Revista Ibero-Americana de Ciências Ambientais
Ibero-American Journal of Environmental Sciences

Mai 2021 - v.12 - n.5

ISSN: **2179-6858**

This article is also available online at:
www.sustenere.co

Synthesis of the current state of ant knowledge in the Brazilian Amazon: a review

In light of the expansion of deforestation in the Amazon and its importance for the balance and maintenance of essential conditions for human well-being, research is required to serve as a basis for decision-making regarding the preservation and recovery of Amazonian ecosystems. Considering the difficulty of studying the entire biodiversity of an ecosystem, research has been focused on key groups that can provide reliable and effective ecological information. Among the several existing species that are effective for such studies, ants deserve special attention because of their great ecological importance regarding the performance of key functions, in addition to being sensitive to environmental changes. To synthesize the information available in the literature, this paper presents a bibliographic review of the articles published on ants in the Brazilian Amazon. A total of 177 articles that covered a period of 52 years were found, with a significant increase in publications since the 2000s. Noticeably, there were a large number of studies based in the states of Amazonas and Pará, mainly near the capitals, which emphasizes the need to significantly expand the research collection areas. Most articles were published in the area of ecology, mainly concerning ecological interactions. Despite the advances in studies concerning Amazonian ants, there is still a lack of standardization regarding the sampling methods. In addition, there is a lack of studies that address the functional diversity of this group, which limits our understanding of the ecosystem services that are being lost owing to anthropogenic activities in natural ecosystems.

Keywords: Biodiversity; Insects; Taxonomic indicators; Tropical forest.

Síntese do estado atual do conhecimento das formigas na Amazônia brasileira: uma revisão

Diante da expansão do desmatamento na Amazônia e sua importância para o equilíbrio e manutenção das condições essenciais ao bem-estar humano, a pesquisa se faz necessária como base para a tomada de decisões quanto à preservação e recuperação dos ecossistemas amazônicos. Considerando a dificuldade de estudar toda a biodiversidade de um ecossistema, a pesquisa tem se concentrado em grupos-chave que podem fornecer informações ecológicas confiáveis e eficazes. Dentre as várias espécies existentes que são eficazes para tais estudos, as formigas merecem atenção especial devido à sua grande importância ecológica no desempenho de funções essenciais, além de serem sensíveis às mudanças ambientais. Para sintetizar as informações disponíveis na literatura, este trabalho apresenta uma revisão bibliográfica dos artigos publicados sobre formigas na Amazônia brasileira. Foram encontrados 177 artigos que abrangiam um período de 52 anos, com aumento significativo de publicações a partir da década de 2000. Visivelmente, houve um grande número de estudos baseados nos estados do Amazonas e Pará, principalmente no entorno das capitais, o que enfatiza a necessidade de ampliação significativa das áreas de coleta de pesquisas. A maioria dos artigos foi publicada na área de ecologia, principalmente no que diz respeito às interações ecológicas. Apesar dos avanços nos estudos com formigas amazônicas, ainda falta padronização quanto aos métodos de amostragem. Além disso, faltam estudos que abordem a diversidade funcional desse grupo, o que limita nosso entendimento sobre os serviços ecossistêmicos que estão sendo perdidos devido às atividades antrópicas nos ecossistemas naturais.

Palavras-chave: Biodiversidade; Insetos; Indicadores taxonômicos; Floresta tropical.

Topic: **Conservação da Biodiversidade**

Reviewed anonymously in the process of blind peer.

Received: **09/04/2021**
Approved: **08/05/2021**

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DOI: 10.6008/CBPC2179-6858.2021.005.0015

Referencing this:
SILVA, W. B.; CAJAIBA, R. L.; SILVA, W. B.; PÉRICO, E.. Synthesis of the current state of ant knowledge in the Brazilian Amazon: a review. **Revista Ibero Americana de Ciências Ambientais**, v.12, n.5, p.167-179, 2021. DOI: http://doi.org/10.6008/CBPC2179-6858.2021.005.0015

INTRODUCTION

The Brazilian Legal Amazon (from here on referred to as the Amazon) constitutes over 60% of the national territory (LIMA et al., 2011), and is renowned worldwide for its high biodiversity and mineral resources (VASCONCELOS et al., 2012; ASSUNÇÃO et al., 2015; MELLO, 2015). In addition, the Amazon performs various ecosystem services at local, regional, and global levels (NUNES et al., 2015), such as carbon sequestration, the regulation of climatic conditions, and the maintenance of freshwater supply (DAVIDSON et al., 2012; AYALA et al., 2016; CASTRO et al., 2016; CAJAIBA et al., 2017).

Despite the international recognition of its importance, the Amazon has suffered the severe degradation of its primary forests over the years (FEARNSIDE, 2006; COPERTINO et al., 2019). In addition, the projections for future forest degradation are not optimistic (BARBER et al., 2014). Data from the National Institute for Space Research (INPE) reveal that deforestation in the Amazon increased by over 34% between July 2018 and August 2019, with deforestation rates being led by the states of Pará, Mato Grosso, Amazonas, and Rondônia, which account for 84.56% of the accumulated deforestation that has been recorded in the Amazon so far (INPE, 2020).

Deforestation in the Amazon is the result of pressure from local and economic development, in which forests are replaced by productive land, aiming to serve the domestic and foreign markets (SILVA et al., 2017; SILVA et al., 2019). There are several, often interrelated, contributors to the increase in deforestation. Among the main causes is the implantation of pasture, mainly for cattle raising (CASTELO et al., 2018). Today, Brazil is one of the largest producers of cattle worldwide, much of which is produced in the Amazon (SILVA et al., 2020). Furthermore, the second largest factor contributing to deforestation in the Amazon is agricultural activities, including both family farming, using small and recurring openings in the forests (SOARES et al., 2018; SOTTA et al., 2019), well as large mechanized productions, such as soy (BARONA et al., 2010; KASTENS et al., 2017; SILVA et al., 2017). In addition, anthropogenic activities, such as mining (SONTER et al., 2017), forest fires (LIMA et al., 2020), and hydroelectric plant installations (EMER et al., 2013), have also contributed considerably to Amazonian deforestation. In addition, the wood industry (mostly illegal), which is considered a strong factor contributing towards forest degradation, exerts great pressure on indigenous territories, private properties, and conservation units (MELLO et al., 2017; CELENTANO et al., 2018).

Studies have demonstrated that the conservation of the Amazon and the preservation of its biodiversity are real and challenging concerns, considering that the functioning of the Amazon is fundamental for the balance of essential conditions for human well-being (GARDNER et al., 2013; CAJAIBA et al., 2018). Despite the growing interest in the maintenance of tropical forests, the real conditions of degradation and the subsequent effects on biodiversity as well as ecological functions are still unknown or limited in many regions (MORRIS, 2010; SOLAR et al., 2016; SPILLER et al., 2018). This reinforces the need for studies that carefully analyze the environmental contributions of different landscapes towards the conservation of biodiversity (APOLINÁRIO et al., 2019), which can then be used to estimate the consequences of human actions regarding the loss of ecosystem services (DEL TORO et al., 2012; LIMA et

al., 2015; TIBCHERANI et al., 2018). Furthermore, this can be used to develop an effective means for restoring deteriorated ecosystems to reestablish the provision of essential ecological services (LAWES et al., 2017).

In this context, studies with key groups are essential for understanding various issues, such as behaviors, ecological relationships, the provision of ecosystem services, patterns of biodiversity (such as richness, species abundance and distribution, death rate, growth, characteristics, and genetic variation), and responses to environmental changes, which can serve as a reference to estimate the degree of conservation or degradation of a given environment (KEMERICH et al., 2014; LIMA et al., 2015). Cortef et al. (1999) and Scott et al. (2006) highlighted characteristics that make certain groups of organisms ecologically effective for studies, including playing an important role in the ecosystem, having a wide distribution, being easy to sample, having a low financial cost, presenting a measurable response to environmental changes, able to reproduce in captivity, and easy to study in situ and in laboratories. In this sense, many groups of animals have been used as a basis for decision making, whether for the recovery of degraded areas or forms of sustainable use (EMER et al., 2013; SEMPRUC et al., 2015; CAJAIBA et al., 2017; BELÉM et al., 2020).

Several studies have demonstrated the importance of incorporating invertebrates in environmental quality investigations (JEREZ-VALLE et al., 2014; CAJAIBA et al., 2017; SPILLER et al., 2018). Among them, ants deserve special attention because of their ecological importance regarding the performance of key functions, such as seed dispersal, herbivory, pollination, nutrient cycling, and soil quality maintenance (DEL TORO, 2012; VICENTE et al., 2016). In addition, ants are potential ecological indicators due to various characteristics, including a high abundance and species richness. Furthermore, specialized taxa are useful for conservation and environmental impact assessments (APOLINÁRIO et al., 2019) as they are ubiquitous (SCHMID et al., 2005; BHARTI et al., 2016), occupy the most varied levels of habitats (from the treetops to the subsoil) (UNDERWOOD et al., 2006; LACAU et al., 2008), and are sensitive to environmental changes (SCHMIDT et al., 2013).

Despite the importance of and countless studies involving this group, there is still a lack of research involving reviews of studies on ants in specific biomes (TIBCHERANI et al., 2018). Therefore, this review aims to create a bibliographic survey of studies on ants in the Brazilian Amazon, to identify: i) general and comprehensive information regarding the publications of scientific articles on ants in the Brazilian Amazon, such as the number of publications, main focuses of studies, and regions/states in the Amazon where the largest amount of research is concentrated, ii) possible knowledge gaps, that is, which aspects of ants in the Amazon still require further study, and iii) the main ecological responses that ants have presented following environmental changes in the Amazon biome.

METHODOLOGY

During April 2020, a consultation was carried out using popular databases, including Google Scholar, Science Direct, Scielo, Web of Science, and Scopus, without restrictions on the date of publication.

The following terms in English and Portuguese were used for the search: "Ants AND Amazon/Formiga AND Amazônia", "Formicidae AND Amazon/Formicidae AND Amazônia", and "Hymenoptera AND Amazon/Hymenoptera AND Amazônia". To achieve the greatest possible number of articles, and considering that the name of the biome in which the study was carried out is not always present in the title, keywords, or summary, we also carried out consultations using the names of the states that are entirely or partially within the Amazon biome and, with that, we also used the terms: "Ants AND *n*", "Formigas AND *n*", "Formicidae AND *n*", and "Hymenoptera AND *n*", where n represents the states of the Brazilian Legal Amazon (Amapá, Roraima, Acre, Amazonas, Rondônia, Mato Grosso, Maranhão, Pará, and Tocantins).

Then, all articles found during the search were screened by reading the title, summary, and materials and methods, discarding any that did not fit the proposed objective. For this research, we only used articles published in journals, and so monographic works, abstracts of congresses, symposia, theses, and dissertations were excluded. We also discarded works that, despite covering ants, did not have them as the main focus of the study (e.g., surveys on soil macrofauna or anthropogenic impacts on the composition of soil invertebrates), with the justification that the collection method used may not have been the most suitable for collecting ants (SANABRIA et al., 2014).

Data analysis was based on scientometric methods. Therefore, information was extracted from the selected articles, such as: i) year of publication; ii) knowledge area, following the CAPES knowledge area table, which includes: ecology (e.g., general ecology, bioindication, ecological interaction, or sampling method testing), zoology (e.g., taxonomy or forensic entomology), agricultural sciences (e.g., pest control), and genetics (e.g., genes); iii) state in which the research was carried out; iv) collection method (e.g., manual, trap, or bait); v) type of bait; and vi) type of habitat studied (e.g., primary forest, secondary forest, pasture, or monoculture).

RESULTS AND DISCUSSION

The research resulted in the analysis of 177 articles, conducted over a period of 52 years, with publication dates ranging from 1967 to 2020 (Figure 1). Although the first articles on ants in the Amazon were published in the 1960s, there was a growing interest in studying this group from the 2000s onwards. Of the 177 articles evaluated, only 37 were published in the first 32 years (1967-1999, an average of 1.2 articles per year), while the remaining 140 were published in the last 20 years (average of 6.6 articles per year) (Figure 1). This increase in studies may reflect the great advances that have occurred concerning scientific studies in Brazil (LETA, 2011; TEODORO et al., 2020).

Del Toro et al. (2012), who conducted a review survey concerning the ecosystem services provided by these invertebrates, also highlighted considerable growth over the years. These results are understandable considering that ants are key organisms in ecosystems, performing a variety of ecological functions that are fundamental for good ecosystem functioning (SCHMIDT et al., 2017; RABELLO et al., 2018), making the study of ant ecology important and necessary. In addition, other factors may have contributed to the increase in the studies of ants in the Amazon, including their use as a tool for

environmental monitoring, which is possible due to their sensitive and rapid responses to environmental changes (BILCE et al., 2011; FERNANDES et al., 2018). Furthermore, ants are one of the most important biological components of the Amazon rainforest, composing a significant part of the animal biomass (DEL TORO et al., 2012; BACCARO et al., 2013).

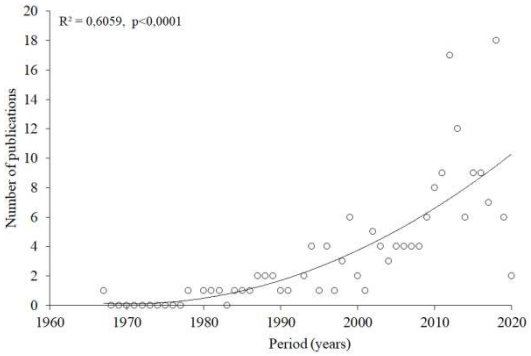

Figure 1: Number of articles published on ants in the Brazilian Amazon per year, with a significant increase since the 2000s. The figure shows a polynomial regression with $R^2 = 0.61$

As for the main areas of knowledge, 76.84% of the studies examined aimed to study ants in the context of ecological aspects, followed by zoology (18.08%), agricultural sciences (3.39%), and genetics (1.69%). These results show that researchers have a great interest in the ecology of ants in the Brazilian Amazon, mainly concerning ecological interactions (both ant/plant interactions as well as ant/animal interactions) and variation in the ant community (richness, diversity, and species composition) in habitats with different environmental characteristics. The greater number of articles published in the area of ecology can be justified by the fact that it is a very comprehensive area of knowledge, which is divided into several other sub-areas, giving rise to a range of issues that can be studied (OLIVEIRA et al., 2020). Among these sub-areas of ecology, biodiversity and the relationship between organisms and the environment (NICHOLS et al., 2007; GUILHERME et al., 2019) are some of the main focuses of studies carried out in the Brazilian Amazon.

Most articles were published in international journals (58.76%). Of the articles published in national magazines, 79.10% were published in English, 19.77% in Portuguese, and 1.13% in Spanish. The publication of articles in English enables an international scope, which allows for a larger number of readers, in addition to favoring the internationalization of Brazilian research (RIBAS et al., 2012), with greater chances for citations when compared with articles in Portuguese or Spanish (ANTUNES, 2015; DI BITETTI et al., 2017).

When analyzing the number of articles published per state, Amazonas presented the largest number of studies on ants (45.20%), followed by Pará (22.60%), while Tocantins presented the lowest number of studies (1.13%) (Figure 2). This can be explained by at least two hypotheses. First, this is likely impacted by the territorial size of these states, considering that Amazonas and Pará are the first and second-largest states in Brazil, respectively (SOMAIN, 2017; IBGE, 2020). In addition, 100% of the territory of these states is within the Amazon biome, while only 9% of the territory of Tocantins is within the biome (IBGE, 2020). Second, the states of Amazonas and Pará host the oldest and most important research centers in the Amazon region. The state of Amazonas has the National Institute for Research in the Amazon

(INPA), headquartered in Manaus, while the state of Pará has the Museu Paraense Emílio Goeldi, based in the city of Belém. Both institutions aim to study the Amazon biome by rely on the collaboration of researchers and partnerships with national and international institutions (PANZU et al., 2015; LOVEJOY, 2019). In addition, the greater or lesser number of studies in a given region can be determined by various factors, such as the number of researchers, the availability of financial resources, the feasibility of access to areas with the desired characteristics, and the feasibility of sampling the areas (TIBCHERANI et al., 2018).

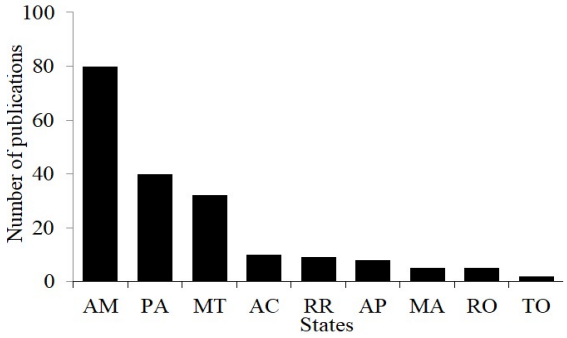

Figure 2: Number of articles published by states in the Brazilian Amazon during the period from 1967 to 2020. AM (Amazonas), PA (Pará), MT (Mato Grosso), AC (Acre), RR (Roraima), AP (Amapá), MA (Maranhão), RO (Rondônia) and TO (Tocantins).

Regarding the main habitats that were studied, research was predominately conducted in primary forests (52.54%), followed by monoculture (17.51%) and secondary forest (16.59%) (Table 1). This shows that there is still a lack of studies on ants in this biome, mainly in environments modified by human activities. Furthermore, there is a lack of studies concerning the impacts of changes on the ant community and, consequently, the functioning of the ecosystem. This is highlighted by the fact that habitats that are the most strongly associated with deforestation in the Amazon (PONTES et al., 2016; SPILLER et al., 2018), such as pasture and monoculture, were studied in only 4.52% and 17.51% of the articles examined in this research, respectively. Fernandes et al. (2018) highlighted that, considering the increasing changes in the Amazon rainforest landscape resulting from variations in land uses, it is essential to concentrate efforts on areas of human interest and the monitoring of the changes and subsequent impacts on biodiversity.

Table 1: Relative frequency of studies by habitats carried out in the Brazilian Amazon in the period from 1967 to 2020.

Studied habitat	**Relative Frequency (%)**
Primary forest/preserved	52,54%
Monoculture	17,51%
Secondary forest	16, 59%
Forest fragment	14,12%
Pasture	4,52%
Urban area	2,26%
Forest management area	2,26%
Area affected by hydroelectric	2,26%
Agroforestry	2,82%
Burnt/fire area	1,69%
Hospital environment	1,69%
Others	1,13%

Regarding the collection method, no ants were collected in 25.99% of the analyzed studies, this was because these studies were based only on observations and/or experiments in situ. Of the 131 publications that collected ants, 81.68% used only one sampling methodology, while 18.32% used more than one

method. Among the methodologies used to capture ants, the most frequently adopted was active manual collection (31.64%), followed by pitfall traps (22.60%, of which 10% used bait) (Figure 3) and bait (15.82%, on paper, plastic, or disposable plates). Souza et al. (2012) indicated that the bait used varies according to the ants' eating habits, which was very evident from the results of this study, where thirteen types of bait were highlighted (sardines, honey, biscuit, honey cake, pork carcass, banana, guava, peanut cream, cassava flour, sugar, beef liver, cheese, and tuna). Of the identified types of bait, the most frequently used were sardines and bee honey, which comprised 57% and 12.2% of the articles that used bait, respectively.

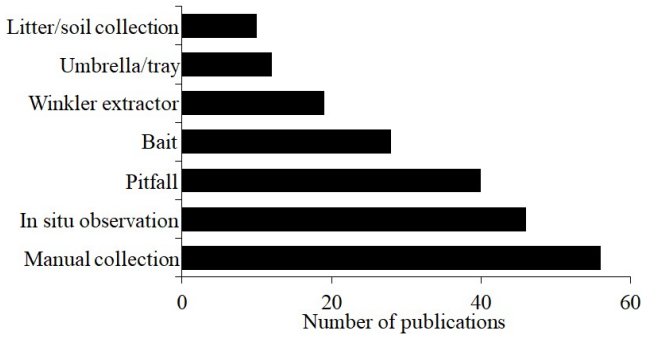

Figure 3: Methods for collecting ants according to the articles published in the Brazilian Amazon from 1967 to 2020.

Manual active collection was the most frequently used method because of the large number of articles focused on ecological interactions. This method is particularly useful when studying the interactions between ants and plants, where capture is carried out via the identification and visualization of the target to collect qualitative and non-quantitative data (ALBUQUERQUE et al., 2009). However, this method requires a great deal of effort and qualified labor, and the results greatly depend upon the skill of the researcher (TEXEIRA, 2012). The use of pitfall traps is widely used in arthropod collections, mainly in ecological fauna surveys, and is effective for collecting ants in the Amazon (SOUZA et al., 2018). Souza et al. (2012), who compared three different methods for collecting ants, concluded that the use of combined techniques (manual and pitfall) obtains a greater species richness. However, when considering each isolated method, the pitfall trap was considered the most effective technique for estimating the richness of ant species in the Amazon in different environments and vegetation types (dense forest, forest in transition, and open environments), as it presented the greatest species richness. Furthermore, in relation to the use of combined techniques or other isolated methods, pitfall traps are economical regarding time and money.

Ant responses to different soil uses in the Brazilian Amazon

Through our review, we detected several studies that were conducted in the Brazilian Amazon showing that ants respond negatively to anthropogenic pressures. Oliveira et al. (2009), Falcão et al. (2015), Solar et al. (2016) and Oliveira et al., (2019) showed significant differences regarding the species richness and composition between forest habitats and disturbed areas (pasture, forestry, or agriculture), with a lower species richness in modified environments. Similar results were also obtained from an analysis of the consequences of forest fragmentation on the ant community, demonstrating that territorial decreases in

and isolation of forests can reflect a decrease in the species richness (VASCONCELOS et al., 2006; EMER et al., 2013). It was also found that the frequent burning of forests can negatively affect the richness and diversity of ant species, especially those that inhabit litter and are directly affected by habitat loss, including nesting sites (SANTOS et al., 2008; PAOLUCCI et al., 2016). These results support the hypothesis that less heterogeneous environments with a lower structural diversity (e.g., degraded environments) have a reduced amount of available habitats and food, in addition to being more susceptible to seasonal variations and, therefore, increases in intra- and interspecific competition (OLIVEIRA et al., 2009; BILCE et al., 2011; SOLAR et al., 2016).

On the other hand, forest succession (secondary forests) supports the recolonization of ant communities. Triana et al. (2019), when analyzing the ant community at four levels of forest succession in the Amazon, noticed that there was a significant difference concerning the species richness and frequency between the levels, with a greater richness and frequency observed in the forests with more advanced succession. From this, the authors concluded that the greater the degree of forest succession, the greater the abundance and richness of species. Solar et al. (2016) recognized that primary forests are richer in species compared to non-forest environments, such as pastures and monocultures. However, the recovery of ant diversity in modified forests is not fully understood, even in secondary forests with more advanced stages. One factor that influences the recovery of ant communities in secondary forests is the land use history, since areas that have experienced more intense uses, such as pastures, may take longer to recover than areas abandoned after use for agriculture or selective logging (VASCONCELOS, 1999; HARADA et al., 2013). In addition, the modification of the landscape may cause a reduction in ant-plant interactions via the local co-extinction of plants and mutualistic ants, giving rise to the invasion of opportunistic ants, thus differentiating the ant fauna from disturbed or fragmented forests from undisturbed forests (EMER et al., 2013).

Future challenges and final considerations

Despite the recent increase in the number of studies on ants in the Brazilian Amazon, research is still in the embryonic stages, since most studies have been conducted close to the state capitals. It is worth noting that the concentration of collection sites, usually around where there are large research centers, also impacts the red lists of states, given that the extinction of a local population of a species can move the conservation status of the species on the list. However, in some cases, this may reflect the lack of geographical coverage of the studies (KEUROGHLIAN et al., 2012). Although the logistics required for the monitoring of remote areas is complex and costly, studies that address the ecological responses of ants to anthropogenic impacts are still required, especially at larger spatial scales and with longer collection periods (VICENTE et al., 2016; CHAVES et al., 2018), which would favor more robust conclusions.

In addition, it is necessary to apply standardized protocols for ant collections, since different collection methodologies make it difficult to compare the results obtained in different studies, leading to erroneous results and, eventually, to erroneous decisions (SILVEIRA et al., 2010; SCHACHAT et al., 2018).

Thus, more consistent studies in the areas of environmental monitoring and evaluation are required to improve our understanding of the relationship between ants and the environment, to better utilize their function as ecological indicators (MIRANDA et al., 2019; PRINGLE et al., 2019).

In future studies, we suggest that the use of functional diversity and functional characteristics be addressed. Functional diversity, which combines biological diversity and ecosystem functioning (MOUCHET et al., 2010; MUMME et al., 2015), has been increasingly used to assess anthropogenic disorders and restoration programs in different parts of the world (CADOTTE et al., 2011; MONTOYA et al., 2012; CAJAIBA et al., 2020). Thus, the use of the functional approach in future studies is justified by the growing evidence that it is a better predictor of ecosystem processes than taxonomic diversity (DE BELLO et al., 2010; CLARK et al., 2012; GAGIC et al., 2015). This is likely because not all species contribute equally to all functions, that is, the relationship between taxonomic and functional diversity is not predictable or linear (CAJAIBA et al., 2020). Environmental complexity prompts significant variations in the functional diversity of the ant community, through variations in different ant characteristics, such as body size, jaw length, eye size, body biomass, and food guilds. These characteristics provide information concerning the adaptations of foraging strategies in response to environmental variables (GUILHERME et al., 2019). Despite the importance of using functional diversity, only 2.26% of the articles found in our study used this approach (see: GUILHERME et al., 2019; PRINGLE, 2019; MENEZES et al., 2020). Thus, the use of taxonomic diversity should be complemented with functional diversity to better understand ecosystem processes in regions of high biodiversity, such as the Amazon.

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