

Major biases and knowledge gaps on fragmentation research in Brazil: Implications for conservation



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ABSTRACT

Habitat loss and fragmentation are among the main threats to global biodiversity and ecosystem services. However, major research biases and knowledge shortfalls in some geographical regions, taxonomic groups and responses studied are recurrent in fragmentation-related research. Therefore, detecting these biases and associated gaps is crucial to steer future research efforts and to guide applicable conservation policies. Here we conducted an exhaustive literature review to evaluate biases on fragmentation research across biomes, taxonomic groups, species responses and fragmentation metrics in Brazil. Overall, we analysed 716 papers, comprising a database with 26 taxonomic groups and 1173 cases studied across the six Brazilian biomes. In general, we observed that fragmentation-related research was biogeographically biased towards forest biomes. Specifically, the Atlantic Forest, the most populated and deforested Brazilian biome, comprised the highest number of studies (63%), while non-forest biomes were largely underrepresented. We also detected a high positive relative taxonomic bias for birds and mammals, while many insect taxa were disproportionately underrepresented in the literature. Altogether, assemblage-level species responses (abundance, diversity and richness) comprised 72% of study cases. Moreover, fragment size was clearly the most considered metric in the studies (43%) followed by habitat quality and edge effects. Our findings indicate major information deficits with regard to fragmentation-related research among taxonomic groups and amongst biomes in a megadiverse country. Therefore, we suggest that fragmentation research conducted in Brazil needs to consider undersampled taxa and to be urgently extended to increasingly degraded non-forest biomes in order to avoid inappropriate inferences.

1. Introduction

Anthropogenic actions have profoundly altered natural landscapes worldwide, and habitat loss and fragmentation are a consistent by-product of the conversion of pristine habitats (Haddad et al., 2015). Such alterations have long been proposed as relevant causes of declining biodiversity and ecosystem services worldwide (e.g., Harrison and Bruna, 1999; Hanski, 2015; Betts et al., 2017). The total reduction of habitat and the extent of fragmentation, which are often concurrent processes (Fahrig, 2003; Tscharntke et al., 2012; Hanski, 2015), not only affect distribution and persistence of populations, but also species' behavioral and functional conditions, genetic variation and ecological interactions (e.g., Crooks, 2002; Cushman, 2006; Magrath et al., 2014;

Jackson and Fahrig, 2016). Although it is widely recognized that habitat loss (reduction in the suitable habitat area in the landscape over time) negatively affects biodiversity, the relative importance of negative versus positive effects caused by fragmentation per se (disruption in the continuity of habitat into disconnected smaller patches) remains controversial (see Fahrig, 2003, 2017 and Fletcher et al., 2018 for opposite views). Despite the growing body of studies on both habitat loss and fragmentation during the last decades, there are major research biases and knowledge gaps (e.g., Deikumah et al., 2014).

Research biases result in unequal distribution of biological surveys and deficient knowledge, which may ultimately have significant consequences for conservation policies and actions (Nelson et al., 1990; Clark and May, 2002; Ribeiro et al., 2016). There are several kinds of

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biases in the scientific literature, particularly taxonomical and biogeographical ones. Taxonomic bias is common in a wide range of biological disciplines, limiting our knowledge of biodiversity (Clark and May, 2002; Bini et al., 2006; Mokany and Ferrier, 2011). Biogeographic bias results in areas, countries or ecosystems neglected or poorly considered in studies, and is particularly evident in developing regions with limited research funding, large countries wherein population and research institutions are unevenly distributed, and extensive tropical rainforests with restricted access routes (e.g., Moerman and Estabrook, 2006; Deikumah et al., 2014; Oliveira et al., 2016). Additionally, global-scale reviews related to habitat loss and fragmentation have exclusively focused on forest biomes (Deikumah et al., 2014; Magrach et al., 2014), neglecting non-forest biomes such as grasslands, savannas or shrublands. Forest-biased research is a common pattern in ecology (Parr et al., 2014; Veldman et al., 2015), although some of the world's biodiversity hotspots are non-forest ecosystems that have been historically altered and threatened by anthropogenic activities (Myers et al., 2000; Thompson, 2005; Overbeck et al., 2015). Moreover, the effects of habitat loss and fragmentation on biodiversity vary both amongst ecosystems (e.g., Bond and Parr, 2010) and among species within ecosystems (e.g., Harrison and Bruna, 1999). Therefore, identifying taxonomic and biogeographic biases, particularly between forest and non-forest biomes in fragmentation research, becomes a relevant issue.

Likewise, assemblage-level species responses (e.g., richness, abundance, diversity) are frequently considered in studies analyzing the effects of habitat loss and fragmentation (Ellis et al., 2011; Deikumah et al., 2014). Conversely, responses related to ecological interactions (e.g., herbivory, predation, seed dispersal), specific (e.g., functional traits) and individual conditions (e.g., reproduction), and genetic diversity (e.g., heterozygosity, allelic richness) are generally neglected, but these may also clarify how habitat loss and fragmentation affect biotic communities, even when species' composition and distribution are unaltered (Ewers and Didham, 2006; Haddad et al., 2015; Wilson et al., 2016). Lastly, fragmentation metrics, i.e., the predictor variables that have been used to explain these response variables, are multiple and can be measured at landscape-, fragment- or other hierarchical levels (Fahrig, 2003; McGarigal, 2015). Some fragmentation metrics (e.g., fragment size, connectivity, edge effects) have been frequently studied whereas others (e.g., matrix quality) are less considered (Fahrig, 2003). Since each fragmentation metric can have different effects on biotic communities (i.e., negative, positive or no effect: Fahrig, 2003; Hanski, 2015), the identification of unevenness in fragmentation metrics considered is of paramount importance to provide suitable decision-makings for conservation policies.

Here, we investigated research biases and knowledge gaps related to habitat loss and fragmentation across biogeographic regions and taxonomic groups as well as among species responses and fragmentation metrics in Brazil, a megadiverse, unevenly sampled country (Jenkins et al., 2015; Oliveira et al., 2016; Ribeiro et al., 2016). Our study encompasses fragmentation in a broad sense, thus including both habitat loss and fragmentation per se. Brazil spans a vast area that comprises different types of highly biodiverse forest and non-forest biomes, including the Amazon, the world's largest rainforest, and two biodiversity hotspots, the Atlantic Forest and Cerrado (Myers et al., 2000). The Cerrado is considered a non-forest biome containing grasslands, different savanna types and riparian forests (IBGE, 2004; Overbeck et al., 2015). Brazil also houses three other non-forest biomes with high biodiversity: the semiarid Caatinga, the Pampa grasslands and the Pantanal, one of the world's largest tropical wetlands (Leal et al., 2005; Junk et al., 2006; Overbeck et al., 2015). Therefore, assessing and quantifying both research biases and knowledge gaps may help to propose focused future studies that ultimately can provide useful information to better support conservation decisions.

2. Material and methods

2.1. Literature survey

We conducted our survey on 20 October 2018 using the Web of Science (WOS: www.webofknowledge.com) and the Scielo platform (www.scielo.br), an electronic database covering a selected collection of Brazilian scientific journals. We searched for the following topics in the title, abstract and keywords of papers: “deforest*” or “edge effect” or “forest loss” or “fragment*” or “habitat loss” or “land cover” or “land use*” and “Brazil”. Subsequently, we searched for each of the previous topics related to fragmentation separately to each Brazilian biome: “Amazon*”, “Atlantic Forest”, “Caatinga”, “Cerrado”, “Pampa” and “Pantanal”. We also searched for “Neotropical savanna*”, “Neotropical wetland” and “Rainforest”.

We exclusively focused on fragmentation research in native terrestrial biodiversity from Brazil, so we excluded data from non-Brazilian Amazon and all other biomes outside the country. We also omitted freshwater and marine ecosystems, and studies specifically focused on naturalized and invasive exotic species. Studies reporting fragmentation effects on carbon emission and sequestration, abiotic (e.g. erosion, flooding) and soil properties, and climate were not considered, thereby restricting our sample to biodiversity. We also excluded studies dealing with computational modeling as well as studies reporting species responses in a single fragment at only one time (i.e., descriptive studies without analyzing any fragmentation metric). Reviews and book chapters including our sampling criteria were also checked to complete our database. Ultimately, our database comprised 716 articles, including 26 taxonomic groups across the six Brazilian biomes (Table A.1), with 1173 cases studied. Twenty-one papers were excluded from our analysis because they were conducted either in transitional areas (e.g. Amazon-Cerrado) or with low-resolution taxonomic identifications (three papers only specifying “insects”).

The database ultimately included the following items: (1) biome (following IBGE, 2004): Amazon, Atlantic Forest, Caatinga, Cerrado, Pampa and Pantanal; (2) geographic coordinates of the study locations (123 papers did not show geographical coordinates or accurate location data so that we could deduce them); (3) taxonomic group studied (following the Tree of Life Web Project -<http://tolweb.org/tree>, accessed on February 2019-; Maddison and Schulz, 2007): plants, fungi and animals; (4) fragmentation metrics reported (compiled from specialized reviews reporting spatial and temporal patterns related to fragmentation that have implications for biodiversity conservation: Fahrig, 2003, 2017; Didham et al., 2012; Hanski, 2015): connectivity, edge effects, fragment number, fragment size, habitat quality and matrix quality; and (5) species responses investigated (following Deikumah et al., 2014; although we considered further explicit categories at species assemblage-level and oriented to biological processes, given their importance on species' distribution and fundamental niche under environmental impacts: Mokany and Ferrier, 2011): abundance, antagonistic interaction, behavior, composition, diversity (alpha and beta, divergence and evenness), functional traits, genetics, mutualistic interaction, reproduction and richness. In fragment size, we included both comparisons of several fragments of different size at the same time and size changes of the same fragment along time. The biomes have the following equivalence in the classification of Olson et al. (2001): Amazon and Atlantic Forest = Tropical and subtropical moist broadleaf forests; Caatinga = Deserts and xeric shrublands; Cerrado and Pampa = Tropical and subtropical grasslands, savannas, and shrublands; and Pantanal = Flooded grasslands and savannas. Studies frequently reported data from multiple taxa and/or several fragmentation metrics and species responses. Therefore, each relationship studied between a particular metric and a specific response for a given species within a paper was termed as a case, to ultimately estimate biases in fragmentation metrics and species responses.

2.2. Data analysis

To estimate biogeographic biases, we recorded human population density, the percentage of loss of original vegetation (IBGE, 2015; MapBiomias, 2017) and the percentage of studies conducted for each biome (Fig. A.1). We used studies instead of cases in order not to under- or overrepresent biomes. To calculate research bias among biomes, we assessed the density of studies for each biome by elaborating Kernel density raster layers (Yang et al., 2013; Ribeiro et al., 2016) with a resolution of 0.0083° (~1 km) in ArcGis v10.5 (ESRI, Redlands, California, USA). The Kernel interpolation function is a method frequently used in geographic information systems (GIS) analysis. This interpolation method is based on the definition of circular areas of influence around occurrence points of a phenomenon. Within the area of influence, the occurrence of the phenomenon decreases from the point to the limits according to a Gaussian function (Silverman, 1986). To determine differences in density among biomes, we generated 50,000 uniformly random points within the whole country and subsequently calculated the mean Kernel density values for each biome (Ribeiro et al., 2016). Differences in these values were tested by using ANOVA and subsequent post hoc Tukey tests in R software (R Development Core Team, 2018).

To determine the taxonomic biases, we recorded richness for each taxonomic group using the List of Species of the Brazilian Flora (Brazilian Flora 2020 project: <http://floradobrasil.jbrj.gov.br/>, accessed on 15 March 2019) and the Taxonomic Catalog of the Brazilian Fauna (<http://fauna.jbrj.gov.br/>, accessed on 15 March 2019), which follow the Tree of Life Web Project. For each taxonomic group, we subsequently assessed (1) the percentage of richness over the total richness (hereafter, percentage of representativeness), (2) the percentage of studies over the total number of publications, and (3) the percentage of studied species over the total number of species included in all papers. From these values, we calculated a relative bias rate (BR_i; Nemésio et al., 2013; Ribeiro et al., 2016) for each taxonomic group through the formulas:

$$BR_i = a_i/b_i \quad (1)$$

$$BR_i = (b_i/a_i) \times (-1) \quad (2)$$

where a_i is the percentage of studies or the percentage of studied species and b_i the percentage of representativeness of the taxonomic group i . When the values of a_i were higher than the values of b_i , we used Eq. (1), and when the values of b_i were higher than the value of a_i , we used Eq. (2). Positive values indicate higher, and negative values lower, percentage of studies or studied species than the percentage of representativeness for a particular taxonomic group.

3. Results

3.1. Biogeographic bias

On average, 20.5 papers/year (ranging from 0 to 65) were published from 1984 to 2018, showing an increase over time (Fig. 1). The Atlantic Forest, the most densely populated and degraded biome, was the most studied one (63% of studies), followed by the Amazonian rainforest (Table A.1; Fig. A.1). Taken together, these two forested biomes comprised 85% of fragmentation research in Brazil. Among the non-forest biomes, the Cerrado was clearly the most studied one, representing about 75% of studies across non-forest biomes. Together, the Caatinga, the Pampa and the Pantanal comprised < 5% of fragmentation research (Fig. A.1). Also associated with the biome-biased research, the distribution of fragmentation studies was biogeographically biased. The mean Kernel density was significantly between four- and five-fold higher in the Atlantic Forest than in the other biomes, but it was concentrated around four large metropolitan areas (Recife and Maceió in the north, and Rio de Janeiro and São Paulo in the south, Fig. 2).

Although the Amazon had a low mean Kernel density, it comprised a high research density near one single large city (Manaus, Fig. 2). Similarly, most of the fragmentation studies in the Cerrado were concentrated near two large cities, Belo Horizonte and Campinas (Fig. 2).

3.2. Taxonomic bias

Our analyses revealed that fragmentation research in Brazil is taxonomically biased. Seed plants are the most studied group, comprising 40% of publications, but they are also the richest component of the flora, thus showing low positive relative biases. High relative biases were especially relevant for most terrestrial vertebrates (Table A.2). For example, mammals showed the highest relative bias rate in terms of studies (Fig. 3a) and birds were disproportionately considered in terms of studied species (Fig. 3b). Conversely, many insect groups showed the lowest relative biases considering their richness (Table A.2). For example, beetles, the most diverse animal group, were only included in 3% of studies (Fig. 3a), and cockroaches exclusively comprised two studied species (Fig. 3b).

3.3. Response and metric biases

Overall, richness (34%), abundance (24%) and diversity (13%) of species were the most studied responses, whereas ecological interactions (2%) and genetics (3%) were underrepresented (Fig. 4). Amazon, Atlantic Forest and Cerrado were the only biomes that comprised all the species responses. Richness was the most considered response category in 20 taxonomic groups, whereas abundance was also the most frequent response (24 groups, Table A.3). Conversely, reproduction was only studied in seed plants, amphibians, mammals and reptiles. Fragment size was clearly the most considered metric in the studies (43%), followed by habitat quality (22%), edge effects (17%), connectivity (12%), matrix quality (4%), and fragment number (2%) (Fig. 5). Similar to species responses, the Amazon, Atlantic Forest and Cerrado included all the metrics. Fragment size was also both the dominant (17 groups) and the most frequently studied metric (22 groups; Table A.2).

4. Discussion

Our review demonstrates the existence of both biogeographic and taxonomic biases in fragmentation-related research in Brazil, with major knowledge gaps in the responses to fragmentation among lineages and across biomes. We found that the Atlantic Forest was largely much more sampled than the other biomes, whereas the Amazon, and especially non-forest biomes, were poorly considered. We also reported high positive bias for most terrestrial vertebrates considering their richness. In contrast, many insect taxa were disproportionately underrepresented. Species abundance and richness were the most commonly studied responses, whereas fragment size was the most considered metric. The observed biases suggest that decisions on conservation policies are based on extrapolation of the studied patterns of richness and abundance of few taxonomic groups in Atlantic Forest fragments. Our data should stimulate and guide researchers to focus future sampling effort on less-studied taxonomic groups as well as other regions and biomes in the country.

4.1. Assessment of biogeographic bias

As a consequence of the historical forest conversion to croplands and livestock activities, the current spatial extent of the Atlantic Forest vegetation is estimated to cover 28% of original vegetation (Rezende et al., 2018; Rezende et al., 2018). Nowadays, this biome is highly industrialized and inhabited by ~125 million people (ca. 60% of the Brazilian population, including large metropolitan areas such as São Paulo and Rio de Janeiro, which have institutions that have concentrated most studies in their immediate vicinity). In the Amazon, the

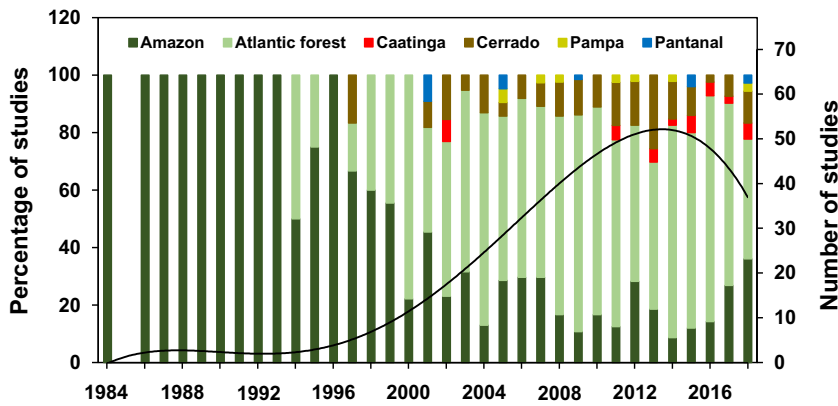


Fig. 1. Temporal variation in the number of papers published on fragmentation across the Brazilian biomes. Data were retrieved from Scielo and Web of Science platforms between 1984 and 2018. The black line represents the line of best fit (third-degree polynomial response) between a number of published articles and years: $R^2 = 0.93$, $p < 0.001$.

studies were mostly concentrated near one large city (Manaus) and have been mostly conducted by an important research project (BDFFP: Biological Dynamics of Forest Fragments Project). The BDFFP, located at 80 km of Manaus, comprises the world's largest and longest-running project of habitat fragmentation (Laurance et al., 2011). Thus, fragmentation research in the Amazon is still weak, especially in remote, poorly unexplored places. The vast area and low population density together with the relatively high undisturbed-forest cover may, therefore, explain the low concentration of studies in this biome.

In non-forest Brazilian biomes, the number of studies and, consequently, the knowledge we have about causes and consequences of fragmentation is still meager compared with forest biomes. This is particularly true for Pantanal, Brazil's best-conserved, least-populous and smallest biome (Fig. 2; Fig. A.1). These three conditions may jointly account for the low number of studies focusing on fragmentation in this biome. However, in the last 30 years, the spread of pastures, soy production and invasive species in the Pantanal (Miranda et al., 2018;

Tomas et al., 2019) has reduced the area of the native vegetation by approximately 11% (MapBiomas, 2017). The Pampa biome, dominated by grasslands, comprises an area and number of studies similar to Pantanal, but the high population density and the traditional ranching practices (Overbeck et al., 2007; Oliveira et al., 2017) have resulted in the highest native vegetation loss rates after Atlantic Forest (IBGE, 2018). Similarly, about 47% of the dry woodlands of the Caatinga have been transformed into agricultural land, pasture and urban areas (IBGE, 2018).

The Cerrado, the most studied non-forest biome, is the second largest and most densely populated biome, and the third most degraded amongst Brazilian biomes, due to increasing expansion of human activities such as agriculture, livestock, mining and soybean monocultures (Lapola et al., 2014). The major part of the studies on Cerrado fragmentation was conducted near large cities, where research centers are located. The observed geographical concentration, together with the relatively low number of studies conducted, are concerning, given that

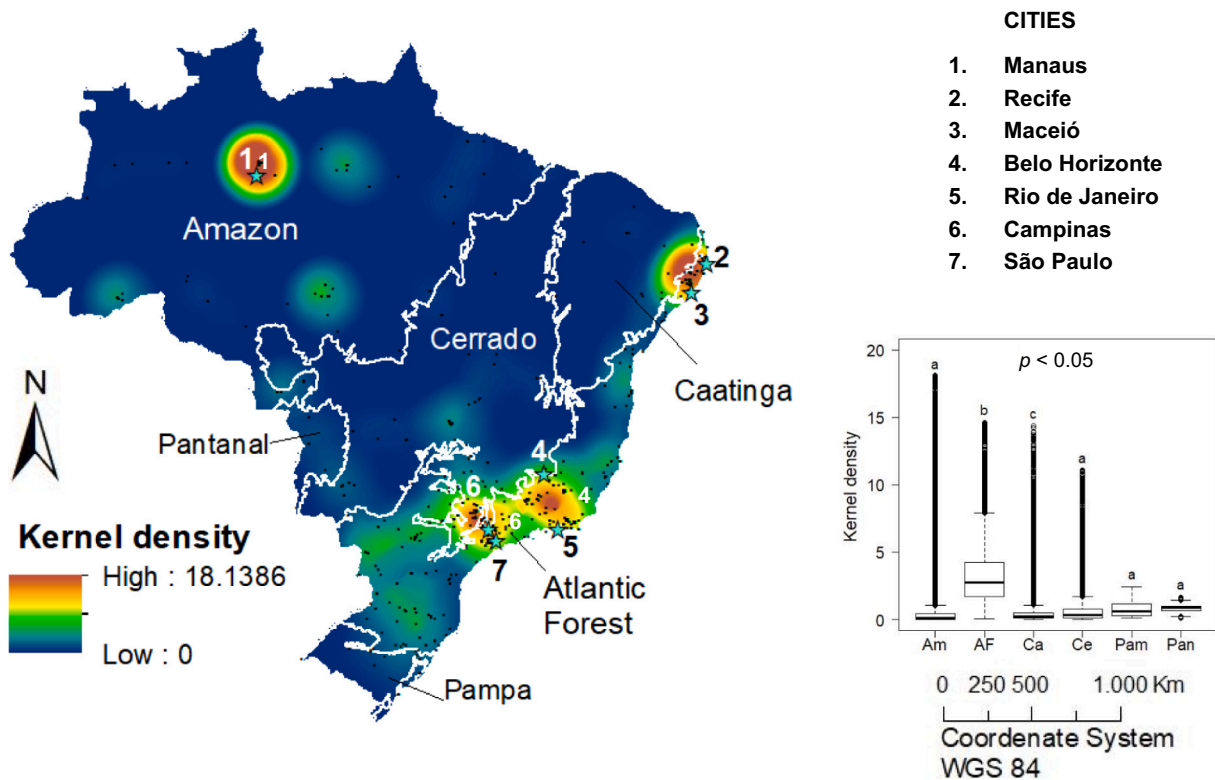


Fig. 2. Mean Kernel density (studies/km²) for cases (each point refers to a single case) of fragmentation-related publications in Brazil. Major cities wherein most of the studies were concentrated (i.e. highest mean Kernel density) are indicated and numbered. The box-plot shows significant differences in the mean Kernel density across biomes. Different letters indicate significant differences ($p < 0.001$).

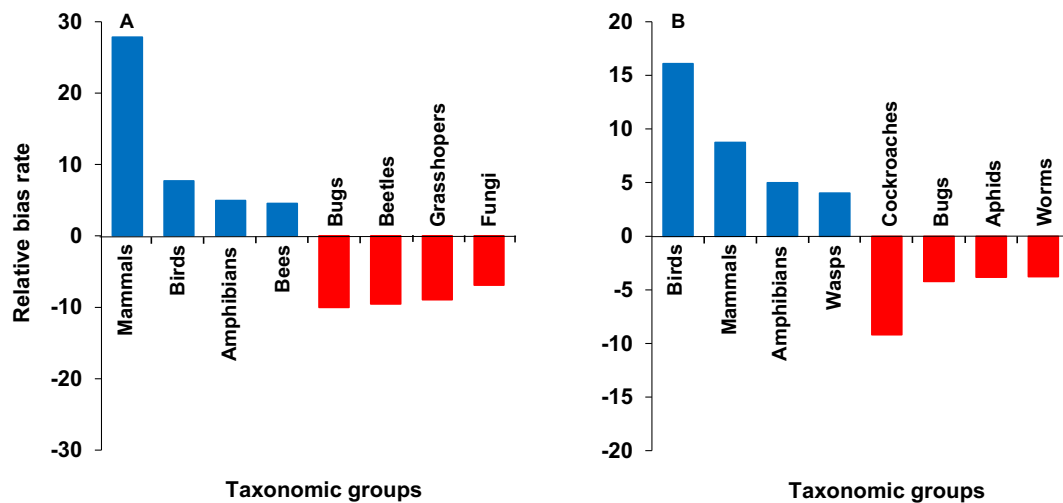


Fig. 3. Relative bias rate for taxonomic groups that showed the highest and lowest values in fragmentation literature in relation to (A) percentage of studies and (B) percentage of species studied over the percentage of total richness representativeness of each considered taxonomic group in Brazil.

this biome is a biodiversity and priority conservation hotspot with a high value in terms of ecosystem services (Myers et al., 2000; Strassburg et al., 2017). Overall, major gaps in fragmentation-related research may compromise biodiversity conservation in non-forest biomes. Given the marked differences in vegetation structure, non-forest biomes are differently affected by fragmentation and habitat loss when compared to forest biomes (Bond and Parr, 2010). As a consequence, non-forest biomes may require different conservation frameworks and strategies than those of forest biomes (Overbeck et al., 2015).

4.2. Assessment of taxonomic bias

We found three main expected taxonomic biased patterns in fragmentation-related studies in Brazil. Firstly, articles on seed plants were dominant among all taxonomic groups considered, which is consistent with the relative dominance of this group in world's tropical forest fragmentation research and its relative abundance when considering Brazilian biodiversity (see Oliveira et al., 2016). Secondly, there was a disproportionate prevalence of number of publications and species examined for mammals and birds, respectively. Many review studies dealing with biodiversity and conservation research worldwide have previously shown notable positive biases in the percentage of papers targeting mammals (e.g., Shine and Bonnet, 2000; Trimble and Van Aarde, 2010; Rosenthal et al., 2017) and in the bird occurrence recordings (Bonnet et al., 2002; McRae et al., 2017; Troudet et al., 2017). Lastly, we detected major negative relative biases for most insect groups, which was especially striking for beetles, the richest animal group in Brazil (Table A.2). This may be associated with the long and

laborious process to identify beetle species and the lack of taxonomic experts for this group (Gardner et al., 2008). Therefore, the interplay between species accessibility, logistic constraints as well as the research capacity and preferences for certain groups largely explains the different taxonomic representation reported here.

We also detected some relevant taxonomic biases and resulting shortfalls that deserve attention. For example, amphibians were highly overrepresented, in contrast to published research on their conservation (Schiesari et al., 2007; McRae et al., 2017). Amphibian-related studies were preferentially conducted in the Cerrado, which spans one of the largest watersheds in Brazil. Complementary streams and wetlands in this biome are increasingly being transformed by agricultural land use, which is particularly detrimental for amphibian species occurrence (e.g., Signorelli et al., 2016). Likewise, we found positive relative biases for Hymenoptera, contrary to patterns for most insects. This overrepresentation is probably due to the high number of researchers working on the ecology of this group in Brazil, raising a great interest in the study of social insects and their ecological services such as seed dispersal, pollination and ant-plant mutualisms (Delabie et al., 2012). Conversely, we found no studies for some diverse animal groups as terrestrial crustaceans and gastropods. Although these taxa are particularly sensitive to fragmentation due to their low mobility (Lydeard et al., 2004; Nicolai and Ansart, 2017), many species persist in specialized niches of very small areas, thus surviving extensive fragmentation (e.g., snails; Raheem et al., 2009). Overall, uneven fragmentation-related taxonomic research and resulting major gaps may hinder our understanding of the fragmentation consequences on biodiversity. One resulting problem is the potential misuse of the knowledge of the fragmentation effects on a given taxonomic group to predict the effects

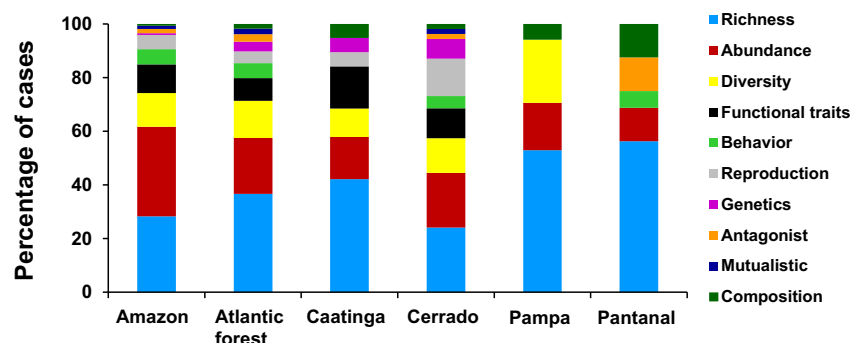


Fig. 4. Percentage of studies representing each of the ecological responses across Brazilian biomes.

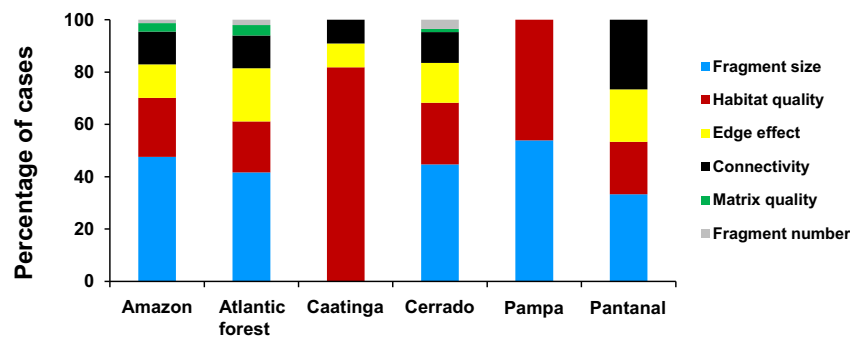


Fig. 5. Percentage of studies representing each of the fragmentation metrics across Brazilian biomes.

on other taxa.

4.3. Assessment of response and metric biases

Our results based on patterns (i.e., abundance, richness and diversity) prevalent in the literature on fragmentation research in Brazil are consistent with previous studies (Ellis et al., 2011; Deikumah et al., 2014). These distribution-based responses are cost-effective indicators to evaluate the effects of fragmentation on biological communities. By contrast, many fragmentation-mediated responses related to biological processes such as interspecific interactions, genetics and individual conditions (e.g., reproduction) are more difficult to record and require observations over extended timeframes to be publishable (Ewers and Didham, 2006). For example, detecting genetic responses involves costly laboratory equipment and time, thus limiting studies to one single species (> 80% of publications on genetics compiled here were single-species studies). We also found uneven use of fragmentation metrics, with a marked prevalence of fragment size. This result was expected as fragment size in our study included both the amount of available habitat among different patches within the landscape and temporal loss of habitat area, both of which constitute important threats to biodiversity (e.g., Harrison and Bruna, 1999; Hanski, 2015; Betts et al., 2017). However, edge effects and connectivity, two metrics commonly considered in fragmentation research (Murcia, 1995; Fahrig, 2003, 2017), have comparatively received little attention.

5. Conclusions

Based on our findings, we suggest that fragmentation research needs to be largely extended to non-forest biomes and, to a lesser extent, should include unexplored areas of Amazon and Atlantic forests. Further information on fragmentation-based studies across under-sampled regions and taxa will also be essential to improve the progress towards the Goal 15 of the 2030 Agenda for sustainable development in Brazil, which seeks the protection of degraded terrestrial ecosystems and the reduction of biodiversity loss (UN General Assembly, 2015). Lastly, we recommend that future research should consider species responses beyond distribution studies and target behavior, functional

Appendix A

Table A.1

Number of studies per biome for each of the taxonomic groups reported on fragmentation research in Brazil. Taxonomic groups follow the Tree of Life Web Project (Maddison and Schulz, 2007).

| Group | Biome | | | | | | Total |
|---|--------|-----------------|----------|---------|-------|----------|-------|
| | Amazon | Atlantic forest | Caatinga | Cerrado | Pampa | Pantanal | |
| Land plants (Embryophytes) | | | | | | | |
| Bryophytes (Bryophyta, Anthocerotophyta and Marchantiomorpha) | 3 | 8 | 0 | 0 | 0 | 0 | 11 |

(continued on next page)

traits, genetics and interspecific interactions, as well as consider alternative fragmentation metrics based on fragment size to fully understand how fragmentation affects tropical biotic communities in a megadiverse country.

CRediT authorship contribution statement

Alberto L. Teixeira: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project Administration. **Stela R. A. Gonçalves:** Methodology, Data Curation, Writing – Review & Editing. **Gilberto J. F. Arellano:** Data Curation, Writing – Review & Editing. **Wesley Dáttilo:** Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Thiago J. Izzo:** Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Viviane M. G. Layme:** Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Leonardo F. B. Moreira:** Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Luis G. Quintanilla:** Conceptualization, Methodology, Data Curation, Writing – Original Draft, Writing – Review & Editing.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there have been no significant financial support for this work that could have influenced its outcome.

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Table A.1 (continued)

| Group | Biome | | | | | | Total |
|---|--------|-----------------|----------|---------|-------|----------|-------|
| | Amazon | Atlantic forest | Caatinga | Cerrado | Pampa | Pantanal | |
| Pteridophytes (Lycopodiopsida and Polypodiopsida) | 1 | 11 | 0 | 1 | 0 | 0 | 13 |
| Seed plants (Spermatopsida) | 55 | 185 | 9 | 42 | 2 | 3 | 296 |
| Fungi | 1 | 3 | 0 | 1 | 0 | 0 | 5 |
| Animals | | | | | | | |
| Worms (Annelida) | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
| Arthropods (Arthropoda) | | | | | | | |
| Springtails (Collembola) | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Scorpions (Scorpionida) | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| Mites (Acari) | 0 | 7 | 0 | 6 | 0 | 0 | 13 |
| Spiders (Araneae) | 3 | 4 | 0 | 0 | 1 | 0 | 8 |
| Insects (Insecta) | | | | | | | |
| Dragonflies (Odonata) | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| Cockroaches and termites (Dictyoptera) | | | | | | | |
| Cockroaches (Blattaria) | 0 | 3 | 0 | 0 | 0 | 0 | 3 |
| Termites (Isoptera) | 2 | 4 | 0 | 2 | 0 | 0 | 8 |
| Grasshoppers and crickets (Orthoptera) | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Stoneflies (Plecoptera) | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Bugs and aphids (Hemiptera) | | | | | | | |
| Bugs (Heteroptera) | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
| Aphids (Aphidomorpha) | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| Beetles (Coleoptera) | 8 | 12 | 0 | 1 | 0 | 0 | 21 |
| Flies (Diptera) | 3 | 11 | 1 | 0 | 0 | 0 | 15 |
| Butterflies and moths (Lepidoptera) | 2 | 12 | 0 | 0 | 1 | 0 | 15 |
| Hymenoptera | | | | | | | |
| Ants (Formicidae) | 8 | 16 | 2 | 1 | 1 | 1 | 28 |
| Wasps (Vespidae) | 1 | 8 | 0 | 4 | 0 | 0 | 13 |
| Bees (Apoidea) | 6 | 19 | 0 | 2 | 0 | 0 | 27 |
| Vertebrates (Vertebrata) | | | | | | | |
| Amphibians (Amphibia) | 9 | 15 | 1 | 4 | 2 | 1 | 32 |
| Reptiles (Reptilia) | 4 | 11 | 0 | 0 | 1 | 0 | 16 |
| Birds (Aves) | 26 | 54 | 1 | 9 | 2 | 1 | 91 |
| Mammals (Mammalia) | 34 | 67 | 2 | 10 | 1 | 2 | 116 |

Table A.2

Richness, number of studies, number of studied species and relative bias rates for each of the taxonomic groups reported on fragmentation research in Brazil. Percentages of richness, number of studies and number of studied species over total richness, publications and considered species, respectively, are in brackets. Taxonomic groups are listed by number of species. Richness for plant groups were extracted from the Brazilian Flora 2020 project (<http://floradobrasil.jbrj.gov.br>) and for animal groups from the Taxonomic Catalog of the Brazilian Fauna (<http://fauna.jbrj.gov.br>). ¹0.01; ²0.03.

| Group | Richness | Publication-related bias | | Species-related bias | |
|-------------------|---------------|--------------------------|-----------|-----------------------|-----------|
| | | Number of studies | Bias rate | Number of species | Bias rate |
| Seed plants | 33,325 (27.2) | 296 (39.7) | 1.46 | 11,355 (35.9) | 1.30 |
| Beetles | 33,095 (27.0) | 21 (2.8) | -9.52 | 950 (3.0) | -3.02 |
| Butterflies/moths | 12,715 (10.4) | 15 (1.9) | -5.52 | 1793 (5.7) | -1.36 |
| Flies | 11,169 (9.1) | 15 (2.0) | -4.53 | 403 (1.3) | -2.69 |
| Fungi | 5719 (4.7) | 5 (0.7) | -6.96 | 172 (0.5) | -2.95 |
| Bugs | 3313 (2.7) | 2 (0.3) | -10.07 | 49 (0.2) | -4.21 |
| Spiders | 3145 (2.6) | 8 (1.1) | -2.39 | 984 (3.1) | 1.19 |
| Birds | 1982 (1.6) | 93 (12.5) | 7.72 | 8354 (26.4) | 16.09 |
| Bryophytes | 1572 (1.3) | 9 (1.2) | -1.06 | 734 (2.3) | 1.78 |
| Worms | 1565 (1.3) | 2 (0.3) | -4.76 | 29 (0.1) | -3.76 |
| Grasshoppers | 1480 (1.2) | 1 (0.1) | -9.00 | - | - |
| Ants | 1374 (1.1) | 26 (3.5) | 3.11 | 1330 (4.2) | 3.49 |
| Pteridophytes | 1361 (1.1) | 13 (1.7) | 1.57 | 548 (1.7) | 1.54 |
| Amphibians | 1024 (0.8) | 32 (4.2) | 4.98 | 1336 (4.2) | 4.98 |
| Bees | 981 (0.8) | 27 (3.6) | 4.53 | 555 (1.8) | 2.16 |
| Mites | 937 (0.8) | 13 (1.7) | 2.28 | 336 (1.1) | 1.37 |
| Dragonflies | 828 (0.7) | 21 (0.3) | -2.52 | 58 (0.2) | -1.93 |
| Reptiles | 763 (0.6) | 6 (2.1) | 3.45 | 148 (0.5) | -1.35 |
| Mammals | 685 (0.6) | 116 (15.6) | 27.84 | 1571 (5.0) | 8.75 |
| Wasps | 676 (0.6) | 13 (1.7) | 3.16 | 712 (2.3) | 4.02 |
| Cockroaches | 644 (0.5) | 3 (0.4) | -1.31 | 2 (0.0) ¹ | -9.18 |
| Springtails | 398 (0.3) | 1 (0.1) | -2.42 | - | - |
| Termites | 341 (0.3) | 8 (1.1) | 3.86 | 106 (0.3) | -2.03 |
| Stoneflies | 164 (0.1) | 1 (0.1) | 1.00 | - | - |
| Scorpions | 158 (0.1) | 2 (0.3) | 2.08 | 10 (0.0) ² | -2.03 |
| Aphids | 111 (0.1) | 2 (0.3) | 2.96 | 2 (0.0) ¹ | -3.81 |

Table A.3
Number of cases found for each of the species responses and fragmentation metrics for each of the taxonomic groups reported on fragmentation research in Brazil. Percentage of cases over the total are in brackets.

| Group | Fragmentation metrics | | | | | | | | | | | | | | | |
|-------------------|-----------------------|--------------|-----------|-------------|-----------|-------------------|----------|-------------|--------------|------------|--------------|--------------|-----------------|---------------|-----------------|----------------|
| | Abundance | Antagonistic | Behavior | Composition | Diversity | Functional traits | Genetics | Mutualistic | Reproduction | Richness | Connectivity | Edge effects | Fragment number | Fragment size | Habitat quality | Matrix quality |
| Seed plants | 78 (19.6) | 14 (3.5) | 0 | 7 (1.8) | 47 (11.8) | 73 (18.3) | 19 (4.8) | 6 (1.5) | 54 (13.5) | 101 (25.3) | 23 (7.3) | 75 (23.7) | 9 (2.8) | 136 (42.9) | 66 (20.8) | 8 (2.5) |
| Beetles | 14 (34.2) | 0 | 2 (4.9) | 2 (4.9) | 5 (12.2) | 1 (2.4) | 2 (4.9) | 0 | 0 | 15 (36.6) | 2 (5.6) | 1 (2.8) | 0 | 17 (47.2) | 14 (38.9) | 2 (5.6) |
| Butterflies/moths | 2 (11.1) | 0 | 1 (5.6) | 0 | 3 (16.7) | 0 | 0 | 0 | 0 | 13 (54.2) | 2 (22.2) | 0 | 0 | 3 (33.3) | 4 (44.4) | 0 |
| Flies | 7 (29.2) | 0 | 0 | 0 | 4 (16.7) | 0 | 0 | 0 | 0 | 13 (54.2) | 0 | 6 (33.3) | 0 | 6 (33.3) | 6 (33.3) | 0 |
| Fungi | 1 (25.0) | 0 | 0 | 0 | 0 | 1 (25.0) | 0 | 0 | 0 | 4 (50.0) | 0 | 0 | 0 | 0 | 4 (100.0) | 0 |
| Bugs | 1 (50.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 (50.0) | 0 | 0 | 0 | 2 (100.0) | 0 | 0 |
| Spiders | 7 (53.8) | 0 | 0 | 0 | 3 (23.1) | 0 | 0 | 0 | 0 | 3 (23.1) | 0 | 3 (27.3) | 0 | 3 (27.3) | 5 (45.5) | 0 |
| Birds | 33 (23.2) | 7 (4.9) | 12 (8.5) | 2 (1.4) | 18 (12.7) | 10 (7.0) | 2 (1.4) | 5 (3.2) | 0 | 53 (37.3) | 22 (18.2) | 8 (6.6) | 1 (0.8) | 65 (53.7) | 20 (16.5) | 5 (4.1) |
| Bryophytes | 4 (14.3) | 0 | 0 | 3 (10.7) | 1 (3.6) | 2 (7.1) | 1 (3.6) | 0 | 0 | 17 (60.7) | 4 (16.7) | 5 (20.8) | 0 | 15 (62.5) | 0 | 0 |
| Worms | 1 (33.3) | 0 | 0 | 0 | 0 | 1 (33.3) | 0 | 0 | 0 | 1 (33.3) | 0 | 0 | 0 | 2 (66.7) | 1 (33.3) | 0 |
| Grasshoppers | 1 (100.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ants | 2 (4.4) | 1 (2.2) | 0 | 0 | 10 (21.7) | 1 (2.2) | 0 | 5 (10.1) | 0 | 27 (58.7) | 5 (11.1) | 5 (11.1) | 0 | 16 (35.6) | 16 (35.6) | 3 (6.7) |
| Pteridophytes | 1 (4.6) | 0 | 1 (4.6) | 0 | 4 (18.1) | 1 (4.6) | 0 | 0 | 0 | 15 (68.1) | 3 (15.0) | 4 (20.0) | 0 | 6 (30.0) | 4 (20.0) | 3 (15.0) |
| Amphibians | 15 (27.3) | 0 | 3 (5.5) | 0 | 8 (14.6) | 4 (7.3) | 5 (9.1) | 0 | 3 (5.5) | 17 (30.9) | 5 (9.6) | 14 (26.9) | 1 (1.9) | 14 (26.9) | 17 (32.7) | 1 (1.9) |
| Bees | 26 (36.1) | 0 | 4 (5.6) | 1 (1.4) | 13 (18.1) | 0 | 0 | 1 (1.4) | 0 | 27 (37.5) | 14 (20.0) | 16 (22.9) | 4 (5.7) | 26 (37.1) | 7 (10.0) | 3 (4.3) |
| Mites | 3 (30.0) | 2 (20.0) | 0 | 0 | 2 (20.0) | 0 | 0 | 0 | 0 | 3 (30.0) | 0 | 1 (20.0) | 0 | 3 (60.0) | 0 | 1 (20.0) |
| Dragonflies | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 (100.0) | 0 | 0 | 0 | 0 | 0 | 0 |
| Reptiles | 7 (24.1) | 0 | 2 (6.9) | 0 | 6 (20.7) | 0 | 1 (3.5) | 1 (3.5) | 1 (3.5) | 11 (37.9) | 2 (14.2) | 1 (7.1) | 0 | 6 (42.9) | 4 (28.6) | 1 (7.1) |
| Mammals | 65 (34.2) | 2 (1.1) | 32 (16.8) | 3 (1.6) | 23 (12.1) | 6 (3.2) | 3 (1.6) | 1 (0.5) | 4 (2.1) | 51 (26.8) | 32 (19.9) | 19 (11.8) | 3 (1.9) | 69 (42.9) | 30 (18.6) | 8 (5.0) |
| Wasps | 1 (7.1) | 0 | 1 (7.1) | 0 | 5 (35.8) | 0 | 0 | 0 | 0 | 7 (50.0) | 0 | 1 (11.1) | 0 | 4 (44.4) | 4 (44.4) | 0 |
| Cockroaches | 3 (75.0) | 0 | 1 (25.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 (100.0) | 0 | 0 |
| Springtails | 1 (100.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Termites | 0 | 0 | 1 (14.3) | 0 | 1 (14.3) | 0 | 1 (14.3) | 0 | 0 | 4 (57.1) | 0 | 0 | 0 | 4 (66.7) | 2 (33.3) | 0 |
| Stoneflies | 1 (100.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Scorpions | 1 (25.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 (75.0) | 1 (25.0) | 0 | 0 | 1 (25.0) | 2 (50.0) | 0 |
| Aphids | 2 (100.0) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 (100.0) | 0 | 0 | 0 | 0 |

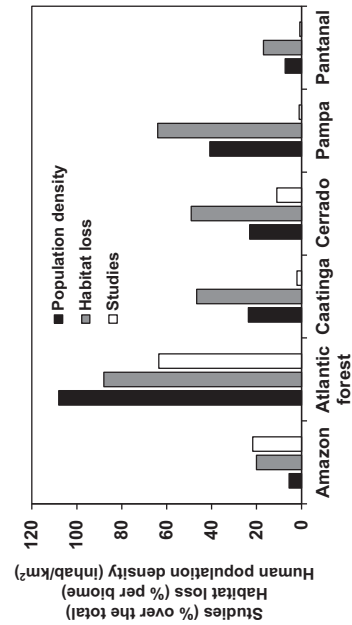


Fig. A.1. Percentage of studies on fragmentation research for each of the Brazilian biomes over total number of studies in relation to human population density (inhabitants/km²) and habitat loss for each biome (%).

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2020.108749>.

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