant species records in the literature and collections. Sinergyse is led by Joice Ferreira and contains compiled datasets at the community level of several organisms in the Amazon Forest, in which ants are one of the focal groups. Additionally, collaboration among graduate programs (e.g., PROCAD-CAPES) usually involves the support of well-developed courses to a course in the initial stage or with difficulties in improving biodiversity knowledge and people's capacity for biodiversity research.

A further direction for future research is regarding the ant socio-biodiversity of Brazilian biomes; despite the high cultural and social diversity, there are few studies on the views of different social groups (e.g., urban, rural, and traditional communities) about ants, regarding their diversity and ecological functions. Studies regarding the knowledge of people about ants (ethnomyrmecology) are extremely useful, since people are in contact with ants in their daily routines and therefore have extensive expertise about ants in their natural habitat, such as where they live, what they feed on, and their behaviors; all of this information could be used for ant diversity conservation. People usually see ants as plagues or organisms that must be eliminated from the human habitat (and view) and do not recognize that ants bring more benefits than harm to the environment (Del Toro et al. 2012). The only way to change this misconception is to disseminate academic knowledge of ants to society. Therefore, to achieve our goals of popularizing ant science and making this valuable and useful for society, we should ask people about what they want to know, what they already know and the best way to exchange scientific knowledge and traditional knowledge.

Therefore, for the first time, we present historical trends of ant diversity studies in Brazil and indicated the critical issues to be solved, which we hope will help myrmecologists identify gaps in research fields and sites that must be better sampled to improve the knowledge of Brazilian ant diversity. Moreover, we believe that with efforts such as the "Formigas do Brasil" workshop, research network establishment, and the increasing positions in public universities and research institutions obtained by ant researchers, it would be possible to have a better picture of ant biodiversity in Brazil and effectively posit it as the largest world center of ant biodiversity studies. Finally, we propose that our study can be replicated in other world regions, allowing for a comprehensive view of studies on ant diversity at a global scale.

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