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SIMONE ALMEIDA PENA

ECOLOGIA E CONSERVAÇÃO DE PEQUENOS MAMÍFEROS NÃO-VOADORES (DIDELPHIMORPHIA, RODENTIA) DA AMAZÔNIA BRASILEIRA

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Tese apresentada ao programa de Pós-Graduação em Ecologia do convênio da Universidade Federal do Pará e Embrapa Amazônia Oriental, como requisito para obtenção do título de Doutor em Ecologia.
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Orientador:
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Carlos Drummond de Andrade

ECOLOGIA E CONSERVAÇÃO DE PEQUENOS MAMÍFEROS NÃO-VOADORES (DIDELPHIMORPHIA, RODENTIA) DA AMAZÔNIA BRASILEIRA

RESUMO GERAL

A Amazônia é a maior e a mais diversa floresta tropical do mundo, onde é possível encontrar regiões com diferentes níveis de conservação e conhecimento. No entanto, a perda de habitat, degradação e fragmentação de paisagens contínuas e conversão de grandes florestas em monoculturas é atualmente uma das maiores ameaças à biodiversidade. E esses efeitos produzidos pelo homem têm levado muitos organismos à extinção local e à redução da diversidade biológica. Por essa razão, considerando as enormes lacunas de conhecimento sobre pequenos mamíferos não-voadores amazônicos e a intensidade com que a Amazônia vem sendo degradada, são necessários estudos que viabilizem medidas eficientes de conservação desta fauna na região, principalmente em savanas amazônicas, que apesar de serem ecossistemas biologicamente ricos, elas têm sido muitas vezes negligenciadas e altamente modificada pela conversão de terras para agricultura em larga escala e incêndios descontrolados. Esse estudo objetiva responder as seguintes questões: (1) Como as espécies de pequenos mamíferos não-voadores se comportam frente às ameaças frequentes de perda de hábitat nas florestas tropicais? (2) Quais as lacunas na conservação de pequenos mamíferos não-voadores na Amazônia brasileira e como elas respondem a essa dinâmica em diferentes unidades de conservação? e (3) Qual a importância da atual rede de unidades de conservação na Amazônia brasileira para pequenos mamíferos não-voadores? Demonstramos através desta investigação que as mudanças causadas por ação humana provocam alterações na estruturação das comunidades deste grupo, além de sanar parte das lacunas de conhecimento existente sobre a distribuição potencial das espécies para a região Amazônica, a fim de subsidiar medidas de proteção para os ambientes de savanas amazônicas, com a identificação de áreas prioritárias para conservação nesse período de escassez de recursos financeiros e intensa alteração da paisagem.

Palavras-chave: Distribuição potencial de espécies, gap analysis, áreas prioritárias, pequenos mamíferos, Amazônia brasileira.

ECOLOGY AND CONSERVATION OF SMALL NON-VOLANT MAMMALS (DIDELPHIMORPHIA, RODENTIA) IN THE BRAZILIAN AMAZON

ABSTRACT

The Amazon is the largest and most diverse tropical forest in the world, where it is possible to find regions with different levels of conservation and knowledge. However, habitat loss, degradation and fragmentation of continuous landscapes, and conversion of large forests into monocultures is currently one of the greatest threats to biodiversity. And these man-made effects have led many organisms to local extinction and a reduction in biological diversity. For this reason, considering the huge gaps in knowledge about small non-volant Amazonian mammals and the intensity with which the Amazon has been degraded, studies are needed to enable efficient conservation measures for this fauna in the region, mainly in Amazonian savannas, which despite being Although they are biologically rich ecosystems, they have often been neglected and highly modified by land conversion for large-scale agriculture and uncontrolled fires. This study aims to answer the following questions: (1) How do species of small non-volant mammals behave in the face of frequent threats of habitat loss in tropical forests? (2) What are the gaps in the conservation of small non-volant mammals in the Brazilian Amazon and how do they respond to this dynamic in different conservation units? and (3) How important is the current network of conservation units in the Brazilian Amazon for small non-volant mammals? We demonstrate through this investigation that changes caused by human action cause changes in the structure of communities in this group, in addition to filling part of the gaps in existing knowledge about the potential distribution of species in the Amazon region, in order to subsidize protection measures for the environments of Amazonian savannas, with the identification of priority areas for conservation in this period of scarcity of financial resources and intense change in the landscape.

Keywords: Potential distribution of species, gap analysis, priority areas, small mammals, Brazilian Amazon.

SUMÁRIO

1. INTRODUÇÃO GERAL

As florestas tropicais abrigam mais da metade das espécies do planeta (Wilson 1988) e estão entre os hotspots de biodiversidade mais ricos do mundo (Gardner 2010). No entanto, a vegetação natural presente nesses biomas vem diminuindo aceleradamente, provocando o desaparecimento de espécies e a consequente redução das funções ecossistêmicas que elas desenvolvem (Haddad et al. 2015). Essas ameaças vêm se intensificando nos últimos séculos devido à perda e fragmentação do hábitat e conversão da paisagem em mineração, pastagens, agricultura intensiva, urbanização e mudanças climáticas (Lewis et al. 2009; Myers et al. 2000; Meyer et al. 2016). Assim, é esperado que algumas fitofisionomias, como as savanas amazônicas, sejam perdidas ou alteradas no presente século, principalmente pelas mudanças no uso da terra (Chapin III et al. 2000; Sala et al. 2000).

No Brasil, esse cenário não é diferente. O bioma Amazônia tem experimentado, de acordo com seu histórico de uso da terra, uma dinâmica muito veloz no processo de desmatamento (Laurance et al. 2004). Este bioma já perdeu ~12% de sua extensão original, e projeções futuras dizem que perderá ainda mais, podendo alcançar de 9 a 28% até 2050 (Soares-Filho et al. 2006, 2013). Essas ameaças provêm principalmente das atividades de pecuária, do cultivo de soja (Soares-Filho et al. 2006) e das estradas, que acompanham essas atividades e que também causam grandes impactos no ambiente.

O efeito da alteração da paisagem sobre a biodiversidade é observado em diferentes grupos taxonômicos, como fungos (Melloni et al. 2003), macroinvertebrados (Cunha et al. 2017), peixes (Clapcott et al. 2012), mamíferos (Prado et al. 2007) e aves (Gagné and Fahrig 2011). Alguns estudos têm demonstrado que estas mudanças drásticas da paisagem exercem efeitos sobre a diversidade da fauna (Donald 2004; Fitzherbert et al. 2008) e submete as espécies a novas condições ambientais e, às vezes, em posição de alta vulnerabilidade (Foden et al. 2013). A redução na riqueza de espécies de aves (Aratrakorn et al. 2006; Azhar et al. 2011; Peh et al. 2006), de morcegos insetívoros (Bernard et al. 2009) e de pequenos mamíferos não-voadores (Phomonexay et al. 2011), foram algumas das observações apontadas por estes estudos. E a resposta das espécies e/ou sua persistência na paisagem podem variar, dependendo das novas condições ambientais oferecidas, da sua habilidade para se adaptar a uma nova paisagem, além das características e demandas ecológicas de cada espécie (Nally et al. 2000). Sendo os mamíferos, por apresentarem alta diversidade morfológica e fisiológica e responderem aos impactos antropogênicos, são indicados como bons modelos para se estudar as mudanças no uso e cobertura do solo (Bierregaard et al. 1992; Founier-Chambrillon et al. 2000; Pardini et al. 2005; Santos-Filho et al. 2012).

Os pequenos mamíferos não-voadores, são aqueles com peso inferior a um quilo, pertencentes às ordens Didelphimorphia (família Didelphidae) e Rodentia (famílias Cricetidae, Muridae e Echimydae). Constituem um dos grupos mais diversos e com ampla distribuição da mastofauna neotropical (Gardner 2008; Patton et al. 2015; Wilson and Reeder 2005). São essenciais para a manutenção dos ecossistemas naturais, agindo como dispersores e predadores de sementes (Maser and Maser 1988; Pyares and Longland 2001; Vander Wall et al. 2001). Além disso, influenciam a ocorrência e abundância de plantas e invertebrados (Careya et al. 1999, Gunther et al. 1983), contribuindo para a regeneração de florestas (Careya et al. 1992) e representam as principais presas para diversos predadores (Forsman et al. 1984). As espécies desse grupo possuem adaptações morfológicas distintas, o que os permite selecionar hábitats específicos (Pardini et al. 2009) e em diferentes escalas espaciais (macrohábitat, mesohábitat e microhábitat) (Dalmagro and Vieira 2005; Finlayson et al. 2008; Lacher and Alho 1989; Moura et al. 2005). Além de possuírem capacidades e estratégias de locomoção diversas, como terrestres, escansoriais, arborícolas, fossoriais e semiaquáticas (Eisenberg and Redford 1999; Nowak 1999). Assim como a possibilidade de partilha dos recursos alimentares tendendo à onivoria, frugivoria, herbivoria, insetivoria, folivoria ou granivoria (Paglia et al. 2012).

Visto que a modificação da paisagem ocorre de forma mais acelerada que o acesso dos pesquisadores à essa informação (Soares-Filho 1999; Name 2010), o uso do Sistema de Informação Geográfica (GIS, sigla em inglês) representa uma alternativa ao acesso da modificação da paisagem em estudos que buscam entender como a estrutura da paisagem influencia na ocorrência e distribuição das espécies, assim como contribuem para o conhecimento e conservação das comunidades e do ecossistema como um todo. Nesse contexto, este projeto de tese busca estudar e utilizar a ferramenta GIS, para a avaliação da conservação de pequenos mamíferos não-voadores na Amazônia brasileira, frente as mudanças climáticas e à pressão da degradação antrópica, gerando informações que contribuam para o conhecimento sobre a distribuição e ecologia de pequenos mamíferos não-voadores da Amazônia Brasileira. Assim, o questionamento central dessa tese é: Como conservar a biodiversidade de pequenos mamíferos não-voadores na Amazônia Brasileira?

Considerando que os fatores responsáveis pela estruturação das comunidades biológicas nos ecossistemas podem ser de natureza intrínseca (características ecológicas e evolutivas, competição) e/ou extrínseca (clima) (Ricklefs 1996), no capítulo 1, intitulado "*State of the art on the knowledge: a scientometric analysis of small non-volant mammals from Brazil (Didelphimorphia and Rodentia)*", realizamos uma análise cienciométrica sobre pequenos mamíferos não-voadores da região neotropical, identificando os padrões temporais, espaciais e os principais temas abordados nas publicações nos últimos 50 anos (1970 – 2020), com ênfase no Brasil e analisamos como as espécies de pequenos mamíferos não-voadores se comportam frente às ameaças frequentes de perda de hábitat nas florestas tropicais.

Devido ao acelerado processo de perda e fragmentação da biodiversidade, consequência da ação humana, o conhecimento sobre a distribuição das espécies e lacunas existentes na conservação de pequenos mamíferos não-voadores na Amazônia brasileira e como essas espécies respondem a essa dinâmica em diferentes redes de reserva, torna-se urgente. Com isso, no capítulo 2, intitulado "*Where are the small non-volant mammals (Didelphimorphia and Rodentia) of the Brazilian Amazon and who will protect them*?", identificamos as áreas com maior diversidade de pequenos mamíferos não-voadores, das ordens Didelphimorphia (Didelphidae) e Rodentia (Cricetidae; Echimyidae; Caviidae) e a contribuição das Áreas de Proteção Integral (SPA), Áreas de Uso Sustentável (SUA) e Terras indígenas (IT) para a conservação das espécies e dos serviços ecossistêmicos na Amazônia brasileira, dando ênfase aos enclaves de Cerrado (savanas amazônicas).

Por fim, para avaliar o papel das Unidades de Conservação existentes na Amazônia brasileira para a conservação da biodiversidade de pequenos mamíferos não-voadores, o terceiro capítulo intitulado "*Priority enclaves of the Amazon*

Cerrado for the conservation of small non-volant mammals (Didelphimorphia, Rodentia) in the Brazilian Amazon" testa se a atual rede de terras protegidas existente na Amazônia brasileira é adequada para a conservação da biodiversidade de pequenos mamíferos não-voadores, identificando a importância dos enclaves de Cerrado (savanas amazônicas) e se essas áreas estão localizadas em áreas já degradadas ou sobre áreas ainda com vegetação presente na Amazônia.

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2. Sessão I

State of the art on the knowledge: a scientometric analysis of small non-volant mammals from Brazil (Didelphimorphia and Rodentia)

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State of the art on the knowledge of small non-volant mammals (Didelphimorphia, Rodentia) from Brazil

Short tittle: The knowledge of small non-volant mammals from Brazil

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Abstract: Considering the diversity of non-flying small mammals in the Neotropical region, the impact of landscape change, and the lack of knowledge about the real impacts on this mega group, we developed a scientometric analysis over a 50-year interval. The study focuses on Neotropical countries, especially Brazil, and aims to point out how these communities are structured in different environments. We searched for word combinations in the databases of the Science, Scielo, and Scopus websites, resulting in 5,144 records, of which 2,941 were removed from the analysis due to their inadequacy of our topic. Of the 2,203 manuscripts that fit the objective of our study, 816 articles were carried out in Brazil, representing 46% of all publications related to the Neotropical region. The biome with the highest number of publications was the Atlantic Forest. At the same time, the knowledge gaps about the Cerrado and Amazon biomes are still evident. It is known that, in Brazil, the inequality in the concentration of investments in research is also reflected in quality scientific production. In this sense, our results highlight the need for a severe policy of investments in science and technology in the country, with partnerships between states and evaluation of the least studied biomes.

Key-Words: Brazil; Cerrado; Didelphimorphia; Landscape structure; Rodentia.

Resumo: O estado da arte sobe o conhecimento de pequenos mamíferos não-voadores (Didelphimorphia e Rodentia) do Brasil. Considerando a diversidade de pequenos mamíferos não voadores na região Neotropical, o impacto da mudança da paisagem na diversidade de espécies e a falta de conhecimento sobre os reais impactos neste grupo megadiverso, desenvolvemos uma análise cienciométrica sobre o grupo nos últimos 50 anos. O estudo tem como foco os países neotropicais, especialmente o Brasil, e tem como objetivo apontar como essas comunidades se estruturam em diferentes ambientes. Buscamos combinações de palavras nas bases de dados Web of Science, Scielo e Scopus, resultando em 5.144 registros, dos quais 2.941 foram retirados da análise por inadequação ao nosso tema. Dos 2.203 artigos que se enquadram no objetivo do nosso estudo, 816 artigos foram realizados no Brasil, representando 37% de todas as publicações relacionadas à região Neotropical. O bioma com maior número de publicações foi a Mata Atlântica. No entanto, as lacunas de conhecimento sobre os biomas Cerrado e Amazônia ainda são evidentes. Sabe-se que, no Brasil, a desigualdade de concentração de investimentos em pesquisa também se reflete na produção científica de qualidade. Nesse sentido, nossos resultados evidenciam a necessidade de uma política séria de investimentos em ciência e tecnologia no país, que apoie parcerias e pesquisas realizadas em estados e biomas menos estudados.

Palavras-Chave: Brasil; Cerrado; Didelphimorphia; Estrutura da paisagem; Rodentia.

INTRODUTION

The Neotropical region runs from Central Mexico to Southern Brazil, including Central America such as Caribbean islands and a large part of South America (Morrone, 2014; Noguera-Urbano & Escalante, 2017;). It is the most diverse biogeographic realm, comprising about 25% of mammalian diversity (Burgin *et al.,* 2018) and seven of 35 biodiversity hotspots (Williams *et al.,* 2011). However, the existing biodiversity and ecosystem services in this region are under constant threat. At least ¼ of 14,000 species from known taxonomic groups are at risk of extinction in terrestrial, freshwater, and marine environments (Joly, 2018). Neotropical species are still poorly studied or unknown, and their ecological aspects, origin and evolutionary history are not fully understood (Antonelli & Sanmartin, 2011; Tinoco *et al.,* 2015; Turchetto-Zolet *et al.,* 2013). Within the Neotropical region, Brazil occupies almost half of South America and is home to two of the world's biodiversity conservation hotspots (Cerrado and Atlantic Forest; Myers *et al.,* 2000), as well as a large part of the Amazon rainforest.

Estimates indicate that Brazil is home to between 15% to 20% of the 1.5 million described species in the world (Lewinsohn & Prado, 2002), of which 775 species are mammals, comprising 11 orders, 51 families, and 247 genera (Abreu Jr. *et al.,* 2022; Quintela *et al.,* 2020). The most diverse orders are Rodentia (267 species), Chiroptera (182 species) and Primates (131 species). Cricetidae (Rodentia) is the most diverse family, with 155 species (Abreu Jr. *et al.,* 2022; Quintela *et al.,* 2020). Although mammals are the best-known group of organisms, it is estimated that there are still many species to be discovered and described, mainly species of rodents, marsupials, and bats (Mendes-Oliveira *et al.,* 2015a). Despite the increase in current inventories, which are associated with a cytogenetic and molecular approach, it is still possible to find sampling gaps for species and ecosystems, especially from Cerrado, and Amazon regions (Mendonça *et al.,* 2018).

A large amount of Neotropical mammals is sensitive to human activities, which cause changes in the structural complexity and heterogeneity of habitats (Uhl & Vieira, 1989). However, habitat loss appears to have a more negative impact on species loss than the effect of fragmentation itself (*e.g.,* changes in habitat configuration and isolation; Fahrig, 2003; Fahrig *et al.,* 2019). Depending on the impact, intensity and modification, replacement and/or simplification of habitats, these changes may reflect on the availability of food resources, protection, or support, which influence the structure of biological communities in a given area (Malcolm, 1995). Community responses to habitat loss may differ according to the type of impact and the ecological characteristics of the species (Bernard *et al.,* 2011).

Small non-volant mammals, that belongs to the orders Didelphimorphia (family Didelphidae) and Rodentia (families Cricetidae, Muridae, and Echimydae), comprises one of the most diverse groups of Neotropical mammals (Gardner, 2008; Patton *et al.,* 2015). They present diverse strategies of habitat use, including terrestrial, arboreal, scansorial, semi-aquatic, semi-fossorial, and fossorial animals (Cunha & Vieira, 2004; Dalmagro & Vieira, 2005; Merritt, 2010), and a varied diet, being omnivores, insectivores and frugivores (Paglia *et al.,* 2012; Pena & Mendes-Oliveira, 2019; Pinheiro *et al.,* 2002; Pinto *et al.,* 2009; Vieira, 2003). There are also carnivore/vermivore (some small marsupials), folivore and granivore (several small rodents) species (Verde Arregoitia & D'Elía, 2021).

The assessment of the state of the art of mammalogy in pioneering studies in Brazil, at the beginning of this century, were marked by the contributions of Alipio de Miranda Ribeiro, Hermann von Ihering, Paulo Schirch, Emilio Goeldi, G. Hagmann and Emilia Snethlage (Ávila-Pires, 1960). Currently, biodiversity is an object of study by researchers all over the world, and its main documentation relies on scientific collections (Prudente, 2003). However, in recent years, the concern with monitoring scientific production has grown, mainly due to the discovery of new species (Zaher & Young, 2003). Therefore, metric, quantitative, and qualitative studies are increasingly needed. Among the applied methods, scientometrics stands out as the area dedicated to quantitative studies of scientific activities related to the production, propagation, and use of scientific information by a given country, scientific community, or institution (Spinak, 1998).

Thus, considering the high diversity of mammals of the Didelphimorphia and Rodentia orders and the impact of landscape change on species richness and diversity, we carried out a scientometric study with small non-volant mammals from the Neotropical region. We identify the temporal and spatial patterns, and the main themes addressed in publications over 50 years (1970-2020), emphasizing the studies conducted in Brazil. With this study, we were able to answer: (i) What is the temporal trend of scientific articles regarding small non-volant mammals of the Neotropical region and Brazil? (ii) In which Brazilian biomes small non-volant mammals are more studied? (iii) What are the most studied species of small non-volant mammals in

Brazil? (iv) What is the contribution of Brazilian states to the development of research with small non-volant mammals in Brazil? (v) What is the number of articles per area of knowledge/subject produced in Brazil? and, finally, (vi) What are the main landscape variables used to study the community structure of small non-flying mammals in areas with different landscape matrices in Brazil?

MATERIAL AND METHODS

We built a database reviewing all scientific articles published in indexed journals for a period of 50 years (from 1970 to 2020). We searched for studies carried out with small non-volant mammals in the Neotropical region, restricted to the Americas, in all databases of the Clarivate PLC (Web of Science – https://clarivate.com/webofsciencegroup/solutions/web-of-science), SciELO (Scientific Electronic Library Online – https://scielo.org), and Scopus (https://www.scopus.com) in January 2021, comprising publications in Portuguese, English, and Spanish. The first search field was selected to include all articles related to small mammals. We used a combination of the following terms: "small mammal" OR "small mammals" OR "Rodentia" OR "rodent" OR "sigmodontine" OR "Cricetidae" OR "cricetid*" OR "Didelphimorphia" OR "Didelphidae" AND "Neotropical" OR "Neotropics". Where retrieved from each of the databases from 1970 to 2020: 19,469 documents, of which 198 corresponded to Brazil (WOS); 10,799 documents, of which 524 corresponded to Brazil (Scopus) and 645 documents, of which 94 corresponded to Brazil (Scielo).

These combinations resulted in 5,144 records. A second stage was carried out, where 2,941 were removed from the analysis (scientometrics, meta-analyses, summaries, book chapters, monographs, dissertations, theses and reviews), as they are works that do not have wide circulation and the majority have not gone through an editorial board, which may restrict the reach of these works by researchers from other countries, as well as duplicate records. After examining the abstracts and refining the database, only articles that fitted our objectives were listed. Therefore, we proceeded with a scientometrics on small non-volant mammals from the Neotropical region, emphasizing the studies carried out in Brazil, which resulted in a total of 2,203 articles.

Finally, each abstract was carefully read and checked against the following criteria to determine if the reference was appropriate for our assessment: article title, journal, year of publication, DOI, countries, and continent where the work was carried out. For articles that were performed in Brazil, we collected the following information: biome; search area; whether they were marsupials or rodents; which species were studied; in which Brazilian states the studies were conducted; and which articles used predictor variables (*e.g.,* environmental variables) in the study. All this information was gathered in tables using Microsoft Excel (2013). Regarding taxonomy, in order not to homogenize the names of the species mentioned in the articles, since several have undergone taxonomic revisions and changes in delimitation and nomenclature, we have reviewed and adapted the species using data compiled by several authors (Abreu Jr. *et al.,* 2022; Gardner, 2008; Patton *et al.,* 2015; Pavan, 2019; Pavan *et al.,* 2012; 2014; Quintela *et al.,* 2020).

We compared the number and percentage of articles published by each Neotropical country in the 50-year period using bar and pie charts. We also quantified the number of species included in the different IUCN red list categories per year for Brazil using Sperman's correlation analysis that considered the number of studies per year and the number of species listed by the IUCN.

We constructed the temporal trend of the number of articles for the Neotropical region (restricted to the Americas) and Brazil, investigating the number of articles published per year in Brazil; in the Neotropical region (excluding Brazil); and the number of articles published in the world. The lines of the graph represent all publications found in this study, where one line shows the number of publications from the Neotropical region (Americas without data from Brazil) that were selected by our scientometrics per year, divided by the total number of articles that were published in the world *per annum.* The second line on the graph went through the same process; however, there is a limit, but with the number of publications made in Brazil, excluding Neotropical data. For the time trend, the number of articles was transformed into relative frequency (number of articles of interest to this study divided by the total number of articles indexed in ISI, Scielo and Scopus in the year, multiplied by 100). We divided the annual article production by the total article production to eliminate the effect of the temporal increase (Nabout *et al.,* 2012).

We quantified the percentage of studies performed for non-volant small mammals in Brazilian biomes using a map with biome divisions to demonstrate our results and implemented a temporal trend analysis. To verify the number of citations that each species obtained in studies carried out in Brazil, we set up an updated table

(Table S1 – supplementary material) with the taxonomy of the species based on data compiled by Abreu Jr. *et al.* (2022); Díaz-Nieto & Voss (2016) for *Marmosops;* Gardner (2008), Patton *et al.* (2015), Pavan *et al.* (2017); for *Monodelphis;* Quintela *et al.* (2020); Voss & Jansa (2009) and Voss *et al.* (2019) for *M. myosuros.*

We categorize the contribution of Brazilian states to the development of research on small non-volant mammals by calculating the percentage of publications carried out by each state and we demonstrate the results through a map of political divisions. We identified the total number of articles developed in Brazil by the area of knowledge through a bar graph, where we plotted the most studied subject, allocating each article in only one study category. The categories of the knowledge area were defined, for example: Parasitology – Studies that assess parasites, their hosts and the relationships between them; Geographic distribution – Describes and explains the distribution of communities of living beings and their relationships with other elements of the physical and human environment; Diet – It features the ability of a species to take advantage of a more advantageous food source at a given time; Genetics – Study the mechanisms of heredity or biological inheritance; Morphometry – Way or act of measuring the body dimensions of a certain species.

Articles published in Brazil that evaluated local environmental metrics were placed together with landscape variables (Table 1) applied to study the community structure of small non-volant mammals in areas with different landscape matrices. Additionally, we implemented a hierarchy chart considering the main journals in which studies carried out in Brazil between 1970 and 2020 were published. The analyzes were performed in the R environment (R Core Team 2021) and the maps in the QGis 3.10 program (SIG, 2013).

RESULTS

Of the 2,203 manuscripts selected regarding small non-volant mammals, 816 were carried out in Brazil, representing 37% of all works published about the Neotropical region (Figure 1). Argentina was the second country that most contributed with publications (25.2%), followed by Chile (7.2%). Countries such as El Salvador, Guatemala, Nicaragua and the Caribbean region contributed less than 5% of publications each (Figure 1).

Correlation analysis (Figure 2) showed that publications focused mainly or majority on species with conservation status of Least Threat Concern (Figure 2A– Least concern) (p = 0,0001; r = 0,9275), and critically endangered species (Figure 2B – Critically endanged) (p = 0,839; r = -0,0950) or in danger were less studied with increasing number of publications in Brazil. At the same time, species with deficient data (Figure 2C – Data deficient) (p = 0,0001; r = 0,8693) or that have not yet been analyzed because they were recently described or revalidated, do not have criteria or the data are inefficient for their assessment as a threat.

As evidenced by the time trend graph (Figure 3), in the years 1979, 1987, 1995, 2004, 2015, 2018 and 2020, Brazil surpassed other countries in the Neotropics in terms of the number of publications. Even showing the same general trend in 1996, Brazil showed a considerable drop between the years 1982, 1985, 1989, 1996 and 1998

(Figure 3). Despite the fluctuations over the years, Brazil had a peak in the number of publications in 2009 (Figure 3).

The biome with the highest number of publications was the Atlantic Forest, with 478 articles (Figure 4). The Cerrado (with 232 articles) and the Amazon (113) were the second and third biomes with the largest number of studies carried out with small non-volant mammals in Brazil, respectively (Figure 4). The Pampa (87 articles), the Caatinga (71 articles) and the Pantanal (20 articles) were the biomes with the lowest number of documents.

According to our data, studies on the Amazon biome were first published in 1995, but the percentiles of studies increased only in 2001 (Figure 5). Although with notable “ups and downs”, the Atlantic Forest curve shows a general upward trend, from the late 1970s to the mid-2010s (Figure 5), however, the curve shows a general downward trend in the last five years studied. A similar pattern is shown by the Cerrado biome and, to a lesser extent, the Pampa biome. The Caatinga, Amazon and Pantanal biomes seem to show a more stable trend (Figure 5).

In the 816 studies carried out in Brazil, 395 of them carried out research at the species level, while 406 addressed themes in the community of species. In our study, we recorded six families, eight subfamilies, 74 genera and 261 cited species (58 marsupials and 203 rodents) (Table S1 - Supplementary material). Compared with other groups of mammals, the study with small non-volant mammals in Brazil is scarce, however, there is a significant amount of information in the literature that addresses and cites a high number of species: of the 984 citations of species, 547 were citations of rodent species and 437 of marsupial species, representing 55.5% and 44.4% of the citations, respectively (Table S1 – Supplementary material).

Of the 260 species mentioned in the works carried out in Brazil, 217 are included in some IUCN (International List of Threatened Species) threat category (Supplementary material): 61.5% (164 species) listed as Least Concern – LC; 3% (nine species) listed as Threatened – EN; 2.6% (six species) listed as Near Threatened – NT; 1.1% (four species) listed as Critically Endangered – CR; 1.9% (six species) listed as Vulnerable – VU; and 10.7% (28 species) listed as Deficient Data for Conservation – DD. However, there is not enough information for, for example, species like *Neacomys marajoara, Neacomys vossi* e *Neacomys xingu,* that have been recently described, are evaluated and validated for their threat (Semedo *et al.,* 2020). Of the Brazilian species cited in the articles, 28 are on the Red List of Endangered Brazilian Fauna (ICMBio, 2018), with 17 species classified as Endangered – EN; eight as Vulnerable – VU and three as Critically Endangered – CR.

Among marsupials, the most cited species were *Didelphis aurita* (Wied-Neuwied, 1826) (14% of citations), *Didelphis albiventris* Lund, 1840 (13.5%), *Gracilinanus microtarsus* (Wagner, 1842) (8.8%), *Metachirus nudicaudatus* (Geoffroy, 1803) (8.2%) and *Gracilinanus agilis* (Burmeister, 1854) (7.8%) (Supplementary Material). Among rodents, the species with the highest percentage of citations were *Necromys lasiurus* (Lund, 1841) (11.7%), *Nectomys squamipes* (Brants, 1827) (9.6%), *Akodon montensis* Thomas, 1913 (7.,3%) and *Akodon cursor* (Winge, 1887) (7%) (Table S1 – Supplementary Material). These rodent species are classified as Least Concern – LC by IUCN (2020).

We observed a high spatial heterogeneity of scientific research activities in Brazil, where the regional pattern of publications is highly concentrated in the Southeast region (Figure 6), especially in Rio de Janeiro (198 articles), Minas Gerais (158 articles) and São Paulo (151 articles) states. Compared to other regions of the country, the North region has the lowest numbers of published articles, especially the states of Amapá (19 articles) and Roraima (nine articles).

Considering the total number of articles developed in Brazil and the subject of study (Figure 7), we observed that most publications were inventories of species (76 articles), followed by Parasitology (74), Geographical distribution (63), Diet (41), Genetics (38) and Morphometry (28) (Figure 7). It is noteworthy that we did not include some articles because they have less than ten manuscripts per area of knowledge, such as Use of Habitat (8 publications), Predation (8), Endozoochory (7) and Effect of fire (6).

Among the works published and carried out in Brazil, we identified the most used environmental variables to measure the distribution of species in the environmental gradient. Use of Habitat and Microhabitat (35 articles) was the most discussed topic to study the community structure of small non-volant mammals in areas with different landscape matrices, followed by Seasonality (25) and Climate Change (13) (Table 1).

In addition to these data, we observed that the articles analyzed in Brazil were published in 108 different journals. The journal Mammalia (82 articles) and the Journal of Mammalogy (78 articles) published the majority of studies carried out in Brazil, representing 9.9% and 9.4% of the total number of journals, followed by Mammalian Biology (46 articles, 5.6%) and Neotropical Biota (41 articles, 5%) (Figure 8).

DISCUSSION

Although the number of publications on small terrestrial mammals in Brazil is the largest for the Neotropical region, the study of the group is still restricted to some regions, ecosystems and taxa (Rossi & Bianconi, 2011) of species described for Brazil, knowledge is not linear. Brazil is a continental, developing and megadiverse country (Lewinsohn & Prado, 2002), and this greater diversity may reflect its larger area and greater diversity of environments in relation to neighboring countries. And much of this diversity, still unknown, requires a more accelerated investigative taxonomy (Quintela *et al.,* 2020) to establish future scientific measures and advances to address environmental changes that have a negative impact on biodiversity (Marques & Lamas, 2006).

The Atlantic Forest, which covers about 15% of the national territory and is the third biodiversity *hotspot* in the world (Mittermeier *et al.,* 2002), has only 4.7% of its total area within protected areas (CNUC, 2020). However, even though it is the most studied biome, as evidenced in our study (Figures 4 and 5), it has been facing intense degradation and fragmentation for decades, and this leads to a greater number of threatened species, both in richness and in absolute numbers (ICMBio, 2018). At the same time, there are still gaps in terms of geographic and taxonomic information about the group of small non-flying mammals, mainly in the Amazon biome, perhaps due to the low number of researchers in these regions, or even the difficulty of sampling in these areas (Bini *et al.,* 2006; Diniz-Filho *et al.,* 2010; Lambert *et al.,* 2005; Mendes *et al.,* 2011; Mendes-Oliveira *et al.,* 2015b; Nóbrega & De Marco, 2011; Rocha *et al.,* 2018; Silva *et al.,* 2013; Whittaker *et al.,* 2005).

The Cerrado biome, which has only 2.2% of its total area legally protected in federal conservation units (Cavalcanti & Joly, 2002; Françoso *et al.,* 2015), remains one of the least studied morphoclimatic domains (Oliveira & Marquis, 2002). Although highly threatened by land grabbing and the advance of grain cultivation (Aguiar *et al.,* 2014; Barbosa *et al.,* 2007). Cerrado areas in the Amazon biome have been suffering similar pressures, especially in the state of Amapá, where savanna areas have been converted to grain crops (mainly soybeans and corn) in the last 20 years (Carvalho & Mustin, 2017). These regions, home to rich and unique flora and fauna, including endemic animals, remain undersampled for most taxa (Mustin *et al.,* 2017). Even so, new species records were found in the state (Costa-Campos & Freire, 2015; Silva *et al.,* 1997; 2013), increasing the possibility of better sampling in the region.

Despite the species richness of small non-volant mammals (Burgin *et al.,* 2018; Cole *et al.,* 1994; Wilson *et al.,* 1996), the Neotropical region is still poorly studied regarding the importance of these organisms to the ecosystem (Ernest & Mares, 1986; Fleming, 1975; Stallings, 1989), as these animals play an important role in the maintenance and regeneration of tropical forests, presenting vital ecological functions and being key in the structuring of biological communities (Grelle, 2003; Sánchez-Cordero & Martinez-Gallardo, 1998), in addition to being good indicators of local changes in habitat and landscape (Pardini & Umetsu, 2006).

Of the 1300 species of fauna and flora endemic to Brazilian biomes that are threatened with extinction (ICMBio, 2018), the species *Caluromysiops irrupta* Sanborn, 1951 is the only one described for the genus. It is listed in the IUCN (2020) in the Least Concern (LC) category, however, little is known about this rare species, including topics as basic as reproduction (Collins, 1973). The endemic species of the Cerrado biome, *Oligoryzomys rupestris* Weksler & Bonvicino, 2005, is evaluated as Data Deficit (DD) on the IUCN List (2020), has limited distribution, occurring only in conserved areas, and has restricted habitat use (Bonvicino *et al.,* 2002). Already the species *Kerodon rupestris* (Wied-Neuwied, 1820), restricted to the Caatinga, it is classified as Least Concern by the IUCN (2020), but the expansion of agricultural activities represents the main threat factor for these species, followed by hunting (Lapola *et al.,* 2014). Regional lists classify species as: critically endangered (CR), endangered (EN) and vulnerable (VU), respectively, reflecting these scenarios.

Although Brazil leads the production of scientific articles compared to other Latin American countries, our results highlight the spatial heterogeneity of scientific production and collaboration within the country. Even with world-renowned research institutions and renowned researchers, according to the National Council for Scientific and Technological Development (CNPq) and the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil has been showing a drop in investments in teaching and research. Since 2015 In Brazil, 80% of science and technology research is linked to postgraduate programs at public universities (Hilu & Gisi, 2011; Van Noorden, 2014). Since the second half of 2019, due to interruptions in the payment of scholarships, there has been a technological gap in laboratories and universities that have risked several scientific programs (IPEA, 2020), and this ends up influencing the scientific production of these institutions.

As observed in this study, the survey of scientific production on small non-flying mammals, through studies on various topics, such as inventories and lists of species, carried out in Brazilian biomes, contributes to the state of the art of the group and helps in the discovery of new species and expands the knowledge about the geographic distribution of these species. Research topics such as Species Inventories, Geographical Distribution, Taxonomy, Reproduction, Diet and Genetics are extremely relevant for ecological studies of this group. However, the number of studies related to “habitat fragmentation” was low compared to other areas of knowledge. The lack of specialists in the area and the scarcity of studies on various topics and for many taxa can be one of the negative points in the search for knowledge of these organisms (Mendes-Oliveira *et al.,* 2015c). These works characterize the composition of species in the environment, contributing to the taking of measures for the delineation of areas destined for management and conservation, in addition to establishing parameters for comparison with degraded or fragmented areas (Pardini & Umetsu, 2006).

Although Brazil hosts a large number of mammal specimens in its collections, this number is far from representing the diversity of mammals in the country (one article observed in this study). Given the diversity of existing species, the geographic coverage of collections is mainly regional or national (Chiquito *et al.,* 2021). Recently, the Sociedade Brasileira de Mastozoologia included a list of Brazilian mammal species (Abreu Jr. *et al.,* 2022) that are formally described and have confirmed records in Brazil through specimens deposited in scientific collections or have documented records of occurrence in the Brazilian scientific literature.

It is known that in Brazil the assessment of science is unequal and that the inequality in the concentration of investments in research is also reflected in the production of quality science. However, even with fewer researchers compared to the global average, Brazilian scientists stand out for their relevance in cutting-edge scientific production (FAPESP, 2021; OCTI, 2021). In this sense, our results highlight the need for a better investment policy in science and technology in the country, which supports alliances and research in the least studied states and biomes. In this way, it will be possible to address important issues for the knowledge and conservation of small mammals, such as fragmentation and habitat loss.

The survey of scientific production in Brazil on small non-Volant mammals (Didelphimorphia and Rodentia) contributes to the knowledge of the state of the art of the group, identifying the main characteristics addressed in the works. It also reflects the large number of works carried out in different areas of knowledge and in different Brazilian biomes, especially in the Brazilian Amazon. However, studies with this group should be expanded, especially in the northern states of the country, due to the scarcity of studies carried out compared to the great existing diversity.

The present study demonstrated a considerable advance in the knowledge of small non-volant mammals (Didelphimorphia and Rodentia) in the last 50 years. Despite the large number of articles on topics in ecology, it is understood that it is necessary to expand studies on the composition and inventory of species in these groups in environments, due to their importance in providing subsidies in the design of priority areas for conservation.

It is also suggested that future research on the quantitative study of small mammals be expanded, with the aim of recognizing the characteristics present in the scientific production of non-indexed articles.

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DECLARATION OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest in relation to this article.

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SUPPLEMENTARY INFORMATION ONLINE

Appendix S1. List of small non-volant mammals (Rodentia, Didelphimorphia) that occur in Brazil and their conservation status based on national (ICMBio 2018) and international lists of threatened species (IUCN 2019). The number of citations recorded for each species addressed in the selected articles was based on data compiled by Abreu Jr. et al. (2021); Díaz-Nieto & Voss (2016); Gardner (2008), Paglia et al. (2012), Patton et al. (2015), Pavan & Voss (2006); Quintela et al. (2020); Voss & Jansa (2009) and Voss et al. (2019). Acronyms: CR = Critically Endangered, DD = Data Deficient, EN = Endangered, LC = Least Concern, NT = Near Threatened, VU = Vulnerable. Dataset: https://bjm.emnuvens.com.br/bjm/article/view/77

Appendix S2. Final database reviewing all scientific articles published in indexed journals for a period of 50 years (from 1970 to 2020) for small non-volant mammals (Didelphimorphia and Rodentia). Dataset: https://bjm.emnuvens.com.br/bjm/article/view/77

Table 1: Type of landscape descriptors and analyzes of predictor variables addressed in articles on small non-volant mammals (Didelphimorphia and Rodentia) that were published in Brazil.

Landscape variables	Landscape analysis	Number of publications
Complexity and environmental heterogeneity	Correlating the heterogeneity and complexity of different phytophysiognomies with the composition, abundance, and richness of small mammals (vegetation density in vertical strata)	6
Climate changes	Effect of weather and wind; Temperature (°C); Relative humidity; El Niño effects; light intensity, wind speed and direction; ambient noise and rain; fire effect in places of different ages	13
Forest fragments	Connectivity between forest fragments and vegetation patches; vegetation corridors (corn plantations, pastures, human buildings, vegetation corridors); secondary forests in different stages of regeneration; influence of fragment size on capture success through radio tracking	7
Anthropic impact	Effect of grazing at different pressures; different management regimes; possible effects of future deforestation on mammals using the species-area relationship; clearings caused by mining that produce an edge effect on the assemblage of small mammals; amount of deforested area; construction of hydroelectricpower stations; hunting	11
Habitat and microhabitat use	Analysis of the species' meso and macro habitats; changes in microhabitat use patterns; use of the matrix of open areas and the frequency of species' movements between fragments; whether individuals actively select different diameters and slopes of branches; whether vegetation structure and availability of food resources affect functional traits; whether species tolerate habitat disturbance and trophic guild; patterns of species co-occurrence at different spatial scales; whether different habitat matrices affect the diet, locomotion, behavior and home range of species	35
Seasonality	If drought and rain are factors that contribute to population and intrapopulation variation in the breadth of the food niche; whether the area of daily activities is affected by climatic (dry and wet) and reproductive seasons	25

List of Figures

Figure 8. Main journals that published articles about small non-flying mammals (Didelphimorphia, Rodentia) in Brazil, between 1970 and 2020.

Figure 1

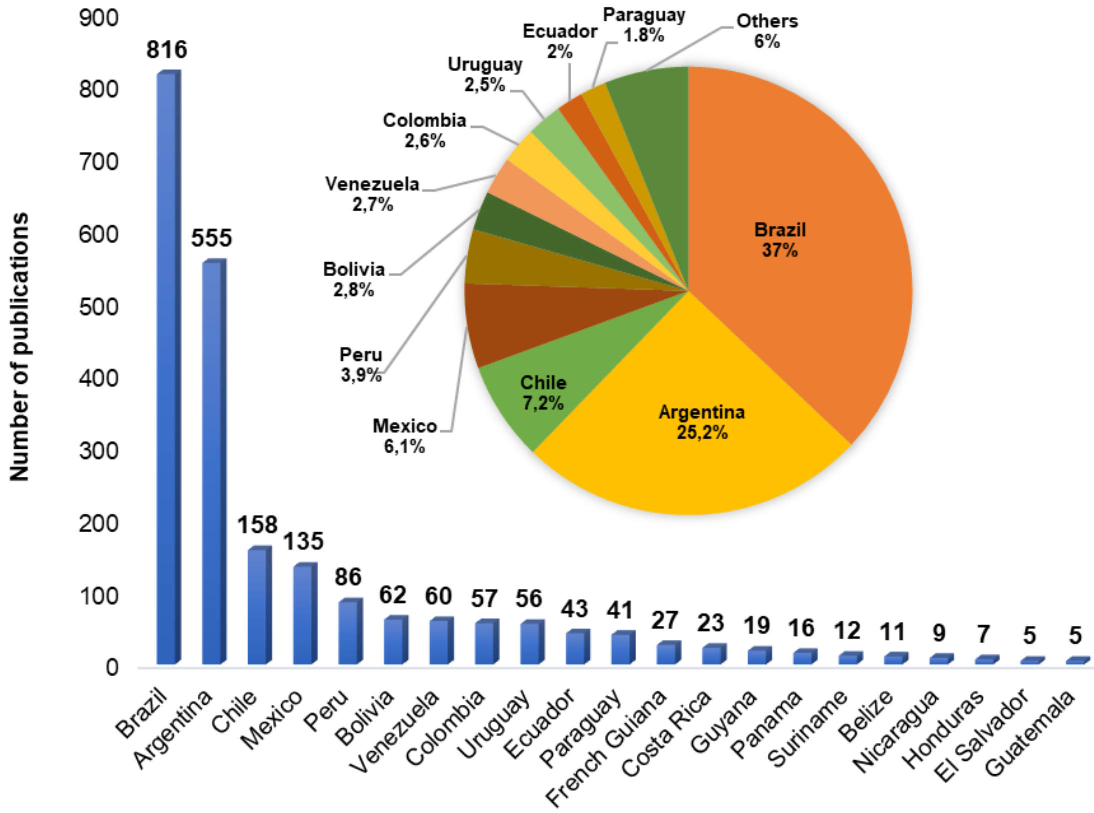

Number of publications
900
800
700
600
500
400
300
200
100
0
816
555
158
135
86
62
60
57
56
43
41
27
23
19
16
12
11
9
7
5
5
Brazil
Argentina
Chile
Mexico
Peru
Bolivia
Venezuela
Colombia
Uruguay
Ecuador
Paraguay
French Guiana
Costa Rica
Guyana
Panama
Suriname
Belize
Nicaragua
Honduras
El Salvador
Guatemala
Brazil 37%
Argentina 25,2%
Chile 7,2%
Mexico 6,1%
Peru 3,9%
Bolivia 2,8%
Venezuela 2,7%
Colombia 2,6%
Uruguay 2,5%
Ecuador 2%
Paraguay 1.8%
Others 6%

Figure 2

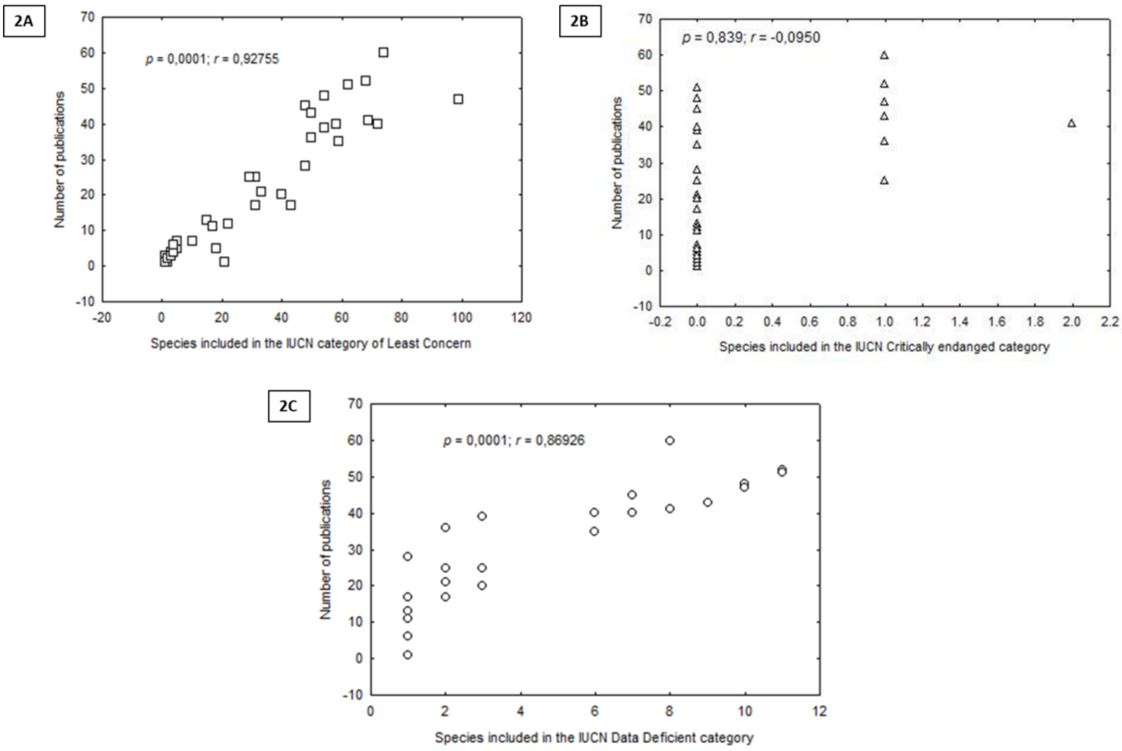

2A
p = 0,0001; r = 0,92755
Number of publications
Species included in the IUCN category of Least Concern
2B
p = 0,839; r = -0,0950
Number of publications
Species included in the IUCN Critically endanged category
2C
p = 0,0001; r = 0,86926
Number of publications
Species included in the IUCN Data Deficient category

Figure 3

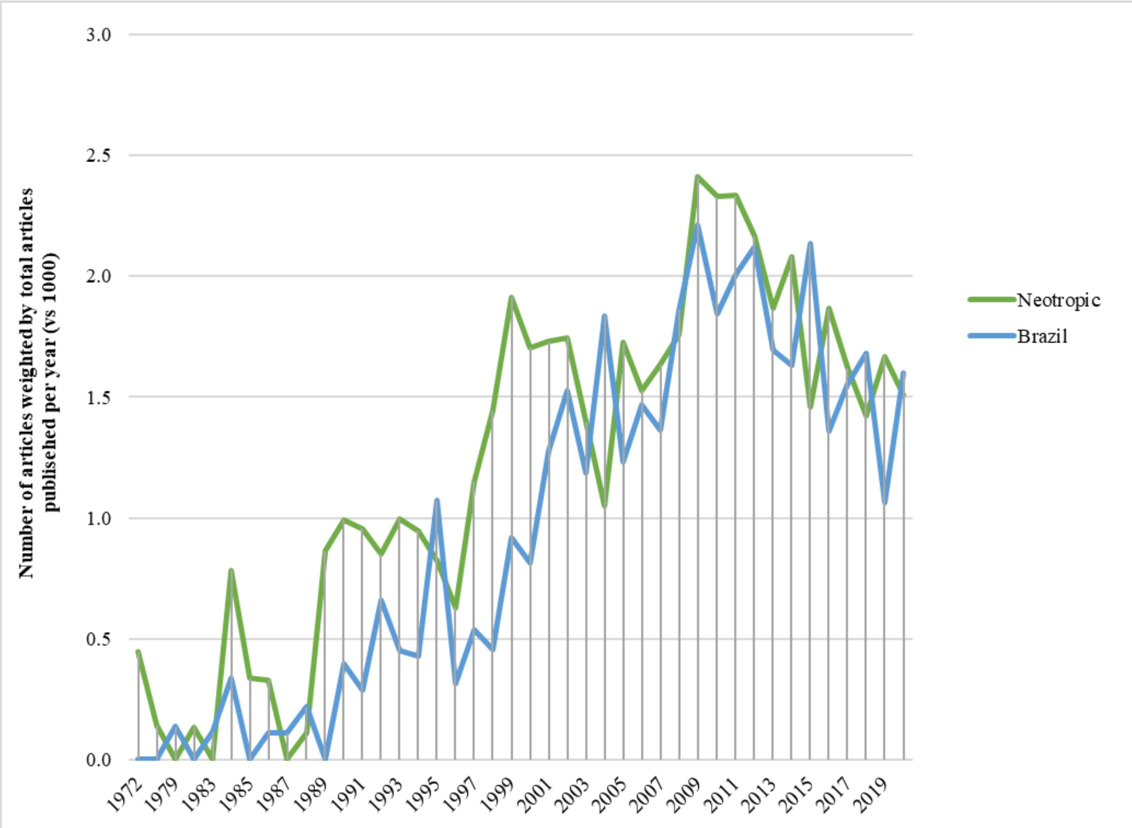

Number of articles weighted by total articles publisehed per year (vs 1000)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1972
1979
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Neotropic
Brazil

Figure 4

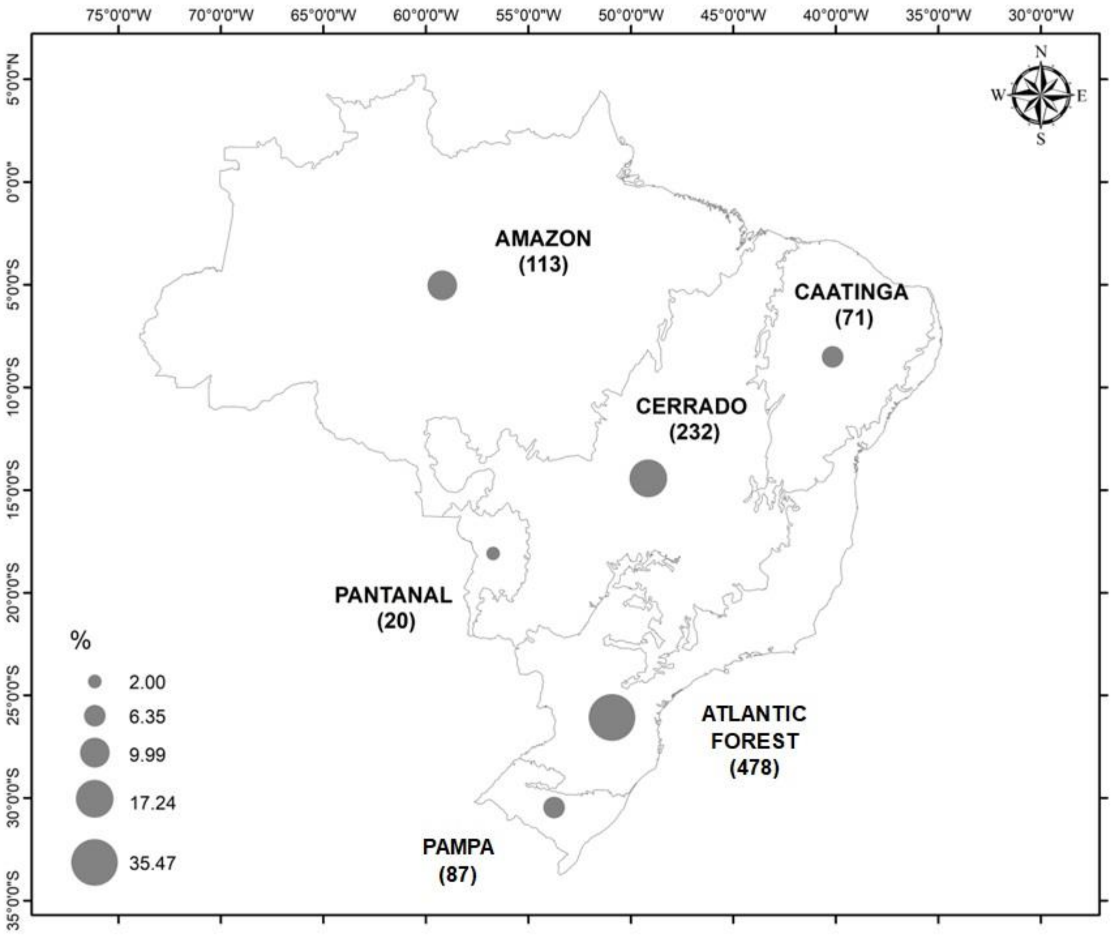
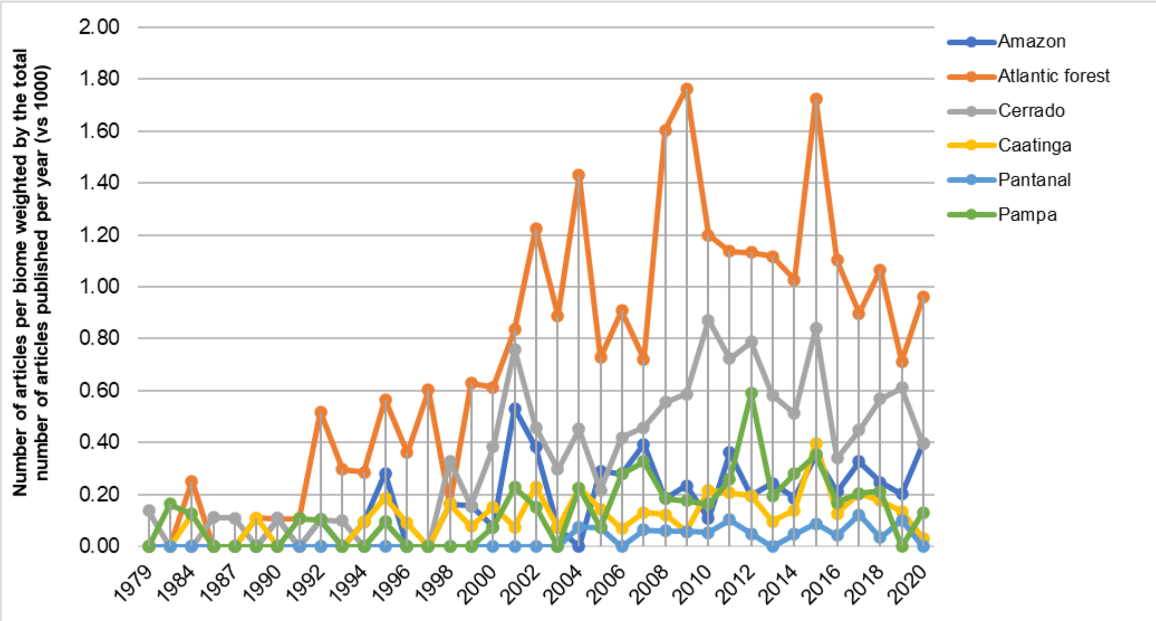

75°0'0"W
70°0'0"W
65°0'0"W
60°0'0"W
55°0'0"W
50°0'0"W
45°0'0"W
40°0'0"W
35°0'0"W
30°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
20°0'0"S
25°0'0"S
30°0'0"S
35°0'0"S
N
W
E
S
AMAZON
(113)
CAATINGA
(71)
CERRADO
(232)
PANTANAL
(20)
ATLANTIC
FOREST
(478)
PAMPA
(87)
%
2.00
6.35
9.99
17.24
35.47

Figure 5



Number of articles per biome weighted by the total number of articles published per year (vs 1000)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1979
1984
1987
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Amazon
Atlantic forest
Cerrado
Caatinga
Pantanal
Pampa

Figure 6

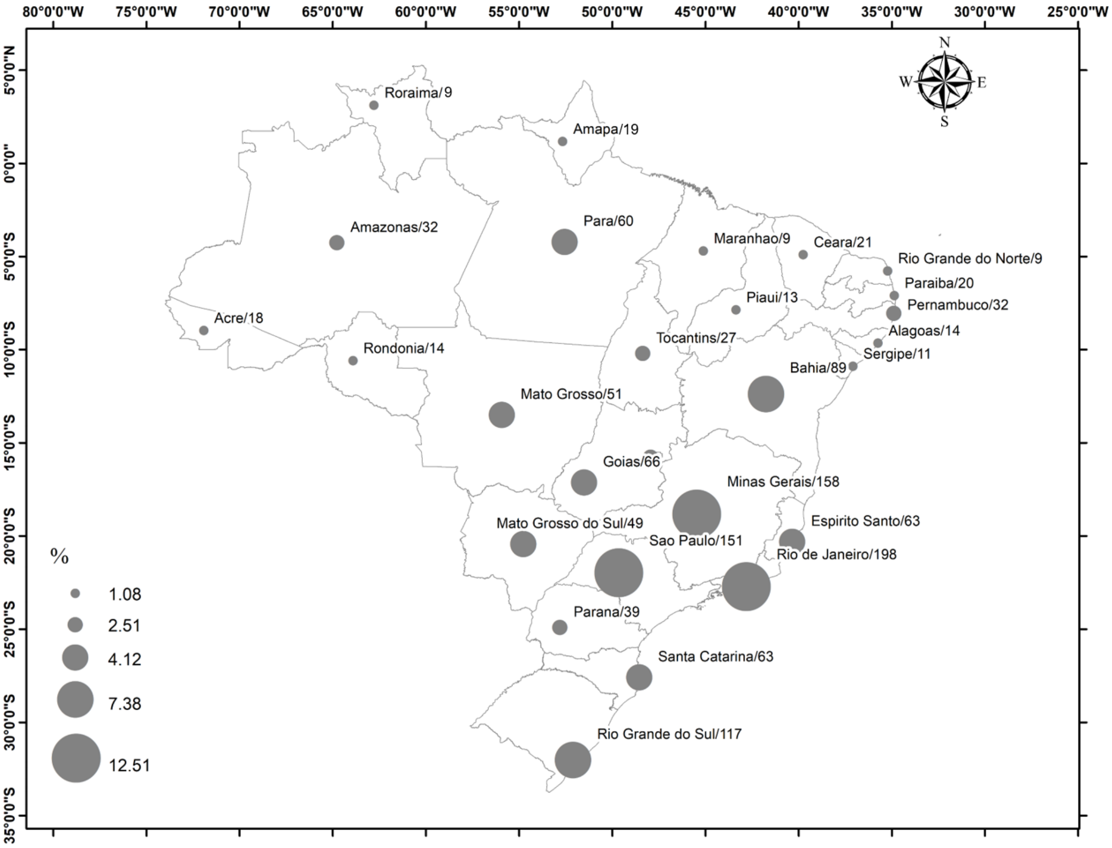

80°0'0"W
75°0'0"W
70°0'0"W
65°0'0"W
60°0'0"W
55°0'0"W
50°0'0"W
45°0'0"W
40°0'0"W
35°0'0"W
30°0'0"W
25°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
20°0'0"S
25°0'0"S
30°0'0"S
35°0'0"S
N
W
E
S
Roraima/9
Amapa/19
Amazonas/32
Para/60
Maranhao/9
Ceara/21
Rio Grande do Norte/9
Paraiba/20
Piaui/13
Pernambuco/32
Acre/18
Alagoas/14
Tocantins/27
Sergipe/11
Rondonia/14
Bahia/89
Mato Grosso/51
Goias/66
Minas Gerais/158
Espirito Santo/63
Mato Grosso do Sul/49
Sao Paulo/151
Rio de Janeiro/198
Parana/39
Santa Catarina/63
Rio Grande do Sul/117
%
1.08
2.51
4.12
7.38
12.51

Figure 7

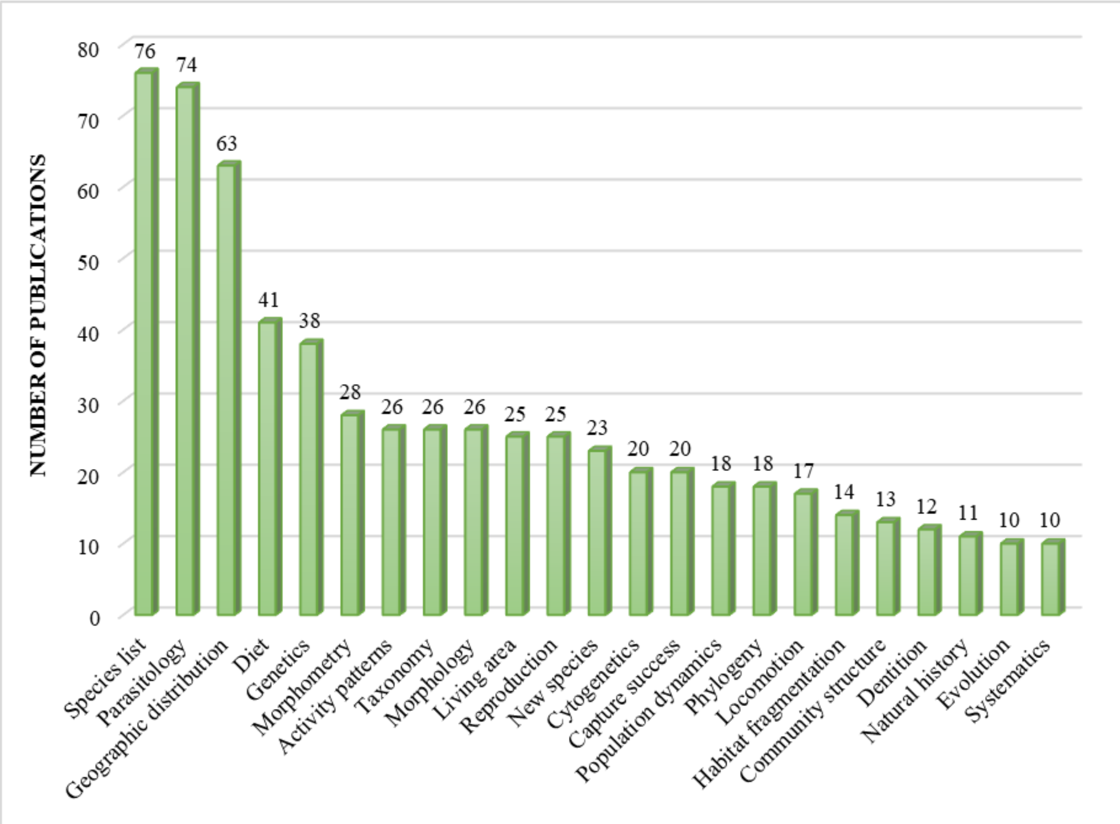
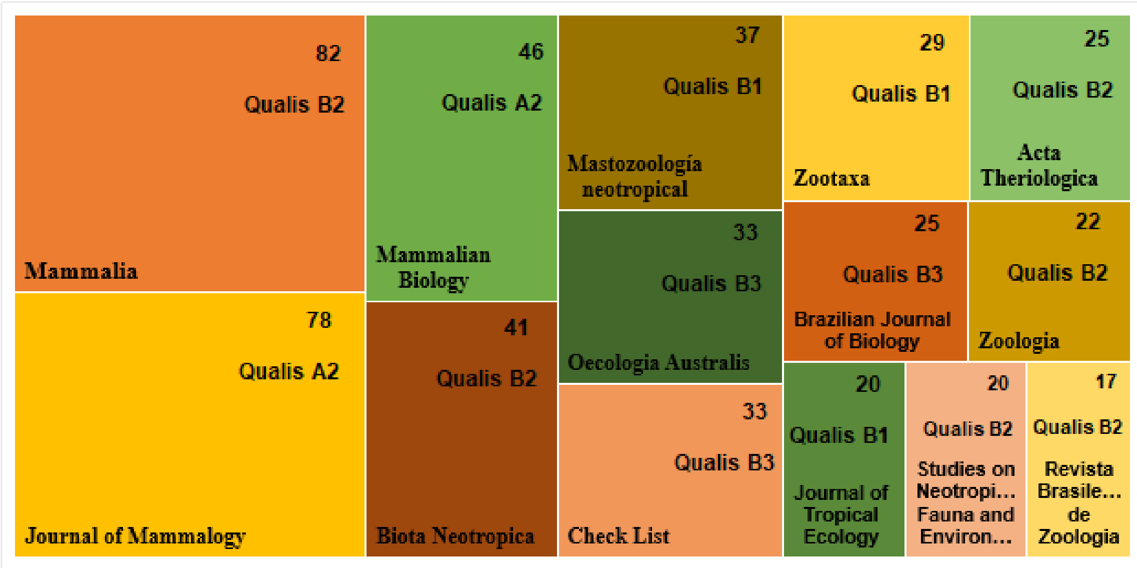

NUMBER OF PUBLICATIONS
80
70
60
50
40
30
20
10
0
76
74
63
41
38
28
26
26
26
25
25
23
20
20
18
18
17
14
13
12
11
10
10
Species list
Parasitology
Geographic distribution
Diet
Genetics
Morphometry
Activity patterns
Taxonomy
Morphology
Living area
Reproduction
New species
Cytogenetics
Capture success
Population dynamics
Phylogeny
Locomotion
Habitat fragmentation
Community structure
Dentition
Natural history
Evolution
Systematics

Figure 8


82
Qualis B2
Mammalia
46
Qualis A2
Mammalian Biology
37
Qualis B1
Mastozoología neotropical
29
Qualis B1
Zootaxa
25
Qualis B2
Acta Theriologica
78
Qualis A2
Journal of Mammalogy
41
Qualis B2
Biota Neotropica
33
Qualis B3
Oecologia Australis
25
Qualis B3
Brazilian Journal of Biology
22
Qualis B2
Zoologia
33
Qualis B3
Check List
20
Qualis B1
Journal of Tropical Ecology
20
Qualis B2
Studies on Neotropi… Fauna and Environ…
17
Qualis B2
Revista Brasile… de Zoologia

3. Capítulo II

WHERE ARE THE SMALL NON-VOLANT MAMMALS (DIDELPHIMORPHIA AND RODENTIA) OF THE BRAZILIAN AMAZON AND WHO WILL PROTECT THEM?

A segunda sessão desta tese foi elaborada e formatada conforme as normas da revista cientifica '*Biodiversity and Conservation'*. Disponível em: https://www.journals.elsevier.com/biological-conservation. Artigo submetido em 22/08/2023.

WHERE ARE THE SMALL NON-VOLANT MAMMALS (DIDELPHIMORPHIA AND RODENTIA) OF THE BRAZILIAN AMAZON AND WHO WILL PROTECT THEM?

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ABSTRACT

The rapid landscape alteration caused by the accelerated process of deforestation in the Amazon has put biodiversity and ecosystem services at risk in recent years. The Cerrado enclaves stand out among the Amazonian ecosystems threatened by anthropic pressures. They are essential for conservation since they are home to a rich and peculiar biodiversity composed of communities of savannah and forest species and numerous endemic species. In this research, we quantify Protected Areas' contribution to conserving the diversity of small, non-volant mammals in the Brazilian Amazon. We create summation models of species richness and present the potential distribution of species. Our results show that for the evaluated marsupials, it is observed that the concentration of richness is located more in the center of the North region, in the states of Pará and Amazonas. The analyzed species tend to present less than 20% of their potential distribution area within the Protection Areas. For rodents, the contribution of each Protection Area represented an average of 9.56% of the potential distribution area of the species. Although, for both marsupials and rodents, the SPA's alone are not enough to contribute to the conservation of the species, when we include all categories, the level of contribution of the protection areas increases.

Keywords: Potential distribution; Protected Area; Small mammals; Savannah; Brazilian Amazon

INTRODUCTION

About 300,000 km² of Amazonian Forest have already been deforested in the Amazon biome in the last 20 years, equivalent to approximately 8% of its area (PRODES/INPE 2021). Between August 2021 and July 2022 alone, 10,781 km² of forest were cut down, the largest area devastated in the last 15 years, representing a 3% increase in deforestation for the period (SAD 2022). This rapid change puts globally important biodiversity and ecosystem services at risk (Albert et al. 2023). In fact, the Amazon has lost 12% of its natural area in the last 37 years, corresponding to 44.5 Mha of native vegetation, which includes forest, savannah and grassland formations, wetlands, and mangroves (MapBiomas 2019). These alterations transform a continuous forest environment into areas of reduced and disconnected forest remnants (Arroyo-Rodríguez and Fahrig 2014), surrounded by matrices of unnatural components, such as agricultural and livestock fields, highways, roads, villages, human settlements, and bodies artificial water sources (Anderson et al. 2007; Benchimol and Venticinque 2014; Laurance et al. 2009; Tee et al. 2018).

Among the Amazon ecosystems threatened by anthropogenic pressures, we highlight the Cerrado enclaves present in the Amazon (Carvalho and Mustin 2017), which are particularly important for conservation, since they are home to a rich and peculiar biodiversity composed of communities of savannah and forest species and including numerous species endemic (Barbosa et al. 2007; Plotkin and Riding 2011). These enclaves represent a distinct and little-known ecosystem within the Amazon (Prance 1996) and are under great anthropic pressure, whether due to land grabbing and the advance of grain cultivation (mainly soy and corn), plantations of exotic species (such as oil palm), woody species (eucalyptus and acacia) or by uncontrolled burning (Aguiar et al. 2014; Barbosa et al. 2007; Carvalho and Mustin 2017). In addition to the impacts arising from the development of industrial and urban infrastructure (Benchimol and Peres, 2015), livestock, logging (Tyukavina et al. 2017), mining (Fearnside 2005; Nepstad et al. 2014; Matricardi et al. 2020), pesticides (IPEA 2015; Lapola et al. 2014) and, more recently, large-scale intensive agriculture (Curtis et al. 2018; Melo et al. 2013; Mendes-Oliveira et al. 2017), another relevant point is the advance of illegal mining. This activity accounted for 74% of the areas mapped as minings in the Amazon.

An alternative to slow down this rapid change in land use and land cover is the implementation of Conservation Units (Integral Protection Areas and Sustainable Use Areas), whose main objective for their creation is to protect areas of great biological importance and areas under high pressure. anthropic (Silva 2005; BRAZIL, Federal Decree No. 5.746/2006). Indigenous Lands (IT's) are recognized through Federal Decree Nº 6,001/1973, which, although prior to the Constitution, remains in force in what does not contradict it and are regulated by Federal Decree Nº 1,775/1996, which guarantees the territorial rights of indigenous peoples. Given the way of life of indigenous peoples, these areas have played an important role in environmental conservation (WWF 2014). These areas correspond to 23% of the Amazonian territory and, although they were not intended for the conservation of biodiversity, they are real allies of the UC's (MapBiomas 2023).

Despite the importance of UC's and IT's for biodiversity conservation, the demarcation of these areas, in many cases, does not consider the conservation of biological groups and are chosen arbitrarily, either because of their probable biological importance, defined without clear scientific criteria, cultural or scenic beauty. Furthermore, areas can be chosen to ensure the sustainable use of natural resources by traditional populations and/or in compliance with monetary and/or political demands (MMA 2014a). This culminates in demarcated areas that do not effectively protect species diversity, as observed for some groups of aquatic insects (Brasil et al. 2022; Dias-Silva et al. 2021), primates (da Silva et al. 2022) and for flying mammals (Pessoa da Silva and De Marco Júnior 2023).

The pressure caused by these events tends to further weaken the protection of biodiversity, which currently, the system of areas intended for environmental protection manages to protect less than half of all Brazilian species (Oliveira et al. 2017). Although some species benefit from human activities, most of them are not very tolerant to changes imposed on their habitats by human activities (Baillie et al. 2004). For example, small non-volant mammals, which in addition to being a very diverse group, 775 native species with confirmed occurrence in Brazil (Abreu Jr. et al. 2022-1), influence the dynamics of Neotropical forests, being considered key species in tropical forests (Ernest and Brown 2001; Holland and Bennett 2009; Pardini 2004; Paglia et al. 1995). In the Neotropics, the influence of this group occurs through predation and dispersal of seeds and mycorrhizal fungi (Mangan and Adler 2000; Pimentel and Tabarelli 2004; Terborgh et al. 2001; Vieira and Izar 1999), acting as primary and secondary consumers (Paglia et al. al. 2012), pollinators (Vieira et al. 1991) and as prey for many species (Carvalho et al. 2005;

Oliveira and Bonvicino 2011; Rossi and Bianconi 2011). They are represented both by species with wide distribution and those with restricted distribution, and may have terrestrial, semi-aquatic and arboreal habits (Bonvicino et al. 2008; Gardner and Creigton 2008; Wilson and Reeder 2005).

Small marsupials and rodents that occur in environments under strong influence of anthropic activities, can suffer direct impacts for the maintenance of viable populations and ecological processes in local communities, since we do not know much about the species of these orders, including their diet, habitat and, mainly on their geographic distribution (Cuarón 2000; Fuentes-Montemayor et al. 2009). This occurs both in areas where there is anthropic disturbance of the habitat (Daily et al. 2003; Naughton-Treves et al. 2003) and in regions with little or no forest alteration (Peres 1996; Peres and Lake 2003), including in the interior of areas protected (Chiarello 2000b; Altrichter and Almeida 2002; Olmos and Galetti 2004). Given this, species distribution modeling (SDM's) is a numerical tool that can act to reduce these gaps, since it combines the occurrence of species with environmental variables and interpolates and extrapolates the potential distribution of species (Brasileiro et al. 2022; Gomes et al. 2017; Liu et al. 2011; Silva et al. 2018; Zurell et al. 2020).

Thus, our objective is to identify the areas with the greatest diversity of small non-volant mammals, of the orders Didelphimorphia (Didelphidae) and Rodentia (Cricetidae; Echimyidae; Caviidae) and the contribution of the Integral Protection Areas (SPA), Sustainable Use Areas (SUA) and Indigenous Lands (IT) for the conservation of species and ecosystem services in the Brazilian Amazon, with emphasis on Cerrado enclaves. For this purpose: (i) We produced an annotated list of species of small non-volant mammals that occur in the Brazilian Amazon; (ii) We prepared summation maps of species richness considering all species, trophic and behavioral guilds, and degree of threat according to the IUCN and (iii) We presented the potential distribution of species classified as Data Deficient (DD) by the IUCN. Additionally, we quantified the contribution of the Protection Areas (SPA's, SUA's and IT's) to the conservation of the diversity of non-volant small mammals.

METHODS

Study area

We defined the portion of the Brazilian Amazon as the study site because this region stands out for its enormous area and for presenting high biological diversity and a high rate of endemism. As a result, there are huge gaps in information about small non-volant mammals that currently make efficient measures for the conservation of this fauna unfeasible. Our study area occupies approximately 4.2 million km^2 (IBGE 2004b), covering 59% of the Brazilian territory, representing 67% of the world's tropical forests (IMAZON 2009) (Figure 1).

List of species and classifications

For the correct taxonomic identification of the specimens, we used the List of Mammals of Brazil (Abreu Jr. et al. 2022) as a basis. For trophic guild in marsupials, we grouped predicted species Frugivore-Onivore, Insectivore-Onivore-Granivore and Insectivore-Onivore in the classification of Omnivore. As for the arboreal stratum of marsupials, we grouped Semiscansorial species in the Terrestrial classification. For marsupial guild and arboreal stratum, we consulted works by Faria et al. (2019) and Paglia et al. (2012). For rodents, we grouped predicted Frugivore-Onivore and Insectivore-Onivore species into the Omnivore classification. For the arboreal stratum of rodents we grouped Semifossorial, Terrestrial-Semiaquatic and Terrestrial-Semiarboreal predicted species in the Terrestrial classification. For guild and arboreal stratum of rodents we consulted works by Patton et al. (2015) and Verde-Arregoitia and D'Elía (2019). These groupings were necessary, since some species had only one characteristic (whether in guild or arboreal stratum), and this would make it impossible to carry out more robust analyses. Additionally, we classified species according to threat level, according to the Red List of Threatened Species (IUCN 2023) (see Appendix 01, Supplementary Material).

Occurrence data and species modeling

We used primary species collection and occurrence data from 1900, restricted to the Neotropics, to prevent the original data from being incompatible with the range of the environmental dataset present in the SpeciesLink digital collections (https://specieslink.net/), GBIF – *Global Biodiversity Information Facility* (www.gbif.org) and AMNH – *American Museum of Natural History* (https://www.amnh.org/research/vertebrate-zoology/mammalogy/collection-information/database). In addition to digital databases such as *ISI Web of Knowledge* (http://www.webofknowledge.com), *Scopus* (https://www.scopus.com) and *Google* Scholar (*https://scholar.google.com.br/*), using a set of keywords ("small mammals"; "non-volant"; "Rodentia"; "rodents"; "rodent"; "Didelphimorphia"; "marsupials"; "marsupial"; "Amazon"). Records of dubious and exotic species were excluded, in addition to data without coordinates. To consult the digital Mastozoological collections, we use data collected through the Brazilian Biodiversity Information System - SIBBR (https://collectory.sibbr.gov.br/collectory/?lang=pt_BR). We created potential distribution models – SDMs, with and without spatial restriction, following the recommendations of Pimenta et al. (2022), using the occurrence points of the entire Neotropical region for species with confirmed occurrence for the Brazilian Amazon (see Appendix 01, Supplementary Material).

Maps of species richness and potential distribution

The species richness values of small non-volant mammals (Didelphimorphia and Rodentia) were the sum of all binary occurrence maps generated by the SDM's procedure. These maps were added considering all species, species by trophic guild, species by tree stratum and species grouped by conservation level according to the IUCN, always differentiating between Didelphimorphia and Rodentia. Finally, the maps of the species classified as DD by the IUCN were spatialized and presented. All maps were built in Qgis 3.28.3 program (https://www.qgis.org/pt_BR/site/forusers/download.html).

Identification of the contribution of each type of unit

To identify how much each type of Protection Area (SPA, SUA and IT) contributed to the maintenance of species, we created a 0.06° grid considering the territorial extension of the Brazilian Amazon as a limit and classified the cells in Areas of Integral Protection (SPA's), Sustainable Use Areas (SUA's) and Indigenous Lands (IT's). This grid was superimposed on the species distribution maps and the values of presence and potential absence of species were extracted. Thus, we obtained the percentage of potential distribution area, for each species, within each type of Protection Area and outside them. The delimitation of state and federal SPA's and SUA's were obtained from the Ministry of the Environment - MMA (http://mapas.mma.gov.br/i3geo/datadownload.htm). IT's were obtained from the National Indian Foundation - FUNAI (http://www.funai.gov.br/index.php/shape).

Later, we used the Analysis of Variance (Anova/ One-Way) to test the contribution of each Protection Area for the conservation of the species. Using the distribution percentage as a continuous variable and the cell classification (SPA, SUA, IT and Unprotected) as a categorical variable, each species being a sampling unit. This same procedure was performed considering the hierarchical contribution of the Protection Areas, thus considering the following groups: SPA's, SPA's + SUA's and

SPA's + SUA's + IT's. Thus, we used the distribution percentage as a continuous variable and the hierarchical classification as a categorical variable, each species being a sampling unit. We performed this analysis for all species, always considering Marsupials and Rodents separately, and later, for each of the groupings (guild, habitat, and threat in the IUCN). All analyzes were carried out considering the historical distribution of the Brazilian Amazon and considering only the Cerrado enclaves in the Brazilian Amazon.

RESULTS

Species list

We found 12,085 records of occurrences of marsupials and 16,713 records of rodents for the Neotropical region. These records were obtained through extensive research in the literature, digital databases, and collections (Figure 2). From these databases, after cleaning the search and deleting data, records of rodent and marsupial species with distribution to the Brazilian Amazon were selected, of which 2,677 are occurrences of marsupials (39 species) and 2,040 occurrences of rodents (72 species) (Table S1, Supplementary Material).

Among marsupials, the species *Didelphis marsupialis* Linnaeus, 1758 was the one that presented the most occurrence points for the Brazilian Amazon (457 points), followed by *Philander opossum* (Linnaeus, 1758) with 258 occurrence points and *Marmosa* (Marmosa) *murina* (Linnaeus, 1758) with 258 occurrence points, 1758) with 217 points of occurrence (Table S1, Supplementary Material). On the other hand, *Hyladelphys kalinowskii* (Hershkovitz, 1992) presented only 5 occurrence points. This species is known only from the Amazon of Peru, southern Guiana, and northern French Guiana and Amapá (Catzeflis et al. 2017; da Silva et al. 2013; Voss et al. 2001).

Among rodents, Necromys lasiurus (Lund, 1841) was the species that presented the most occurrence points for the Brazilian Amazon (165 points), followed by *Hylaeamys megacephalus* (Fischer, 1814) with 149 occurrences and *Proechimys guyannensis* (É. Geoffroy St. Hilaire, 1803) with 106 occurrences. The species *Euryoryzomys emmonsae* (Musser et al., 1998); *Isothrix pagurus* Wagner, 1845; *Kunsia tomentosus* (Lichtenstein, 1830); Neacomys xingu Semedo et al., 2020; *Oecomys catherinae* Thomas, 1909; *Oecomys superans* Thomas, 1911 and *Oxymycterus inca* Thomas, 1900 presented only 5 occurrence points for the Brazilian Amazon (Table S1, Supplementary Material).

Potential distribution

Evaluation of models

The efficiency of each model was evaluated using the analysis test of the True Statistical Ability - TSS, whose amplitude of species distribution for marsupials varied from TSS=0.352 to TSS=1.000 (Table S2, Supplementary Material), while for rodents it varied from TSS =0.219 to TSS=1.000 (Table S2, Supplementary Material). Both tests reflected variation between regular and/or moderate models up to the good predictive capacity of the models. That is, regardless of the categories of protected areas, the distribution of species of small non-volant mammals in the Brazilian Amazon is a random response.

Marsupials

Gracilinanus emiliae (Thomas, 1909), was the only marsupial, present in the study, classified as DD by the IUCN (Figure S01). This species is nocturnal, solitary, and omnivorous, inhabits a forested environment in the lowlands of the primary tropical forest and gallery forest in the transition with the Cerrado (Brandão et al. 2015; Faria et al. 2019), occurring mainly in the upper strata of the Cerrado. forest, although it occasionally occurs in the understory and even on the ground (Vieira and Camargo 2012). Its occurrence had only been documented in French Guiana, Suriname, Guyana, Colombia, Venezuela, and northern Brazil in the State of Pará (Creighton and Gardner 2008a), however, new occurrences of this species have been documented in new inventories (da Silva et al. 2013).

Rodents

Most of the rodents, present in the study and classified as DD in the IUCN, do not have information about trophic guild and arboreal strata, such as the species *Euryoryzomys emmonsae* (Musser et al., 1998) (Figure S02); *Neusticomys oyapocki* (Dubost & Petter, 1978) (Figure S03) and *Oecomys paricola* (Thomas, 1904) (Figure S04). Another example is the species *Proechimys kulinae* da Silva, 1998 (Figure S05), one of the 3 species of echimid rodents (spiky rats) with an existing occurrence in the Juruá River basin, and known from only two locations in western Brazil, State of Amazonas and two in northern Bolivia (Patton et al. 2000).

Species richness

Marsupials

Species richness maps for marsupials (Figure 3) show in red the places where the greatest species richness is concentrated. It is observed that this concentration is located more in the center of the North region, in the states of Pará and Amazonas. For marsupials and their different trophic guilds (Figure S06), the species richness maps show that for generalist species the concentration of richness is more from the center to the north, in the States of Pará, Amazonas and Roraima (Figure S06-B); and for omnivorous species the concentration ranges from the center to the south of the states of Pará and part of Amazonas (Figure S06-C).

For marsupials and their different habitats (Figure S08), the species richness maps show that for arboreal species (Figure S08-A), the highest concentration of richness is more evident in the regions of Acre and northern Amazonas. For Semiscansorial species (Figure S08-B) the highest concentration of species richness is within protected areas. For terrestrial species (Figure S08-C) the highest concentration of richness is observed in the centers of the states of Amazonas and Pará. About the IUCN risk classification (Figure S10) we observe that marsupial species show that species classified with Least Concern (LC) (Figure S10-A) have greater concentration of wealth in the central part of the states of the North region.

Rodents

The species richness maps for total rodents (Figure 4) show that the places where the greatest species richness are concentrated are in red. It is observed that this concentration is located more in the center of the North region, in the states of Pará and Amazonas. For rodents and their different trophic guilds (Figure S07), the species richness maps show that for frugivorous species the greatest richness is concentrated from the center to the east in the states of Pará, Roraima and Amapá (Figure S07-B). Omnivorous species (Figure S07-E) concentrate their richness in the center of the North region states. On the other hand, granivorous (Figure S07-C) and insectivorous (Figure S07-D) species need more representatives in order to really explore the concentration of species richness. For rodents and their different habitats (Figure S09), arboreal species (Figure S09-A) concentrate their greatest richness from the center to the west of the states in the North region. Semi-aquatic species (Figure S09-B) have a concentration of richness in the States of Amapá and Pará. And terrestrial species (Figure S09-C) have a concentration of richness from the center to the south of the states in the northern region.

For rodents and their classifications as a threat by the IUCN (Figure S11) it is verified that species classified as Least Concern (LC) (Figure S11-A) are in greater concentration of richness from the center to the north in the States of Pará, part of Amazonas and Amapá (in this state the Savannah areas are not within protected areas). On the other hand, the species that do not have information regarding the threat in the IUCN (Figure S11-C) concentrate greater richness in the center of the State of Pará, inside and outside IT’s.

Contribution of Conservation Units and Savannahs

Marsupials

The marsupial species analyzed in this study tend to have less than 20% of their potential distribution area within the Protected Areas (Table S3, Supplementary Material). We observed an average of 6.09% of the potential distribution area within Strict Protection Areas, 2.59% in Sustainable Use Areas and 8.13% in Indigenous Lands (Table S3, Supplementary Material). When we analyze hierarchically the percentages vary from 6.02% for SPA's to 16.22% for SPA's + SUA's + IT's (Table S3, Supplementary Material).

When we evaluated marsupial trophic guilds, we observed that Generalist species tend to have an average of 4.81% of the potential distribution area within SPA’s, 1.93% within SUA’s and 6.23% within IT’s (Table S3, Supplementary Material). Frugivorous species, on the other hand, present an average of 3.75% of their potential distribution area within SPA's, 1.49% in SUA's and 5.03% in IT's (Table S3, Supplementary Material). In Omnivorous marsupial species we observed an average of 4.79% of the potential distribution area within SPA's, 1.93% in SUA's and 6.13% in IT's (Table S3, Supplementary Material). When we visualize the results (Table S4, Supplementary material), the test indicates that there is a difference between the groups of the protected areas compared to the species with different trophic guilds (Appendix 03, Supplementary Material).

The species of marsupials in terms of habitat present: Arboreal species with an average of 2.85% of the potential distribution area within SPA's, 1.15% in SUA's and 3.88% in IT's (Table S3, Supplementary Material). For Semiscansorial species, we observed an average of 8.54% of their potential distribution area within SPA's, 3.42% in SUA's and 2.74% in IT's (Table S3, Supplementary Material). Terrestrial species have an average of 4.42% of the potential distribution area within SPA's, 1.76% in

SUA's and 5.76% in IT's (Table S3, Supplementary Material). When we visualize the results (Table S4, Supplementary material), the test indicates that there is a difference between the groups of protection areas compared for species with different habitats, however, all protection areas are equal (Appendix 03, Supplementary Material).

For the species of marsupials classified according to the IUCN threat factor, it is noted that: 12.04% of the species considered of Least Concern (LC) have their potential distribution area within SPA's, 4.84% in SUA's and 15.56% in IT's (Table S3, Supplementary Material). Species classified as vulnerable (VU) by the IUCN have 3.42% of their potential distribution area within SPA's, 1.37% in SUA's and 4.48% in IT's (Table S3, Supplementary Material). When viewing the results (Table S4, Supplementary Material), it is noted that there is a difference between the groups of protected areas compared to species with different habitats, however, they are equal (Appendix 03, Supplementary Material).

When we evaluated the percentage of potential distribution area of marsupial species that are within protected areas only in savannas, we observed an average of 6.17% in SPA's, 5.43% in SUA's and 9.20% in IT's, representing 311,523 km2 of total area (Table S3, Supplementary Material). It is noted that the species *Philander pebas* and *Marmosa* (Micoureus) *rutteri* are the ones with the highest percentage of potential distribution area within savannas, with an average of 83.16% in IT's and 97.54% in SUA's, respectively (Table S3, Supplementary Material).

Rodents

For the analyzed rodent species, we observed an average of 9.57% of the potential distribution area of the species within Areas of Strict Protection, 3.97% within Areas of Sustainable Use and 11.88% within Indigenous Lands (Table S3, Supplementary Material). The contribution of each Protected Area represented an average of 9.56% of the potential distribution area of the species within SPA's, 3.96% in SUA's, 11.88% in IT's and 19.78% outside protected areas (Table S3, Supplementary Material). Hierarchically, the percentages range from 9.56% for SPA's to 25.41% for SPA's + SUA's + IT's (Table S3, Supplementary Material). When we analyze the total data (Appendix 04, Supplementary Material) and hierarchically (Appendix 04, Supplementary Material), it is noted that the test demonstrates that there is a difference between the groups of Protected Areas compared for the species of both classifications (Table S4, Supplementary Material).

For rodent trophic guilds, only 2.82% of the potential distribution area of Foliphagous species is within SPA’s, 1.14% within SUA’s and 3.50% within IT’s (Table S3, Supplementary Material). Frugivorous species presented 4.37% of their potential distribution area within SPA's, 1.78% in SUA's and 5.50% in IT's (Table S3, Supplementary Material). In Granivorous species an average of 0.09% of the potential distribution area is observed within SPA's, 0.06% in SUA's and 0.18% in IT's (Table S3, Supplementary Material). For Insectivorous species, it is noted that only 0.14% of their potential distribution area is within SPA's, 0.07% in SUA's and 0.18% in IT's (Table S3, Supplementary Material). As for Omnivorous species, we observed an average of 9.24% of the potential distribution area of the species within SPA's, 3.81% in SUA's and 11.54% in IT's (Table S3, Supplementary Material). When we visualize the results (Table S4, Supplementary material), the test indicates that there is a difference between the groups of the protected areas compared to the species with different trophic guilds, however, API and AUS are equal, as well as TI and outside of protection areas (Appendix 04, Supplementary Material).

When we evaluate rodent species in terms of habitat: 9.20% of the potential distribution area of Arboreal species are within SPA's, 3.76% in SUA's and 11.18% in IT's (Table S3, Supplementary Material). For Semiaquatic species we observed an average of 3.86% of the potential distribution area within SPA's, 1.61% in SUA's and 4.59% in IT's (Table S3, Supplementary Material). In Terrestrial species, an average of 9.57% of its potential distribution area is within SPA's, 3.97% in SUA's and 11.88% in IT's (Table S3, Supplementary Material). When viewing the results (Table S4, Supplementary material), it is noted that the groups of protected areas compared to the species and their different habitats are equal (Appendix 04, Supplementary Material).

The rodents classified according to the IUCN threat factor, it is observed that: 7.19% of the potential distribution area of the species classified with deficient data (DD) in the IUCN are within SPA's, 2.98% in SUA's and 8.75% in IT's (Table S3, Supplementary Material). In species classified as Least Concern (LC) there is an average of 9.57% of the potential distribution area within SPA's, 3.97% in SUA's and 11.88% in IT's (Table S3, Supplementary Material). When we visualize the results (Appendix 04, Supplementary Material), it is noticed that there is a difference between the groups of the protection areas compared to the species with different habitats, however, the test shows that SPA and SUA are different from each other and IT and outside areas of protection are equal (Table S4, Supplementary Material).

When we evaluated the percentage of potential distribution area of Rodent species that are within protected areas only in savannas, we observed that 11.37% then in SPA's, 9.35% in SUA's and 14.73% in IT's, representing 406,116 km^2 of total area (Table S3, Supplementary Material). It is observed that the species *Oecomys superans* is the only one that has 100% of its potential distribution area within protected areas only in savannas (Table S3, Supplementary material).

DISCUSSION

Most species of small mammals in the Brazilian Amazon are widely distributed throughout the biome (Percequillo et al. 2015). However, many of them are considered locally rare or have few points of occurrence. Although Rodentia is the most representative order of small mammals in the biome, many species do not know about the trophic guild, habitat, or threat. The list of species compiled here fills a gap in information on the occurrence of small non-volant mammals in the Brazilian Amazon (Drummond et al. 2005; Geise et al. 2017; Lessa et al. 2008), with essential data on points of occurrence and potential distribution. Such information is an important parameter for determining a taxon's conservation status and directing strategies to mitigate the environmental impacts of large enterprises. For Brazil, 775 species with confirmed occurrence are recognized, and in this study, four subfamilies, 13 genera, and 39 species of marsupials and three families, 28 genera, and 72 species of rodents were evaluated (Table S1, Supplementary Material).

Although we used the modeling only to represent the conservation of the Brazilian Amazon in terms of protected areas, we modeled the potential distribution of species for the entire Neotropical region. SDM's can be helpful to as a tool to direct sampling efforts for endangered species (Paglia et al. 2012). These models are widely used, for example, to prioritize areas for conservation (Brum et al. 2017; Magioli et al. 2021; Nóbrega and De Marco Junior 2011; Oliveira et al. 2017; Silva et al. 2018), discuss patterns biogeographical data (de la Sancha et al. 2014; Hernández-Mazariegos et al. 2022; Werneck et al. 2012) and to evaluate how the availability of modeled data on past and future climate predicts changes in the distribution of organisms over time (Beyer and Manica 2020; Bonnacorso et al. 2006; Iturralde-Polit et al. 2017; Gonçalves et al. 2021; Pearson and Dawson 2003; Siqueira and Peterson 2003; Williams and Blois 2017). It is known that there are still few works involving collections in new areas indicated by SDMs and the validation of models in the field. However, the results of these studies were satisfactory (Siqueira et al. 2009), including successful examples with small mammal fliers in the Neotropics (Anderson and Raza 2010; Anderson and Gonzalez 2011; Shcheglovitova and Anderson 2013). Therefore, the distribution, sometimes biased, of the occurrence data or even the lack of information on the distribution of many species, the SDMs can contribute to reducing errors in the categorization of the threat status of these species.

The few species sampled in this study, sometimes designated as rare, may reflect the capture method used or the animal's lifestyle (Ardente et al. 2017; Arévalo-Sandi et al. 2021; Cáceres et al. 2011; Emmons and Feer 1997; Palmeirim et al. 2019; Santos-Filho et al. 2015). The species Caluromysiops irrupta, for example, is known for only eight locations, many of them questionable by researchers because they come from hunters (Emmons 2008). With the increase in inventories, the accuracy of the geographic distribution of species increases, thus reducing the Wallacean and Linnean deficits (Abreu-Júnior et al. 2017; Hernandez et al. 2006; Hortal et al. 2015; Stockwell and Peterson 2002). Among the possible survey techniques, live capture traps, which include Sherman, Tomahawk, and pitfalls, are most used, especially for small, non-volant mammals (Ardente et al. 2017). Despite different data collection techniques for sampling small mammals, the canopy stratum is still known as "the last frontier" (Bouget et al. 2011; José et al. 2019; Whitworth et al. 2019a), where 40% 70% of the non-volant mammal biomass is represented (Arévalo-Sandi et al. 2021; Eisenberg and Thorington 1973), and few recent surveys in eastern Amazonia have focused on this stratum (Gregory et al. 2014; Whitworth et al. 2019b).

This study also noted that the rodent species Oecomys superans dramatically depends on the protection areas and the Amazonian Savannahs for its occurrence. The mosaics of savannahs and forests found in some regions represent habitats necessary for the survival of several mammals (Marinho-Filho et al. 2002) in addition to the fact that these species present a high selectivity concerning the use of the habitat, with species that occur strictly in forest areas and others in open areas (Henriques et al. 1997; Marinho-Filho et al. 2002). Studies carried out in these areas have shown that some species of small mammals strongly prefer specific habitats (Alho et al. 1986; Mares et al. 1986; Fonseca and Redford 1984; Ribeiro and Marinho-Filho 2005). Vieira and Palma (2005) compared small mammal community structures across different Cerrado vegetation types, but most of the research is restricted to quick surveys and species checklists. Carvalho and Mustin (2017) found only 136 studies on the Amazonian Savannas, carried out over 80 years, covering nine of the main taxonomic groups, of which almost a third focuses on plants, with much fewer studies on reptiles, birds, and mammals, and invertebrates, and almost none in amphibians and fish.

The North region has a more significant extension of forest areas, which aggregates Conservation Units and a greater concentration of indigenous lands, and the difficulty of access and the high logistical cost can be a limiting factor in data collection (Bernard et al. 2011). Updating the data depends on the initiative of numerous researchers (Amano et al. 2016), and more populated sites tend to have a more excellent biodiversity sampling (Luck 2007b). This also makes the research cheaper and more accessible to the researcher, especially when the sampling is close to the research centers (Hortal et al. 2007; Reddy and Dávalos 2003). Thus, overcoming the Wallacean and Linnean gaps depends on investments in sampling efforts in locations farther from the research centers and less accessible.

Although, for both marsupials and rodents, the SPA's alone are not enough to contribute to the conservation of the species, when we include all categories (SPA's + SUA's + IT's), the level of contribution of the protection areas increases. Natural areas that are protected in Conservation Units (UC's), along with Indigenous Lands (IT's), constitute the most crucial defense mechanisms for biodiversity, as they safeguard the integrity of ecosystems, biodiversity, and ecosystem services, in addition to contributing to securing the right of permanence and culture of previously existing traditional and indigenous peoples (Jenkins et al. 2013; WWF 2014). Furthermore, IT's play a fundamental role, in addition to safeguarding sociocultural diversity, such as the wealth of knowledge and traditional uses, indigenous peoples develop more appropriate ways of managing biodiversity (Bonanomi et al. 2018).

Despite Brazil having a fundamental role in the conservation of global biodiversity, a recent analysis of biodiversity showed that approximately 55% of species are unprotected (Oliveira et al. 2017). Species play a critical role in sustaining the planet, but a growing, disorderly human population puts them under enormous pressure (IUCN 2023). Worldwide, habitat loss and degradation (which affects 40% of species) and hunting or gathering for various uses, affecting 17% of species, are the main threats to mammals (Schipper et al. 2008). This situation is even more worrying when compared to the percentage of protected areas in the Pantanal, the Caatinga, and the world, for example (Sonoda et al. 2021).

Protected areas are recognized as the primary strategy for the in-situ conservation of biological diversity and natural resources (Chape et al. 2005), in addition to being vital in responding to emerging challenges, such as water protection, health, and climate change (Terborgh and van Schaik 2002). Therefore, the expansion of the UC's network must be understood as the primary tool to ensure the protection of biomes for their intrinsic value, human survival, and culture.

Conservation effectiveness is vital to achieving and sustaining global biodiversity protection goals. For this, large georeferenced databases on the distribution of protected areas and species have become a pressing and evident issue (Pimm et al., 2014). As a result, protected areas are still crucial for biodiversity, and their coverage needs to be expanded. Our suggestions are based on species richness, the number of species under some degree of threat, the representativeness of the contribution of protection areas, and identified conservation gaps. Therefore, they did not consider aspects related to urbanized areas or any other physical characteristics or socioeconomic conditions of the regions in question.

Considering, more recently, the accelerated process of conversion of savannas into areas for the cultivation of grains, in addition to the low proportion of preserved areas and the low effectiveness of existing Conservation Units (Veríssimo et al. 2011), the conservation gaps identified in this study are areas of high suitability, but which are still not capable of protecting this richness of species, mainly in the Amazonian Savannas. In these regions, the creation or expansion of conservation units is a necessary and urgent measure since little is known about the distribution of these species within the Amazonian Cerrado enclaves.

Just over half, 54.3%, of the natural areas of the Amazon rainforest are in legally protected areas, such as Indigenous Lands and Conservation Units (except APA). However, it is estimated that only 13.4% of the Amazonian savannas are currently within strictly protected areas (Carvalho and Mustin 2017; MapBiomas 2023). Protected areas are essential to ensure the survival of fauna and to protect places of great scenic beauty, in addition to regulating the climate, supplying water sources, and providing quality of life for human populations (MMA 2014a). Proving the importance of biodiversity and reducing exposure to these threats is essential so that they are not subject to pressure from economic, political, and social interests (Mascia and Pailler 2010).

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Author contributions

Simone Almeida Pena – Redact the original version; conceptualization or the acquisition, analysis, or interpretation of data.

Cláudia Regina Silva – Editing and Review: revised it critically for important intellectual content.

Thiago Bernardi Vieira – Supervision; Data design and analysis: made substantial contributions to the conception or design of the work.

Data availability

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

Figure captions

Fig. 1 - Location of the study area. The upper right corner highlights South America in light grey, Brazil in dark gray outline, the Brazilian Amazon in green, highlighting the Areas Protected by Brazilian legislation: in dark blue the Integral Protection Areas (SPA's), in red the Areas and Sustainable Use (SUA’s) and in black squares the Indigenous Lands (IT's)

Fig. 2 - Potential distribution of species of marsupials and rodents (Didelphimorphia and Rodentia) generated by ENMTML from Protected Areas, based on records of presence and absence of species, projected for the Brazilian Amazon

Fig. 3 - Map of total species richness of marsupials (Didelphimorphia: Didelphidae) for the Brazilian Amazon, with Protected Areas and Amazonian Savannahs

Fig. 4 - Map of total species richness of rodents (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon, with Protected Areas and Amazonian Savannahs

FIGURES

Fig. 1

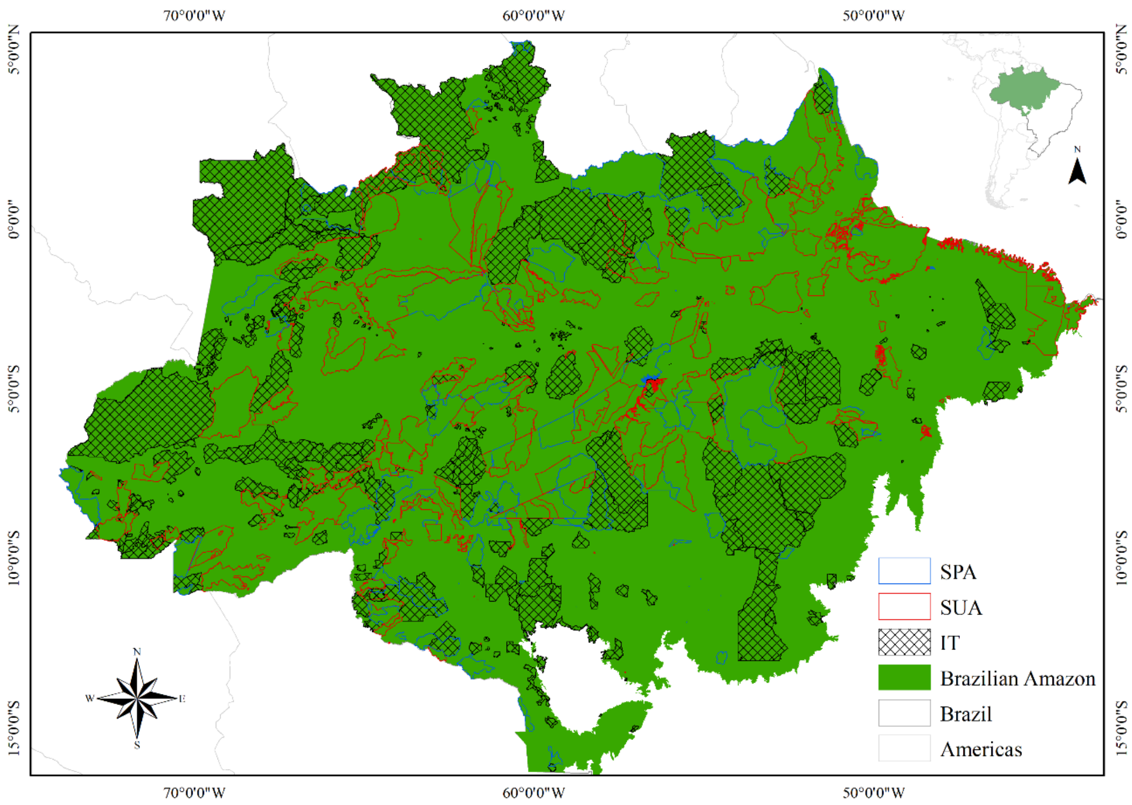


Fig. 2

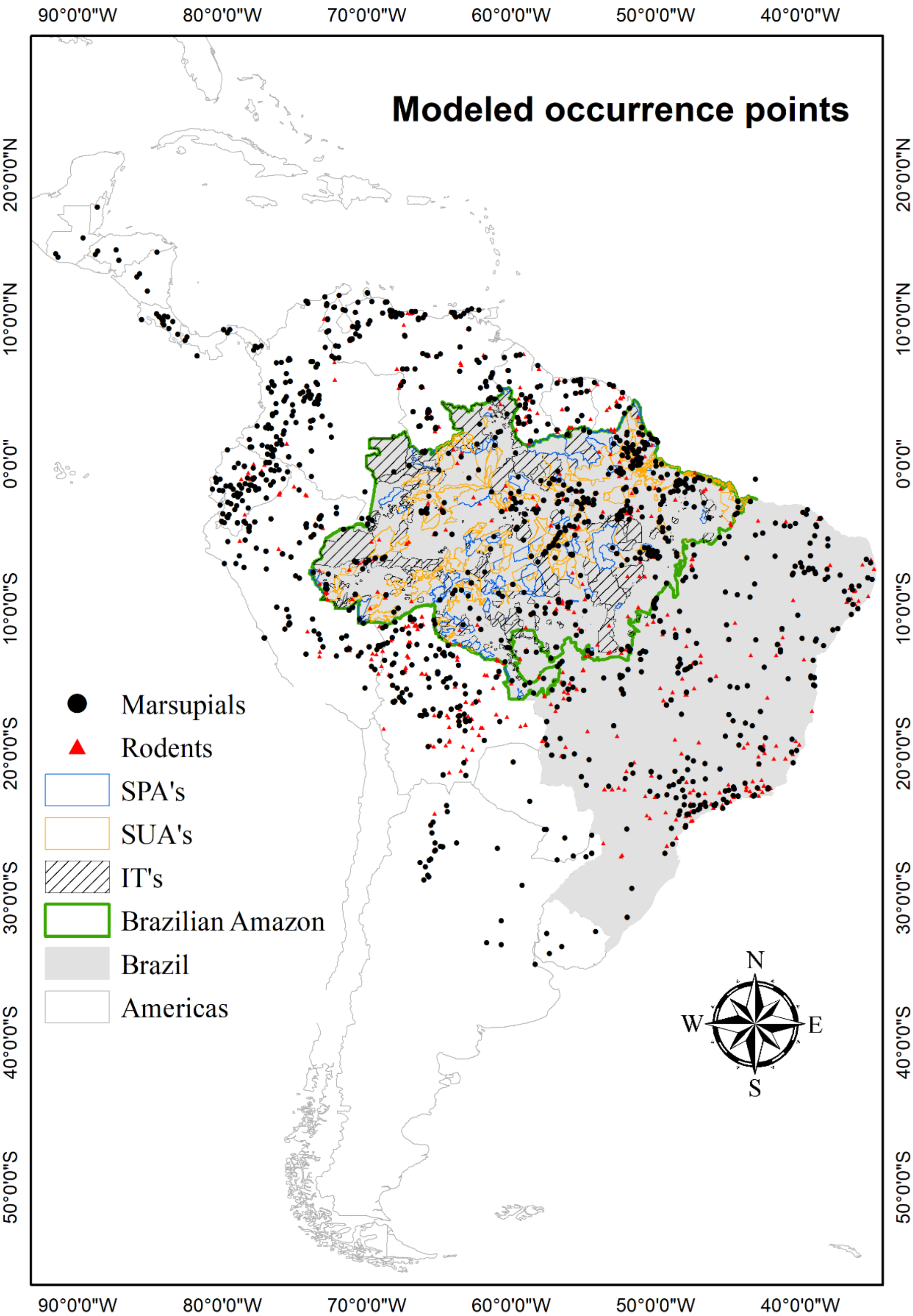

Modeled occurrence points
90°0'0"W
80°0'0"W
70°0'0"W
60°0'0"W
50°0'0"W
40°0'0"W
20°0'0"N
10°0'0"N
0°0'0"
10°0'0"S
20°0'0"S
30°0'0"S
40°0'0"S
50°0'0"S
Marsupials
Rodents
SPA's
SUA's
IT's
Brazilian Amazon
Brazil
Americas
N
S
W
E

Fig. 3

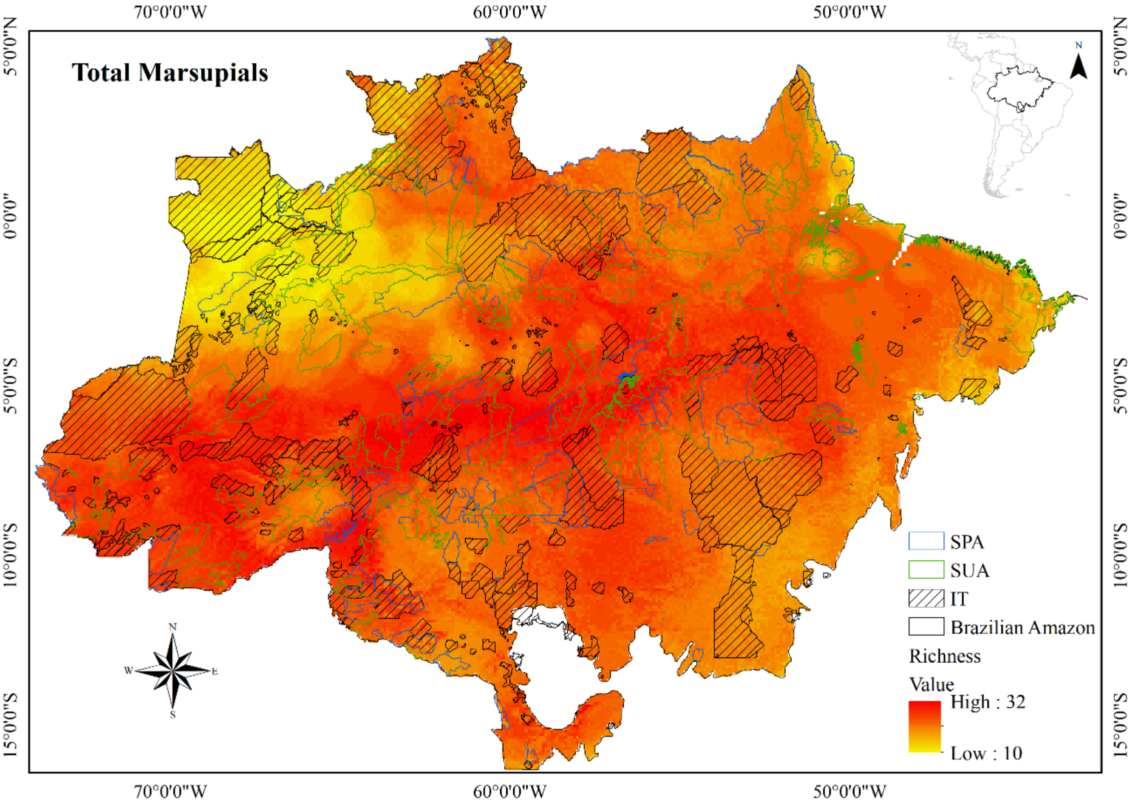
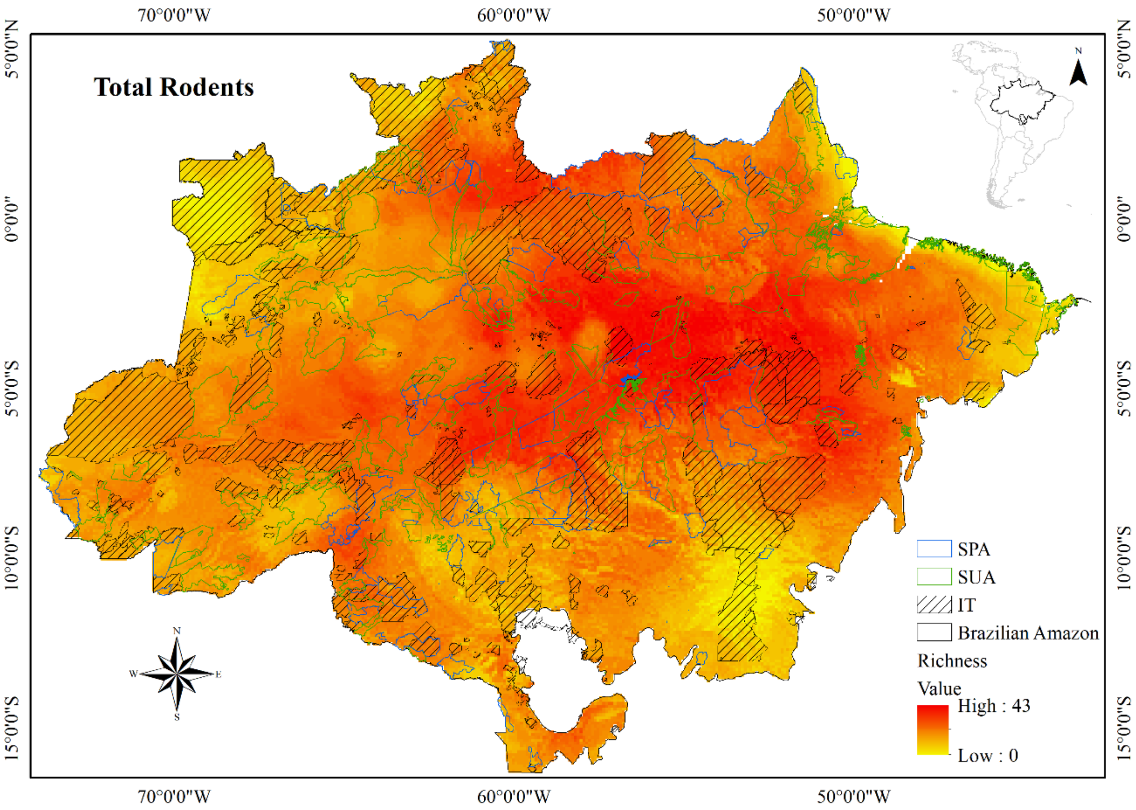

Total Marsupials
70°0'0"W
60°0'0"W
50°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
SPA
SUA
IT
Brazilian Amazon
Richness
Value
High : 32
Low : 10

Fig. 4


Total Rodents
70°0'0"W
60°0'0"W
50°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
SPA
SUA
IT
Brazilian Amazon
Richness
Value
High : 43
Low : 0

4. Capítulo III

PRIORITY ENCLAVES OF THE AMAZON CERRADO FOR THE CONSERVATION OF SMALL NON-VOLANT MAMMALS (DIDELPHIMORPHIA, RODENTIA) IN THE BRAZILIAN AMAZON

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PRIORITY ENCLAVES OF THE AMAZON CERRADO FOR THE CONSERVATION OF SMALL NON-VOLANT MAMMALS (DIDELPHIMORPHIA, RODENTIA) IN THE BRAZILIAN AMAZON

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ABSTRACT

The advancement of impacts caused by human activities has threatened biodiversity in the Amazon in recent years, causing changes in the abundance and habitats of species or even extinctions. This growth has been observed within Conservation Units (UCs), Indigenous Lands (TIs), and enclaves of the Amazon savanna, surpassing the average recorded for the entire Amazon biome, 81%, in the last three years only within TIs. Between August 2020 and July 2021, deforestation in UCs grew 35%, jumping from 767 km2 to 1,035 km2. Amazonian savannas represent a distinct ecosystem within the greater Amazon region, and despite being biologically rich ecosystems, they have often been neglected and threatened by land conversion for large-scale agriculture and plantations and uncontrolled fires. The creation of UCs is one of the main strategies for protecting biodiversity. However, several recent studies evaluated their inefficiency, showing that groups of invertebrates and vertebrates need better represented. Although some species benefit from these events, these changes in the environment impose restrictions on local native fauna and create an uncertain scenario for conservation, such as small non-flying mammals, which influence the dynamics of neotropical forests and are represented both for species with a wide distribution and those with a restricted distribution. In this article, the efficiency of protected areas in the Brazilian Amazon for the conservation of small non-flying mammals was evaluated. To do this, we created potential distribution models (SDMs) using the occurrence points for species with confirmed occurrence in the Brazilian Amazon. We created maps of priority areas for conservation using Zonation as a tool, thus determining the importance of the current network of reserves present in the Brazilian Amazon.

Key words: Priority Areas; Conservation; Savannah; Small Mammals; Brazilian Amazon.

INTRODUCTION

The most relevant advancement of impacts caused by human activities, such as natural areas being converted into areas for the expansion of economic activities, energy production, and (illegal) mineral extraction, has threatened biodiversity in the Amazon in recent years, causing changes in species abundances and habitats, or even extinctions (Brooks et al. 2006; Dirzo et al. 2014 IPBES 2019). The Brazilian Amazon has lost almost 20% (78 Mha) of its original forests (PRODES/INPE 2018), mainly due to deforestation for pastures (Barona et al. 2010) and agriculture (Sparovek et al. 2010). In the same period, there was a 656% growth in illegal mining, 130% in urban infrastructure, and 151% in agriculture and livestock (MapBiomas 2019). In the Amazon, human impacts exceed natural processes (Albert et al. 2023), where deforestation is the primary driver of environmental degradation, mainly associated with the weakening of environmental laws that occurred in Brazil (Escobar 2019; Vale et al. 2021), followed by high-impact logging, habitat fragmentation, fires, and drought.

The growth rates of illegal logging within Conservation Units (CU's) and Indigenous Lands (TI's) exceed the average recorded for the entire Amazon biome (Amigo 2020; Carvalho et al. 2019; Carvalho and Mustin 2017; Conceição et al. 2021). The average annual deforestation rate within the ITs in the last three years (419 km2 year-1) was 81% above the average annual rate from 2012 to 2021 (231 km2 year-1) (Mataveli and de Oliveira 2022). Between August 2020 and July 2021, deforestation in CU's grew 35%, jumping from 767 km2 to 1,035 km2 (PRODES-TerraBrasilis/INPE 2022), an increase of 22% since the last annual report. In the same period, in federal CU's alone, forest deforestation reached 84%, where the most compromised conservation unit in the last 12 months was APA Triunfo do Xingu, with a 30% increase in deforestation (PRODES/INPE 2022). Occupying the second and third positions in the ranking of most deforested CUs are the Jamanxim National Forest (PA) and the Jaci-Paraná Extractive Reserve (RO), respectively (PRODES-TerraBrasilis/INPE 2022). These three conservation units identified as leaders in the degradation ranking are in the area called the Arc of Deforestation, a region that has historically suffered from illegal logging and land invasion (grabbing) and which has gained new elements of pressure: the flexibility of actions of inspection and the possibility of reviewing limits (PRODES-TerraBrasilis/INPE 2022).

Savanna enclaves (Amazonian savannas) are tropical and subtropical phytophysiognomies with open vegetation dominated by the herbaceous stratum (herbs and grasses), where trees and shrubs may or may not be present (Sarmiento 1984: Eiten 1986: Huber 1987; Costa-Neto 2014). South America's largest savanna complexes are the Cerrado in Brazil, Bolivia, and Paraguay, and the Llanos in Venezuela and Colombia (Silva and Bates 2002). However, other savannah islands of varying sizes, known as Amazonian savannas, occur throughout the Amazon biome (Carvalho and Mustin 2017; Prance 1996). The Amazon savannas represent a distinct ecosystem within the greater Amazon region (Prance 1996) and are recognized for their rich and unique biodiversity. This, together with high levels of anthropogenic disturbance, has led to increasing conservation concerns (Klink and Machado 2005). These areas have generally been understudied (Carvalho and Mustin 2017) and despite being biologically rich ecosystems, they have often been neglected by scientists, policymakers, and land managers (Overbeck et al. 2015; Veldman et al. 2015a), with the main current threats to these environments being the conversion of land to large-scale agriculture and plantations, increased infrastructure, and uncontrolled fires (Barbosa et al. 2007; Carvalho and Mustin 2017; Aguiar et al. 2014). For example, in the savannas of Amapá, in 2013, 45.5km2 of soybeans were planted, an area that more than doubled in 2015 (113.7km2) (IBGE 2016), and in 2026, it is estimated that it could cover 4,000 km2 of the State (Silva 2016).

Due to the pressure caused by human activities, despite some species benefiting from these events, most need to be better tolerant to the modifications imposed on their habitats by human activities (Baillie et al. 2004). For example, small non-volant mammals, which, in addition to being a very diverse group, 775 native species with confirmed occurrence in Brazil (Abreu Jr. et al. 2022-1), exert influence on the dynamics of neotropical forests, being considered key species in tropical forests (Ernest and Brown 2001; Holland and Bennett 2009; Lessa et al. 1999; Pardini 2004; Paglia et al. 1995). In the Neotropics, the influence of this group occurs through predation and dispersal of seeds and mycorrhizal fungi

(Mangan and Adler 2000; Pimentel and Tabarelli 2004; Terborgh et al. 2001; Vieira and Izar 1999), acting as primary and secondary consumers (Paglia et al. 2012), pollinators (Vieira et al. 1991) and as prey for many species (Carvalho et al. 2005; Oliveira and Bonvicino 2011; Rossi and Bianconi 2011). They are represented by both species with a wide distribution and those with a restricted distribution and may have terrestrial, semi-aquatic, and arboreal habits (Bonvicino et al. 2008; Faria et al. 2019; Gardner and Creighton 2008; Wilson and Reeder 2005).

Creating Conservation Units (CU's) is one of the main strategies for protecting biodiversity. However, the percentage of each biome in CU's is not homogeneous: Amazon 28%, Caatinga 8.8%, Cerrado 8.3%, Atlantic Forest 9.5%, Pampa 3%, and Pantanal 4.6% (WWF 2019). Only 18% of the entire Brazilian territory is covered by Conservation Units, 6% of which are in Full Protection Units (WWF 2019). If we add indigenous lands to conservation units, which occupy 1,179,560 km2 (14% of Brazilian territory), Brazil protects 30.2% of the country. However, these areas are subject to various pressures, mainly of an economic, political, and social nature (Mascia and Pailler 2010), which lead these units to reduce their size, their degree of protection, and their effectiveness as a protected area, the movement known as PAAD (Declassification, Reduction, and Declassification of Protected Areas) (Bernard et al. 2014; Mascia and Pailler 2010).

Furthermore, in Brazil, initially, protected areas were established to guarantee the protection of areas without specific use or with a relevant aspect in the landscape, such as natural monuments (Rylands and Brandon 2005). Subsequently, the system's main objective was to protect areas of great biological importance and areas under high human pressure (Silva 2005); with this, the Sistema Nacional de Unidades de Conservação – SNUC (in Portuguese) was created. Currently, the definition of priority areas for conservation is aimed at flag species, hunting species, or species with social appeal (Morse-Jones et al. 2012; Verissimo et al. 2011), leaving aquatic and terrestrial insects (Nóbrega and De Marco 2011), small mammals (Galetti et al. 2009) and others less charismatic outside this planning. However, the inefficiency of CU's may be related to the non-protection of rare species (Nóbrega and De Marco 2011) or the insertion of areas that are marginally suitable for species (Sanchez-Fernandez et al. 2013) and the conservation of local biodiversity (Colyvan et al. 1999; Jenkins and Joppa 2009; Rylands and Brandon 2005). Many studies mention that Indigenous Lands (IT's) play an essential role in ensuring efficiency and protecting biodiversity (Barbosa et al. 2007; Brasil et al. 2021; Fagundes et al. 2015; Mataveli et al.

2022; Rorato et al. 2021; Ribeiro et al. 2018; Soares-Filho et al. 2010; Steege et al. 2015), although they were not created for this purpose.

Recent studies have also shown that groups of invertebrates such as arthropods and aquatic insects and vertebrates such as felines, fish, bats, primates, and turtles are not well represented in Brazil (Brasil et al. 2021; Dias-Silva et al. 2021; Fagundes et al. 2018; Frederico et al. 2018; Moraes et al. 2020; Oliveira et al. 2017; da Silva et al. 2022; Silva et al. 2018; Zanin et al. 2021). However, these criteria are generally based only on some groups of vertebrates or plants, and only some approaches consider the ecological services provided and ecological interactions, thus reducing the effectiveness of protected areas. Furthermore, these environmental changes impose restrictions on local native fauna and create an uncertain scenario for conservation (Timo et al. 2015), acting as a selective filter on the movements of animals across the landscape (Chiarello 2000b).

One way to alleviate this problem is by creating and implementing conservation units that combine nature conservation with the sustainable use of resources, making human presence compatible with biodiversity conservation (Galetti et al., 2009). Through land use change processes, habitat loss has been identified as one of the main drivers of biodiversity loss worldwide (Foley et al. 2005; Newbold et al. 2015). As a result, the study on the analysis of gaps in biodiversity knowledge has become a valuable tool in the development of conservation strategies, as it uses species distribution maps to identify which are not sufficiently represented (Rodrigues et al. 2003), if based on the assessment of the coverage of the protected areas network and the identification of gaps in its coverage (Jennings 2000; Rodrigues et al. 2004).

The processes that involve choosing an area destined for species conservation are based, among other criteria, on the type and number of species, the mosaic of landscapes, and the refuge potential that the areas encompass (Bensusan 2006; AMAZON 2012). One way to resolve the inefficiency of these networks is to use species richness, beta diversity, fauna complementarity and the number of endemic species; these same criteria are among the main ones used to define priority areas for conservation (Diniz-Filho et al. 2004; Juen and De Marco 2012). However, changes in species distribution over time could reduce the efficiency of CU's (Araújo et al. 2004). Therefore, to guarantee the efficiency of conservation and maintenance of species over time, the design of CU's must consider a climate change scenario (Araújo et al. 2011). Additionally, using species distribution models (SDM's) can reduce the problem of lack of knowledge about the distribution and protection of entirely suitable areas, creating a more robust approach to conservation.

In this article, the efficiency of protected areas in the Brazilian Amazon for the conservation of small, non-volant mammals was evaluated. To do this, we created potential distribution models (SDM's) with spatial restrictions and without restrictions, using the occurrence points for species with confirmed occurrence in the Brazilian Amazon (see Appendix 01). Subsequently, we created maps of priority areas for conserving small, non-volant mammals, using Zonation as a tool, thus determining the importance of the current network of reserves in the Brazilian Amazon. Therefore, our objectives are: (i) Test whether the current network of reserves in the Brazilian Amazon is suitable for conserving the biodiversity of small non-volant mammals; (ii) Identify the importance of the savannah enclaves existing in the Brazilian Amazon for the conservation of small non-volant mammals, also observing the importance of the units present in the savannah enclaves for the group and (iii) Verify whether the areas that are identified as important for the conservation of the biodiversity of small mammals in the savannah enclaves present in the Brazilian Amazon are located on degraded areas or areas still with vegetation present in the Amazon. To achieve our objectives, we tested the following hypotheses: H1. The current network of Conservation Units is not adequate to preserve the biodiversity of small non-volant mammals in the Brazilian Amazon, as most of them are biased due to unequal coverage in the protection of some biomes (Fonseca and Venticinque 2018; Watson et al. 2014); H2. Savanna enclave areas will have much greater importance than non-enclave areas. Although Amazonian savannas have low species richness (Miranda et al. 2003; Miranda et al. 2006; Ratter et al. 2003), these areas are of particular importance for conservation, housing unique flora and fauna, high species diversity, including a high degree of endemism and species with distribution restricted to these environments (Barbosa et al. 2007; Barnett and Cunha 1998; Lim and Engstrom 2005; Paglia et al. 2012; Plotkin and Riding 2011; Sanderson and Ignacio 2002; Simmons and Voss 1998; Voss et al. 2001). H3. The areas of importance are already degraded areas. Although the Amazon savannas are biologically rich ecosystems, they have suffered great exploitation through the historical and continued human use of these areas due to large-scale agricultural expansion (Carvalho and Mustin 2017; Hilário et al. 2017; Mustin et al. 2017), causing changes in species diversity according to their levels of specialization (Devictor et al. 2008).

MATERIAL AND METHODS

Study area

We defined the portion of the Brazilian Amazon as the study site because this region stands out for its enormous area and presents high biological diversity and a high rate of endemism, in addition to its high deforestation process and conversion of these areas into fragmented environments. As a result, there are huge gaps in information about small, non-flying mammals that currently make efficient conservation measures for this fauna unfeasible. Our study area occupies around 4.2 million km2 (IBGE 2004b), covering 59% of the Brazilian territory and representing 67% of the world's tropical forests (IMAZON 2009) (Figure 1).

Maps of priority areas

For priority areas for the conservation of small, non-volant mammals, we used the *Zonation* software approach (Moilanen 2007), a quantitative technique that prioritizes areas for conservation (Moilanen 2012). Its evaluation is done by removing cells, depending on the objective of the work: *Core-area Zonation*, *Additive benefit function*, and *Target-based planning*. Here, we use the Additive benefit function meta-algorithm as it is the most suitable for a more significant number of species (Moilanen 2012). In this process, the least valuable places receive the lowest ratings (close to 0), and the most valuable areas for biodiversity receive the highest ratings (close to 1). Each map presented was a *Zonation* that was run with the species groupings: for all Marsupials; for all Rodents; for each Marsupial Trophic Guild; for each Rodent Trophic Guild; for each Marsupial Behavioral Guild; for each Rodent Behavioral Guild; for each IUCN threat classification (see Appendix 01 - Occurrence Data and Species Modeling).

The software uses spatial raster data on the distributions of individual biodiversity characteristics (species, habitats, ecosystem services, etc.) to identify which locations in a landscape are most important for biodiversity retention. *Zonation* ranks priority areas based on complementarity (Moilanen et al. 2005). The priority ranking is produced by removing each planning cell or unit that leads to the most negligible total loss of conservation value. The algorithm assigns a hierarchy of importance for conservation to the cells of the analyzed landscape, recalculating the value of each cell at each interaction and removing those with the lowest values. Zoning identifies areas essential for maintaining habitat quality and connectivity for multiple species, indirectly aiming for long-term species persistence.

Data analysis on importance of units

To assess whether the current network of reserves, present in the Brazilian Amazon, is in areas identified as important for conservation, we calculated the average importance of protected and unprotected cells, calculating the significance of the values with the Monte Carlo randomization test with 10,000 randomizations. For this purpose, maps of priority areas were superimposed on those of CU's and IT's. Cells were classified as "protected" (if they were completely or at least 50% within a conservation unit) and "unprotected", cells that did not meet this criterion or were completely outside CU's or IT's. The average importance for conservation (calculated by the *Zonation* algorithm) was calculated for each of the classes of protected areas (SPA's, SUA's and IT's), with this value considered as the average value of importance observed. Subsequently, the same number of cells was randomly selected, and the importance value calculated, thus generating the null distribution of values, and making it possible to calculate the significance of the observed average importance.

The random selection procedure was repeated 10,000 times and the average of these values was considered as the randomized importance value. Significance was calculated by the number of random values greater than or equal to the observed divided by the total number of randomizations (10,000). This procedure was repeated for all conservation prioritization maps for Marsupials, for Rodents, for each Trophic Guild, for each Behavioral Guild and for each type of threat in the IUCN, considering all classes as "protected" and each type of areas of protection (CU's +IT's) separately. As the spatial restriction generates more conservative maps, restricting the occurrence areas to places close to or with the occurrence of the species, we carried out a second modeling, without the spatial restriction (see Appendix 01). The CU's data were obtained from the Ministry of the Environment, both municipal, state and federal (MMA, http://mapas.mma.gov.br/i3geo/datadownload.htm), IT's at the National Indian Foundation (FUNAI, http://www.funai.gov.br/index.php/shape) and over the Amazon savannas were obtained on the platform *Terrabrasilis* (http://terrabrasilis.dpi.inpe.br/downloads/).

To analyze the relationship between protection areas that are important for conservation and the existence of vegetation, we carried out a correlation in environment R with data on land use and coverage. As these maps have different uses, we transformed them into binary maps, assigning 0 where it is anthropic (mining, pasture, etc.) and 1 for forest (vegetation, gallery forest, etc.). We carried out this analysis for the different classifications: protection areas (CU's and IT's), trophic guilds, behavioral guild and IUCN threat level, between marsupials and rodents separately.

Analysis of data on importance of savannah units

To evaluate the importance for the conservation of small non-volant mammals of savannah enclaves present in the Brazilian Amazon, we used the maps generated by *Zonation*, classifying the cells into savannah enclaves and non-savannah enclaves, calculating, and extracting the importance of the enclaves and comparing them with other protection areas. In this section, we redid all the calculations that were described in the randomization phase. The modeling was done without land use and coverage data so that we could observe which areas should be recovered within the Amazon savannah enclaves. This generated positive correlation data (where there is greater vegetation cover within protected areas) and negative correlation (protected areas are degraded). This analysis was carried out for the different classifications: protection areas (CU's and IT's), Trophic Guilds, Behavioral Guild and threat level in the IUCN, between Marsupials and Rodents, separately.

RESULTS

Importance of significance

Marsupials

The identification of priority areas for the conservation of Marsupial species through *Zonation* maps (Figure 2) presents areas with high conservation importance in the central part of the Amazon biome. It is noted that sustainable use areas (SUA's) and Indigenous Lands (IT's) were highly important for species conservation, with values greater than 1 (according to the *Zonation* algorithm) (Table S1, Supplementary Material). However, the savanna areas in the state of Amapá do not have full protection and only a small portion are in areas of sustainable use. It is noted that forest areas were highly important, with a value greater than 1 (according to the *Zonation* algorithm) for marsupial species (Table S1, Supplementary Material).

It is observed that, for all different Guilds of Marsupials (Figure S01), all protection areas had randomized importance, which was different from that observed for the conservation of Frugivorous (Figure S01-A), Insectivorous (Figure S01-C), Nectarivorous (Figure S01-D), Omnivorous (Figure S01-E) and Piscivorous (Figure S01-F), with a value greater than 0.869 (Table S1, Supplementary Material).

For Generalist species (Figure S01-B), it is observed that the observed importance was different from that randomized for SUA's, with a value greater than 0.878 (Table S1, Supplementary Material). It is also observed that forest areas presented a random importance greater than that observed for species from all Trophic Guilds, with a value greater than 0.869 (Table S1, Supplementary Material).

All protection areas showed greater random importance than observed, for Arboreal (Figure S02-A), Semi-aquatic (Figure S02-B), Semiscansorial (Figure S02-C) and Terrestrial (Figure S02-D) species, with value greater than 0.869 (Table S1, Supplementary Material). It is noted that forest areas had an observed importance greater than that expected by chance for Terrestrial species, with a value greater than 0.880 (Table S1, Supplementary Material).

The SPA's and SUA's showed greater observed importance than the random one, for the different classifications regarding the IUCN threat factor for marsupial species (Figure S03), with values varying between 0.873 and 0.885, for species of Least Concern (LC) (Figure S03-A) between the protected areas evaluated (Table S1, Supplementary Material). For species classified as Deficient Data (DD) (Figure S03-B) and Vulnerable (VU) (Figure S03-C), all protection areas presented a randomized importance greater than that observed for conservation (Table S1, Supplementary Material), with a value greater than 0.869. For species with Deficient Data (DD) regarding the threat factor in the IUCN, forest areas had an observed importance greater than that expected by chance (Table S1, Supplementary Material), presenting a value greater than 0.895. Terrestrial species and those with Deficient Data (DD) in the IUCN showed a positive correlation between land use and land cover in relation to savannah areas, that is, the areas of importance are within vegetated areas (with greater vegetation cover) (Table S1, Supplementary Material).

Rodents

The priority areas for conservation through the *Zonation* maps (Figure 3), for rodent species, present areas with high conservation importance in the north-central part of the Amazon biome. It is noted that SPA’s and SUA’s had greater observed importance than the random one for the conservation of the species (Table S1, Supplementary Material), with values varying between 0.894 and 0.905. And soil use and coverage (forest and anthropized areas) did not have a negative correlation of importance for Rodent species, with observed values greater than expected, varying between 0.875 and 0.885 (Table S1, Supplementary Material).

For the different Trophic Guilds of Rodents (Figure S04), it appears that for Foliphagous species (Figure S04-A), SUA's and IT's had greater observed importance than the random one, with values varying between 0.873 and 0.886 (Table S1, Supplementary Material). For Frugivorous (Figure S04-B), Granivorous (Figure S04-C), Insectivorous (Figure S04-D) and Omnivorous (Figure S04-E) species, all protection areas had greater random importance than that observed for the conservation of species, with a value greater than 0.869 (Table S1, Supplementary Material). It is observed that forest areas presented a randomized importance greater than that observed for most of the different classifications on Trophic Guilds, Behavioral Guild, and threat in the IUCN, with a value greater than 0.869 (Table S1, Supplementary Material).

Arboreal species (Figure S05-A) showed greater observed importance than random for all protected areas evaluated, with values varying between 0.872 and 0.895 (Table S1, Supplementary Material). For Semi-aquatic species (Figure S05-B), SPA’s and IT’s showed greater random importance than observed, with a value greater than 0.869 (Table S1, Supplementary Material). However, for Terrestrial species (Figure S05-C), only SUA's showed greater observed importance than the random one for the conservation of the species, with an average value of 0.890 (Table S1, Supplementary Material). It is noteworthy that for all the different habitats evaluated, the randomized importance was greater than that observed in forest areas (Table S1, Supplementary Material).

The different classifications regarding the IUCN threat factor for rodent species (Figure S06) showed greater observed importance than the randomized one for species of least concern (LC) (Figure S06-A) and for species with Deficient Data (DD) (Figure S06-B), with values varying between 0.872 and 0.901, among the protected areas evaluated (Table S1, Supplementary Material). For species classified as Vulnerable (VU) (Figure S06-C), all protection areas presented a random importance greater than that observed, with a value greater than 0.869 (Table S1, Supplementary Material). We highlight in our study that for vulnerable species, forest areas presented a positive mean of observed importance greater than the random one, with a value equal to 0.717 (Table S1, Supplementary Material). When evaluating the correlation of land use and coverage with savannah areas, and extracting the importance of significance of these areas, it is highlighted that the Frugivorous, Granivorous, Insectivorous, Omnivorous and Semi-aquatic species showed a positive correlation, that is, the areas vegetated (with greater vegetation cover) that are of greatest importance for these species are vegetated (Table S1, Supplementary Material).

DISCUSSION

Our results show that protected areas are still extremely important for the conservation of species, especially for those with few sampling points and/or information on trophic guilds and habitat. When we talk about the Amazon savannas, most of them are under protection areas, however, the Amapá savannas are vulnerable, as only a small portion is included in UC for Sustainable Use, on the edge of RESEX Cajari, and is cut by the most important highway in the state. These areas are among the least protected among the Amazon savannas, and have been facing a period of intense fragmentation and degradation since the 1950s (Carvalho and Mustin 2017; Mustin et al. 2017), mainly due to deforestation caused by the expansion of the agricultural frontier (mainly soybean monoculture), exposing these environments to changes in the natural configuration of the landscape, forming fragments of remnants of natural vegetation, reducing the area of habitat available for many species and resulting in irreversible losses of their biodiversity, placing them in a situation of vulnerability (Ewers and Didham 2006; Brockerhoff et al. 2008; Mustin et al. 2017).

As for food, protected areas were extremely important for the conservation of Marsupial species. However, few species have their diet described in specific studies, probably due to methodological difficulties involving analysis of stomach and fecal content (Casella and Cárceres 2006; Castilheiro and Santos-Filho 2013). And the lack of refined species data, such as habitat use, behavioral and reproductive data and feeding ecology, makes it difficult to understand the partition of niches between species. Most small non-volant mammals are generalists, however the diet of these species can vary according to availability in the environment, age, seasonality, or reproductive factors (Casella and Cárceres 2006).

In relation to the different habitats of marsupials and rodents, for both groups, protected areas were of high importance for the conservation of the species. Except for some rodent species for which protection areas were not of significant importance, mainly arboreal and terrestrial species. However, global priority areas have been identified based on richness, species endemism and vulnerability (Brooks et al. 2006; Jenkins et al. 2013). Although these characteristics are important in identifying key regions for biodiversity, these studies focus only on taxonomic diversity, not recording important data, such as the evolutionary history and functional characteristics of species (Díaz et al. 2007; Mazel et al .2014).

Despite the country's fundamental role in the conservation of global biodiversity, the relevance and breadth of Brazil's Conservation units for biodiversity conservation remain little known or scarce (Oliveira et al. 2017), presenting a need for more biodiversity inventories in Brazilian CU’s. Indigenous lands, in particular, play an important role in protecting biodiversity, as these areas strongly prevent deforestation and climate change (Soares-Filho et al. 2010). In this sense, the relaxation of Brazilian environmental laws to allow mining within CU’s (Fearnside 2016) represents a threat to its rich biodiversity, which remains poorly mapped.

Regarding the different classifications regarding the IUCN threat factor for the species of Marsupials and Rodents analyzed in this study, protection areas are of utmost importance for species predicted to be vulnerable and with deficient data. These species may be restricting themselves to these areas, a trend also observed in other regions of the Atlantic Forest for threatened mammals (Bogoni et al. 2018; Magioli et al. 2015). Protected areas are one of the most important mechanisms for slowing biodiversity loss (Godet and Devictor 2018; Gray et al. 2016). However, protected areas alone cannot prevent biodiversity loss (Godet and Devictor, 2018), since at least a third of these areas in the world are under intense human pressure (Jones et al. 2018). In fact, a study carried out with Amazonian primates showed that the current network of CU’s is not adequate to preserve the biodiversity of Amazonian monkeys (Pinto et al. 2014). In this context, without consistent basic information about species, the loss of certain species can cause a decrease in the functional diversity of the Amazon Forest (Petchey and Gaston 2002).

Around the world, several ecosystems retain much of their original biodiversity within protected areas, maintaining essential ecological functions and ecosystem services (Bogoni et al. 2020a; Magioli et al. 2021) and slowing biodiversity loss (Godet and Devictor 2018; Gray et al. 2016). However, protected areas alone cannot halt biodiversity loss (Godet and Devictor 2018), many of them are currently under intense human pressure (Jones et al. 2018), in addition to strong economic pressures for the installation of large projects and a vast network of illegal roads that extends over protected areas, especially in Sustainable Use Areas (SUA's), where a large part of these roads are associated with illegal logging, mainly in Pará and Mato Grosso (IMAZON 2012). Although small non-volant mammals are a megadiverse group in the Brazilian Amazon, their species are poorly sampled or adequately inventoried within CU's and IT's, and these knowledge gaps hinder conservation initiatives and adequate infrastructure for the implementation of new protection areas (ICMBio and WWF 2011). However, our results demonstrate that Indigenous Lands were more important for the conservation of small non-flying mammal species in the Brazilian Amazon.

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Data Accessibility Statement

All data is in the article.

Conflict of Interest

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Simone Almeida Pena – Redact the original version; conceptualization or the acquisition, analysis, or interpretation of data.

Cláudia Regina Silva – Editing and Review: revised it critically for important intellectual content.

Thiago Bernardi Vieira – Supervision; Data design and analysis: made substantial contributions to the conception or design of the work.

Data Accessibility Statement

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

Conflict of Interest

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Thiago Bernardi Vieira – Supervision; Data design and analysis: made substantial contributions to the conception or design of the work.

Figure captions

Figure 1 - Location of the study area, highlighting the different uses and land cover existing in the Amazon. The upper right corner highlights the Brazilian Amazon in green. In the lower right corner, the Areas Protected by Brazilian legislation stand out: in dark blue the Full Protection Areas (SPA's), in red the Sustainable Use Areas (SUA's) and in black squares the Indigenous Lands (IT's).

Figure 2 - Importance map of priority areas for total marsupials (Didelphimorphia: Didelphidae) for the Brazilian Amazon, with Protection Areas and Amazonian Savannas.

Figure 3 - Importance map of priority areas for total rodents (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon, with the Protection Areas and Amazonian Savannas.

Fig. 1

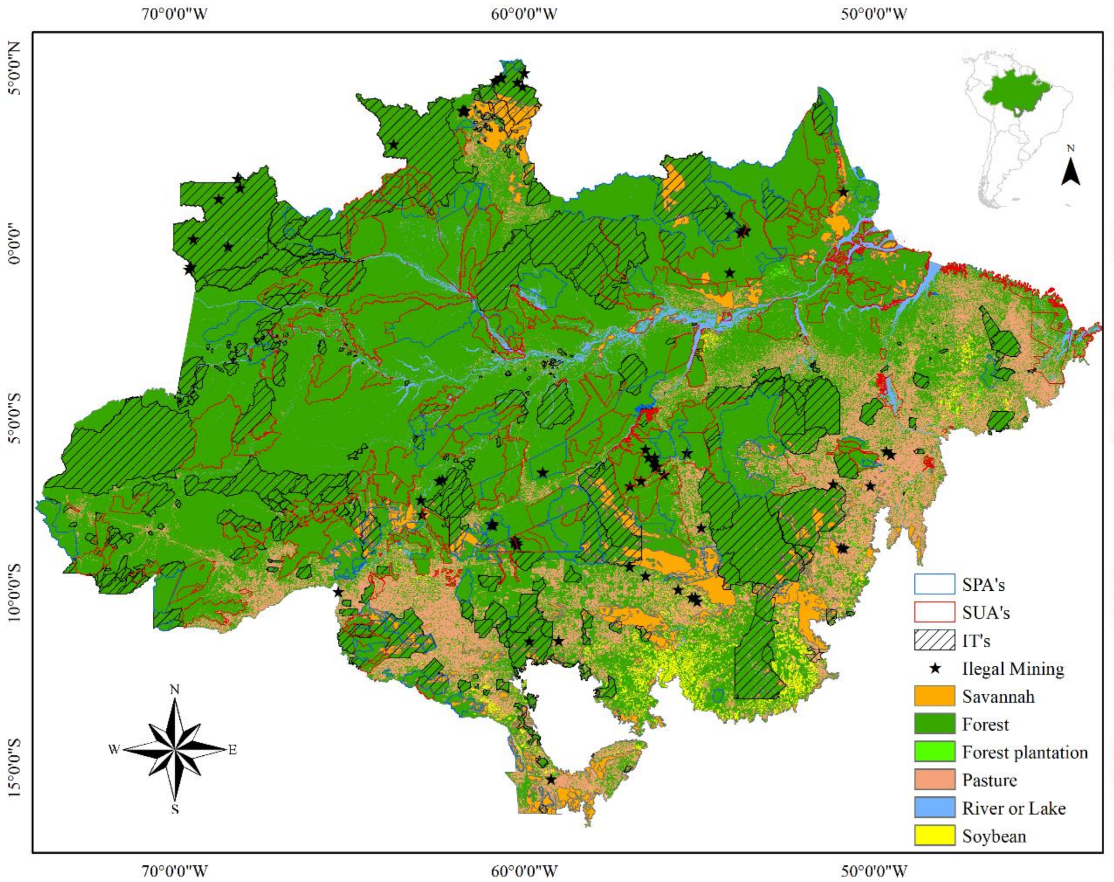

70°0'0"W
60°0'0"W
50°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
SPA's
SUA's
IT's
Ilegal Mining
Savannah
Forest
Forest plantation
Pasture
River or Lake
Soybean
N
S
W
E

Fig. 2

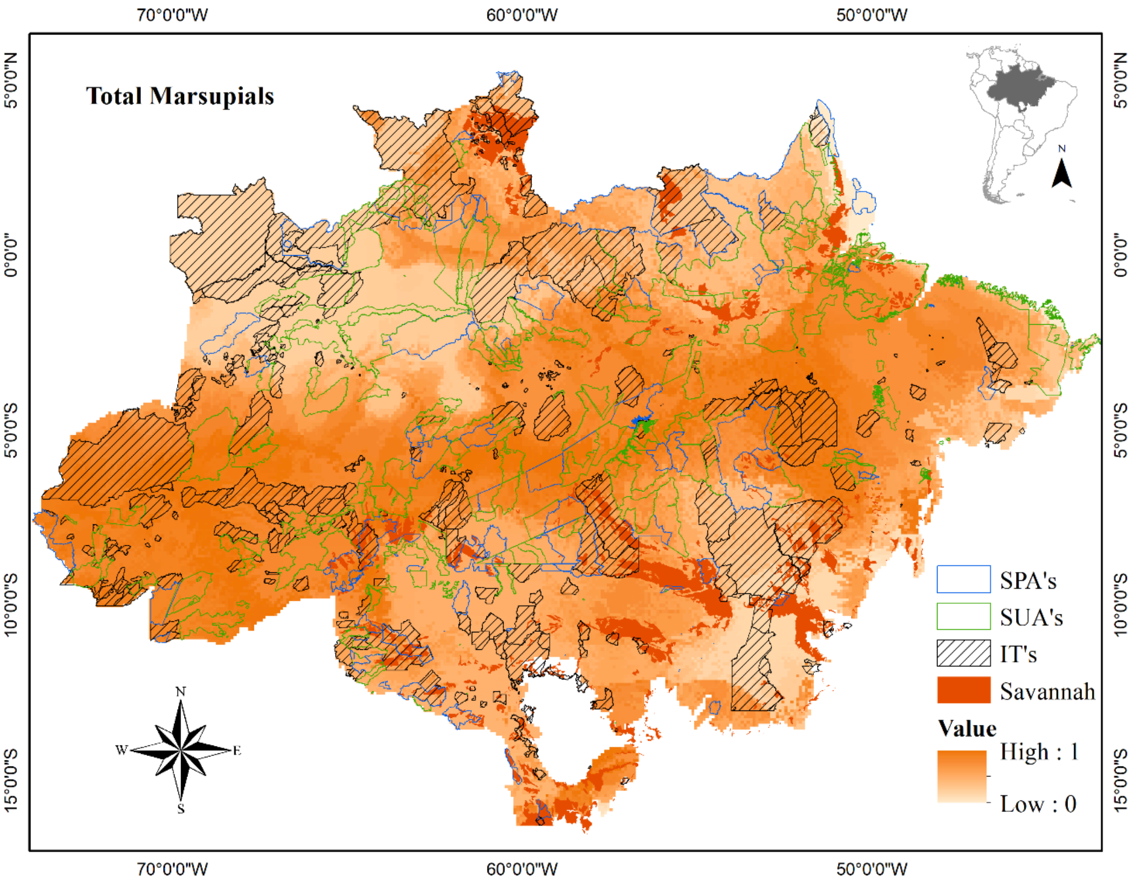
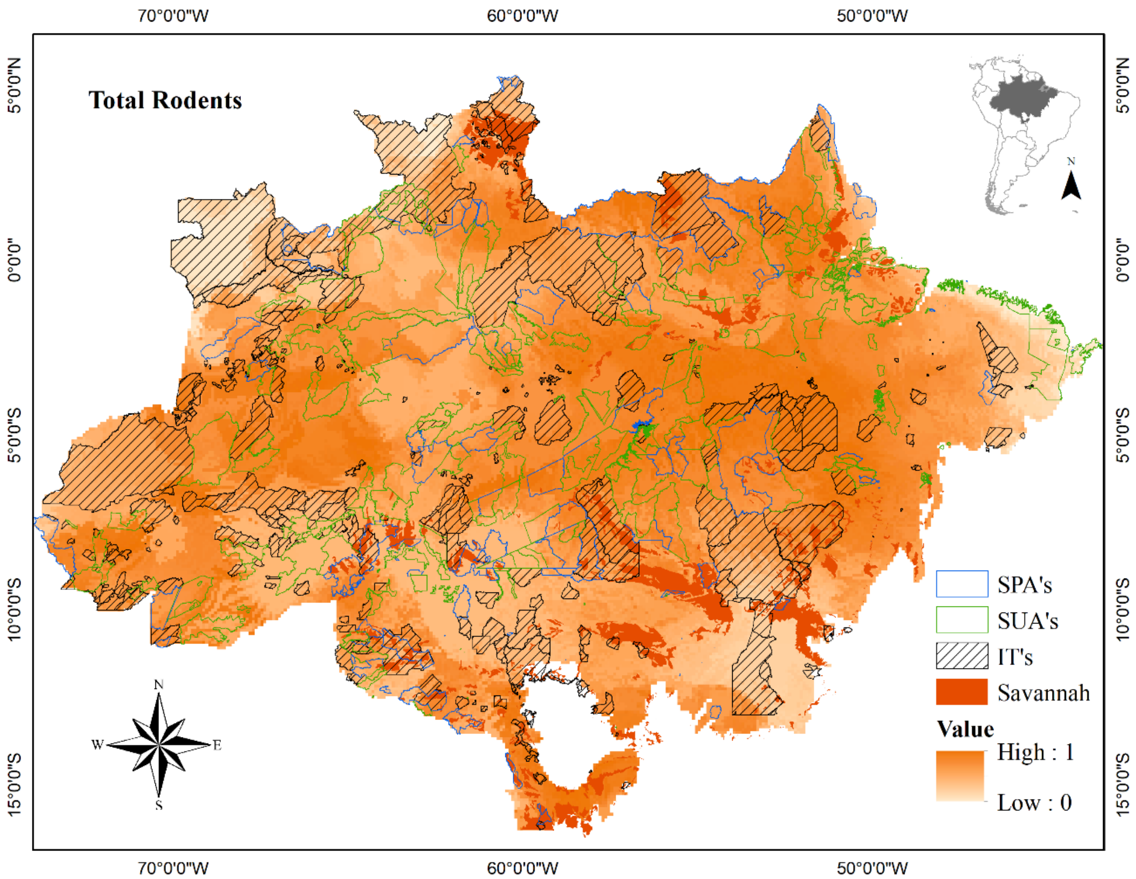

Total Marsupials
70°0'0"W
60°0'0"W
50°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
SPA's
SUA's
IT's
Savannah
Value
High : 1
Low : 0
N
S
W
E

Fig. 3


Total Rodents
70°0'0"W
60°0'0"W
50°0'0"W
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
15°0'0"S
N
S
W
E
SPA's
SUA's
IT's
Savannah
Value
High : 1
Low : 0

5. CONCLUSÃO GERAL

Diante das evidências, concluí que apesar da modelagem ter sido usada para descrever a conservação da Amazônia brasileira em termos de áreas de proteção, tanto para marsupiais quanto para roedores, ficou evidente que as Unidades de Conservação por si só não são suficientes para a proteção da biodiversidade do grupo. As áreas naturais que estão protegidas em Unidades de Conservação (UC's), juntamente com as Terras Indígenas (TI's), constituem os mecanismos de defesa mais importantes para a biodiversidade, pois resguardam a integridade dos ecossistemas, a biodiversidade e os serviços ecossistêmicos, além de contribuírem para assegurar o direito de permanência e a cultura de populações tradicionais e povos indígenas previamente existentes. A seguir destaco as principais conclusões e sugestões por capítulo: Primeiro capítulo – o panorama da produção científica acerca do conhecimento sobre pequenos mamíferos não-voadores no Brasil e no Neotrópico (lacunas de conhecimento) foi caracterizado detalhadamente evidenciando a necessidade de melhor política de investimentos em ciência e tecnologia no país, que apoie parcerias e pesquisas em estados e biomas menos estudados. Segundo capítulo – as Unidades de conservação, sozinhas, não são suficientes para proteger as espécies de pequenos mamíferos não-voadores na Amazônia brasileira (lacunas de conservação) pois espécies não estão sendo protegidas, já que a distribuição potencial das espécies de marsupiais e roedores se concentra em terras indígenas. Essas áreas não foram pensadas para a proteção da biodiversidade e sim para uso de povos e comunidades tradicionais. Terceiro capítulo – A distribuição potencial das espécies mostra onde mais Unidades de Conservação na Amazônia brasileira para a proteção da biodiversidade de pequenos mamíferos não-voadores deveriam ser criadas, identificando as áreas de maior importância para as espécies. Por meio da correlação do uso e cobertura do solo e as Unidades de Conservação, evidenciam que a maioria dos agrupamentos de espécies apresenta correlação negativa, ou seja, as áreas de importância estão dentro de ambientes antropizados (de menor cobertura vegetal). Todavia, as TI's continuam a ser importantes para a conservação das espécies de pequenos mamíferos não-voadores na Amazônia brasileira, embora a eficácia dessas áreas, que não são projetadas especificamente para a proteção da biodiversidade, ainda esteja em debate.

6. APÊNDICES

Capítulo 2

Appendix 01 – Details on the small mammal potential distribution model's protocol.

List of species and classifications

The classification of species according to threat level, according to the Red List of Threatened Species (IUCN 2023): DD – Data Deficient (when the information is insufficient to make a direct and indirect assessment of their risk of extinction, with based on its distribution and/or population status); LC – Least Concern (this category includes abundant and widely distributed taxa); NT – Near Threatened (when it has been assessed against the criteria, but does not qualify as Critically Endangered, Endangered or Vulnerable now, but is close to qualifying or likely to qualify for a threatened category in the near future); VU – Vulnerable (when available data indicates that it is at high risk of extinction in the wild); EN – Endangered (when the best available evidence indicates that it faces a very high risk of extinction in the wild); CR – Critically Endangered (when available evidence meets the criteria indicating that it faces an extreme risk of extinction); EW – Extinct in the wild (when it is known to survive only in cultivation, captivity or naturalized population, outside its previous distribution area); EX – Extinct (when extensive research conducted in its known or presumed habitat, at appropriate periods and throughout its distribution, does not record the presence of any individual) and NE – Not Evaluated (when it has not yet been analyzed according to the criteria established by the IUCN).

Environmental variables

We used 19 bioclimatic variables (resolution 9.4 x 9.4 km) for the entire Neotropical region obtained from the WorldClim database (http://www.worldclim.org/) (Hijmans et al. 2005) as a basis for creating of ecological niche models. They are: Average annual temperature; Monthly average daytime temperature; Isothermality; Seasonality temperature; Maximum temperature of the hottest month; Minimum temperature of the coldest month; Annual temperature range; Average temperature of the wettest quarter; Average temperature of the hottest quarter; Average temperature of the coldest quarter; Annual precipitation; Precipitation of the wettest month; Precipitation of the driest month; Seasonality precipitation; Precipitation from the driest quarter; Precipitation from the wettest quarter; Precipitation from the warmest quarter; Precipitation of the coldest quarter.

These variables belong to a group of climate variables derived from monthly temperature and precipitation values sampled over 1970-2000 from the WorldClim 2.1 version (Fick and Hijmans 2017). These data are often used for Species Distribution Modeling (SDM) to assess the potential distribution of species (Lee et al. 2012). To reduce multicollinearity in our dataset, we performed a Principal Component Analysis (PCA) (Legendre and Legendre, 2012) and used the eigenvalues as environmental variables. We then selected only the axes that represent an explanation equal to or greater than 95% (De Marco and Nóbrega 2018), using these axes as model variables. Only data from species that had more than 5 occurrence points been modeled, thus avoiding high spatial correlation between occurrence points (Figure 2).

Algorithm

We adjusted the models, according to Pimenta et al. (2022), using four algorithms: Support Vector Machine (SVM, Guo et al. 2005), Random Forests (RDF, Prasad et al. 2006), Maxent, using only linear and quadratic features (MXS, Anderson and Gonzalez 2011; Phillips et al. 2017) and Gausian-Bayesian (GAU, Golding and Purse 2016), so that an ensemble combining the final fitness maps was generated by the four algorithms (Araújo and New, 2007; Diniz-Filho et al., 2009; Marmion et al. 2009). These algorithms were chosen because they cover different theoretical bases for fitness estimates and are widely applicable in species distribution modeling (Beeman et al. 2021; Ingram et al. 2020; Lemes et al. 2019; Sillero et al. 2021 Velazco et al .2019). The RDF and SVM algorithms require species absence data.

To minimize model uncertainty, we consider an ensemble as the final model (Velazco et al., 2019, Pimenta et al., 2022). This model consists of the average adequacy of models whose Jaccard threshold value (Pimenta et al. 2022) were greater than the average threshold for each species (Velazco et al., 2019). The Jaccard threshold was selected with the aim of minimizing omission and overprediction (commission) errors in the models (Pimenta et al. 2022).

Additionally, we evaluate ENMs (Ecological Niche Models) and perform spatial restriction on the models, thus minimizing excessive prediction (overprediction) in distribution models (Mendes et al., 2020; Pimenta et al., 2022), so that the metric used in order to capture the specific characteristics of a set of species (mainly for species that will have many points), that is, a more restrictive threshold. Subsequently, only the pixels in which the species was predicted and have a record of the species or pixels in which the species was predicted and are close to pixels with prediction and points of occurrence, were maintained in the species' potential distribution map (Pimenta et al. 2022). As a partitioning method, we used the work of Pimenta et al. (2022) who developed specific modeling protocols for the different taxonomic groups: Block (for species > 30 occurrence points) - map partition using the checkerboard method (De andrade, Velazco and Júnior, 2020) and Bootstrap (for species < 30 points) - Random selection of a percentage of points for modeling and another for evaluation, with 70% of the points selected for the model and 30% for evaluation (Pimenta et al. 2022).

As the spatial restriction generates more conservative maps, restricting the occurrence areas to locations close to or with the occurrence of the species, we carried out a second modeling, without the spatial restriction. In this way, we have a more restrictive and conservative model (model with spatial restrictions) and a smaller conservative model, containing areas with environmental suitability without considering the occurrence or not of the species. All procedures were performed with the *Enmtml* function implemented in the ENMTL package (Andrade et al. 2020) for the R environment (R Development Core Team 2010). The processing of georeferenced data, reclassifications and creation of maps will be carried out using the Qgis 3.28.3 software (https://www.qgis.org/pt_BR/site/forusers/download.html). For the final model, the ENMs were adjusted using all occurrence records, with this procedure being applied to each algorithm within each species, adjusting the main components and specific layers (Brasil et al. 2021).

Model evaluation

The evaluation was carried out using operating characteristic curves (ROC), and the efficiency of each model was evaluated using the True Skill Statistics - TSS (True Skill Statistic) analysis test (Table S2, Supplementary Material), which has been widely used. advocated as a suitable discrimination metric that is independent of prevalence (Allouche et al. 2006; Shabani et al. 2018). TSS is an intuitive method for measuring the performance of DEMs, which calculates sensitivity (true positive fraction) and specificity (true negative fraction) values, in which predictions are expressed as presence-absence maps. This test restricts the area of occurrence a little more, leading to a less inclusive map, considering errors of omission in the distribution of species (false negative) and commission (false positive), with a variation between -1 and +1 (Sensitivity + Specificity) to indicate the predictive capacity of the models. Models with TSS values close to +1 reflect the good predictive capacity of the model, models with TSS of 0.2 – 0.6 are considered regular and/or moderate and models with TSS close to 0 and negative indicate low capacity. We then measure the model's predictive ability by its value for True Skill Statistics (TSS), True Positive Rate (TPR), and True Negative Rate (TNR). This procedure is considered appropriate in studies on the geographic distribution of species (Allouche et al. 2006).

<u>Appendix 02</u> - Script in R environment with all distributions of species evaluated in this study.

Marsupial's species

```
###################################################################################
############################## Marsupialia Distribution Maps #############################

###################################################################################
####################################### Packages and data #############################


library.list<-library()


if(length(which(library.list[[2]][,1]=="raster"))==0){
  install.packages("raster")
  library("raster")}else{
  library("raster")
  }


if(length(which(library.list[[2]][,1]=="profvis"))==0){
  install.packages("profvis")
  library("profvis")}else{
    library("profvis")
  }


load("MarsupMaps.Rproj.RData")


########################## Occurrences point ################################
occurences<-read.table("Occurrences.txt",head=T)


############################## Maps #######################################
setwd("Maps")
marsup<-list.files(pattern = ".tif")
sp<-stack(marsup)


# See the species of marsupials present in the list "marsup" (below) choose one specie, copy and paste in
sp_map
```

```
marsup

# As a example, We choose  "Didelphis_imperfecta.tif".
# You need to copy all information,
# including the quotation marks and the .tif.
sp_map<-"Didelphis_imperfecta.tif"

#Alternatively, you can use sp_map as 0 (default) and see all of the 164 maps.
sp_map<-0

# See your map now!
for (i in 1:1){
  if (sp_map==0){
    for (j in 1:length(marsup)){
    id.sp<-j
    plot(sp[[id.sp]],main=names(sp[[id.sp]]))
    pause(2)
    points(y~x,data=occurences[which(occurences$sp==names(sp[[id.sp]])),],pch = 1)
    print(c(names(sp[[id.sp]]),paste(length(which(occurences$sp==names(sp[[id.sp]]))),"Unique Points")))
    pause(2)
    }
  }
  id.sp<-which(marsup==sp_map)
  plot(sp[[id.sp]],main=names(sp[[id.sp]]))
  points(y~x,data=occurences[which(occurences$sp==names(sp[[id.sp]])),],pch = 1)
  print(c(names(sp[[id.sp]]),paste(length(which(occurences$sp==names(sp[[id.sp]]))),"Unique Points")))
}

# Enjoy!
```

Rodent's species

```
#############################################################################################
################################## Rodentia Distribution Maps ###############################

#############################################################################################
########################################### Packages and data ################################


library.list<-library()


if(length(which(library.list[[2]][,1]=="raster"))==0){
  install.packages("raster")
  library("raster")}else{
  library("raster")
  }


if(length(which(library.list[[2]][,1]=="profvis"))==0){
  install.packages("profvis")
  library("profvis")}else{
    library("profvis")
  }


load("RodentMaps.Rproj.RData")


############################# Occurrences point ####################################
occurences<-read.table("Occurrences.txt",head=T)


################################## Maps ###########################################
setwd("Maps")
rodent<-list.files(pattern = ".tif")
sp<-stack(rodent)


# See the species of rodentia present in the list "rodent" (below) choose one specie, copy and paste in sp_map
rodent
```

```
# As a example, We choose  "Calomys_callosus.tif".
# You need to copy all information,
# including the quotation marks and the .tif.
sp_map<-"Calomys_callosus.tif"

#Alternatively, you can use sp_map as 0 (default) and see all of the 164 maps.
sp_map<-0

# See your map now!
for (i in 1:1){
  if (sp_map==0){
    for (j in 1:length(rodent)){
    id.sp<-j
    plot(sp[[id.sp]],main=names(sp[[id.sp]]))
    pause(2)
    points(y~x,data=occurences[which(occurences$sp==names(sp[[id.sp]])),],pch = 1)
    print(c(names(sp[[id.sp]]),paste(length(which(occurences$sp==names(sp[[id.sp]]))),"Unique Points")))
    pause(2)
    }
  }
  id.sp<-which(rodent==sp_map)
  plot(sp[[id.sp]],main=names(sp[[id.sp]]))
  points(y~x,data=occurences[which(occurences$sp==names(sp[[id.sp]])),],pch = 1)
  print(c(names(sp[[id.sp]]),paste(length(which(occurences$sp==names(sp[[id.sp]]))),"Unique Points")))
}

# Enjoy!
```

Appendix 03 – Marsupials range plots.

Figure 01. Range plots of the One-Way Anova test of total marsupial species (Didelphimorphia: Didelphidae) for the Brazilian Amazon.

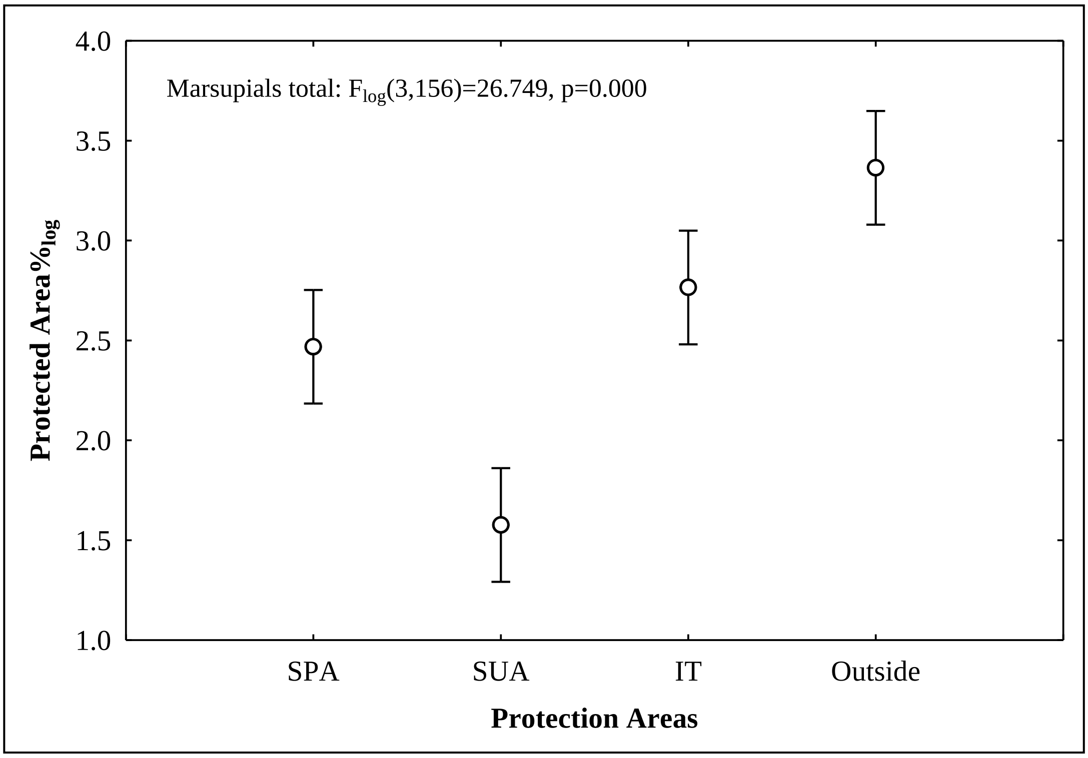


Figura 02. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) and their classification of Protected Areas evaluated hierarchically for the Brazilian Amazon.

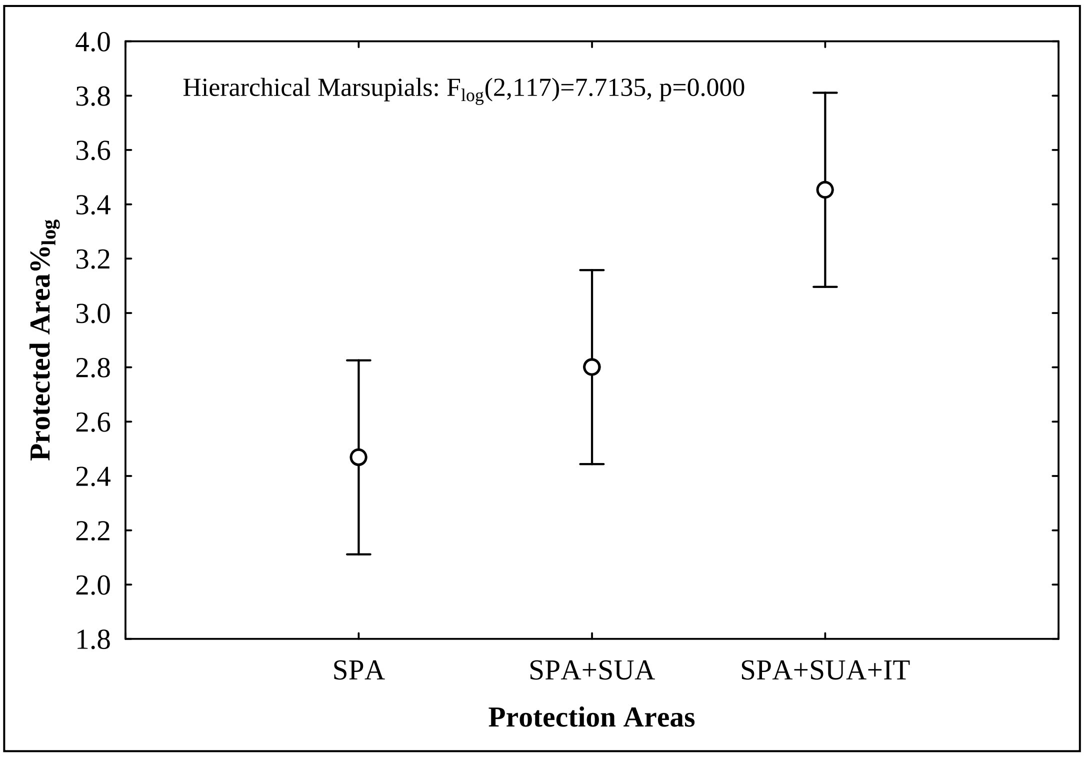


Figura 03. Range plots of the non-parametric Kruskal-Wallis test of marsupial species (Didelphimorphia: Didelphidae) and their classification according to the Frugivore Guild for the Brazilian Amazon.

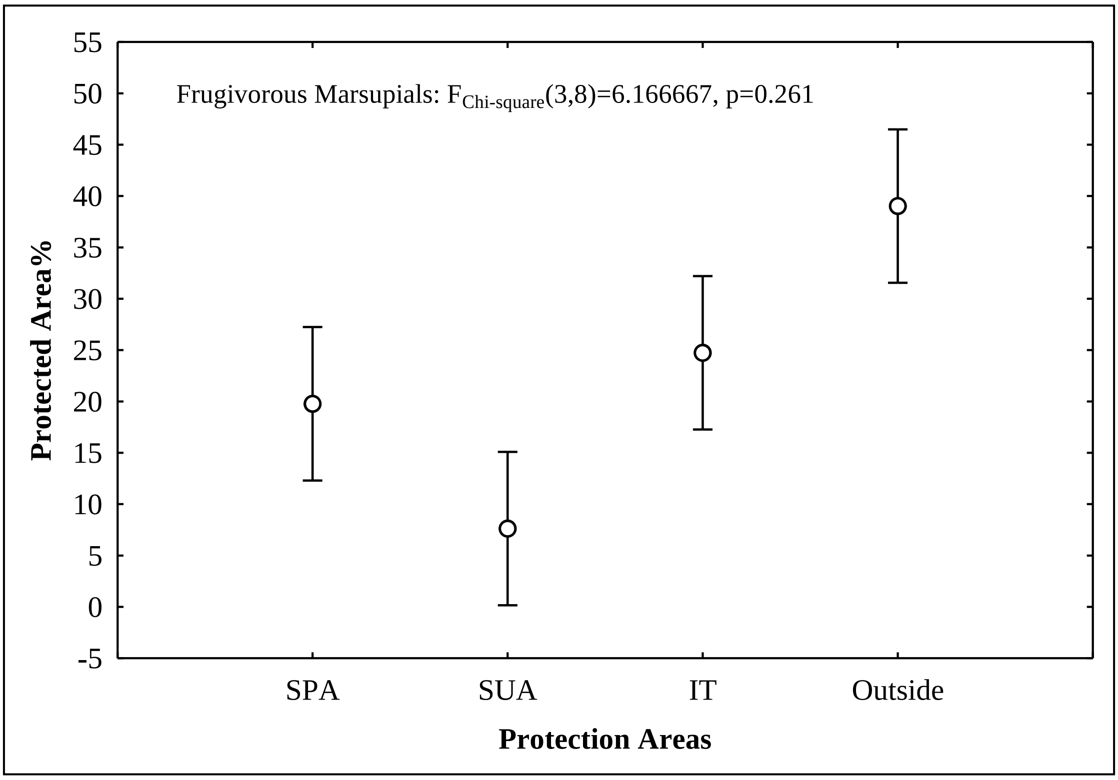


Figura 04. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) and their classification according to the Generalist Guild for the Brazilian Amazon.

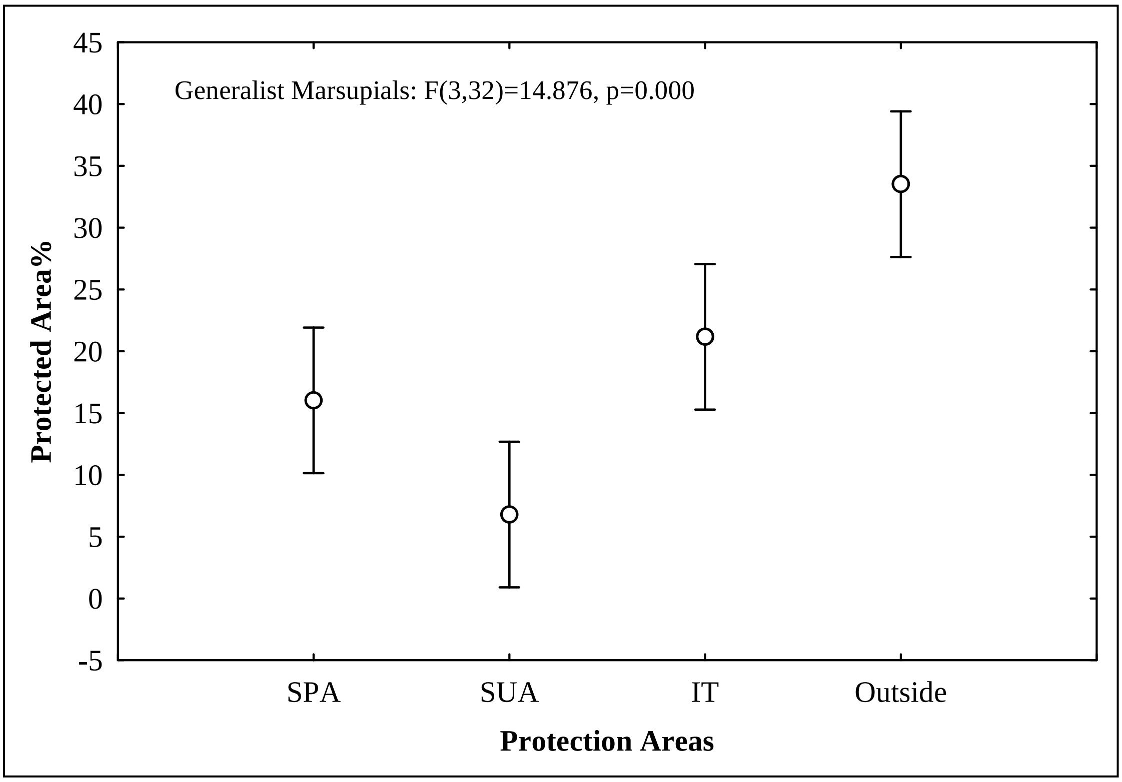


Figura 05. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) and their classification according to the Omnivorous Guild for the Brazilian Amazon.

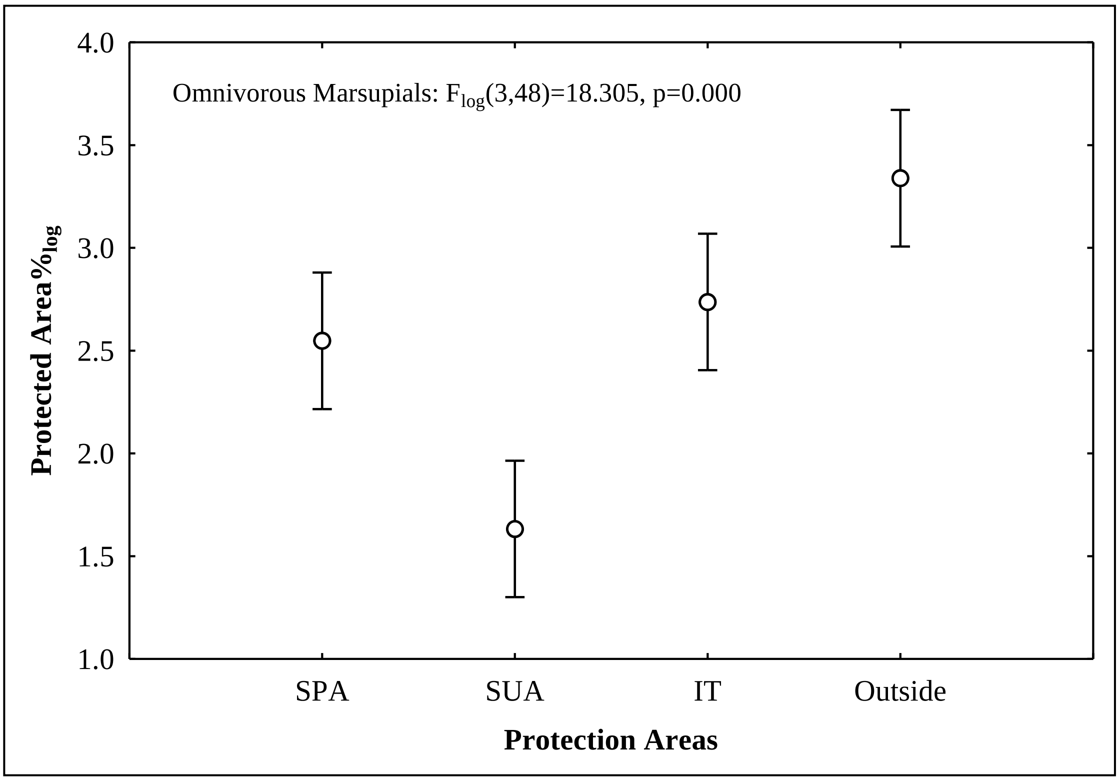


Figura 06. Range plots of the One-Way Anova test for marsupial species (Didelphimorphia: Didelphidae) without information on trophic guilds for the Brazilian Amazon.

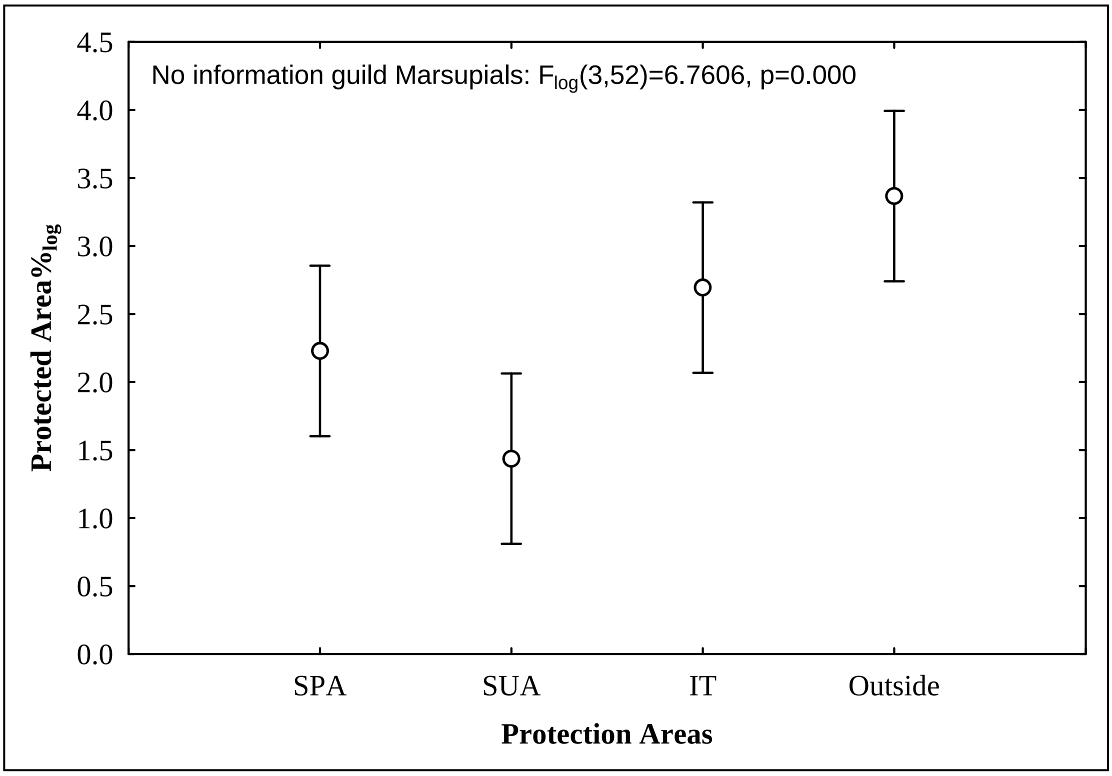


Figura 07. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) from Arboreal habitats for the Brazilian Amazon.

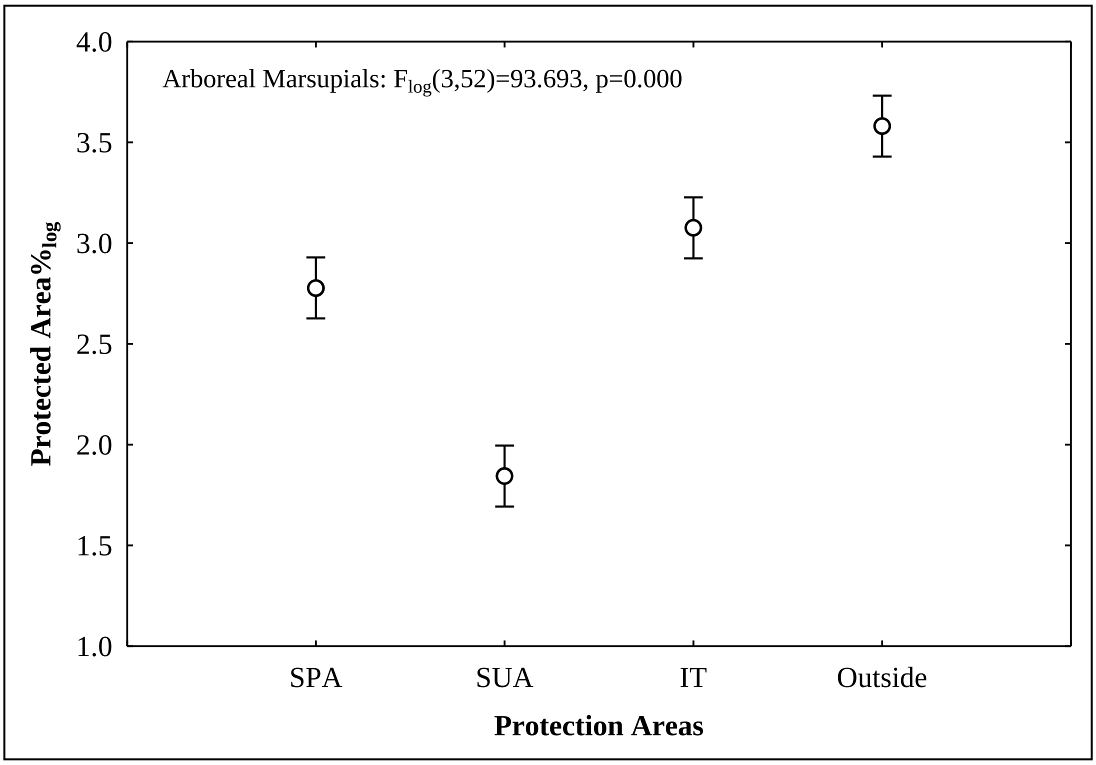


Figura 08. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) from Semiscansorial habitats for the Brazilian Amazon.

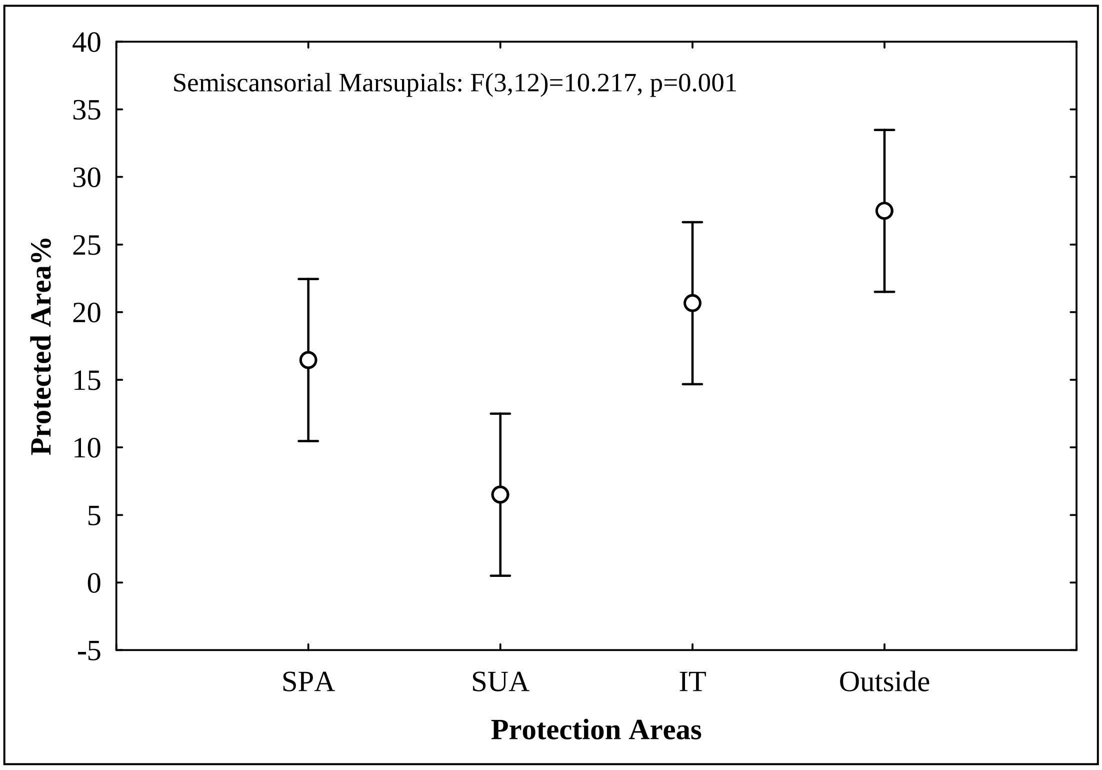


Figura 09. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) from Terrestrial habitat for the Brazilian Amazon.

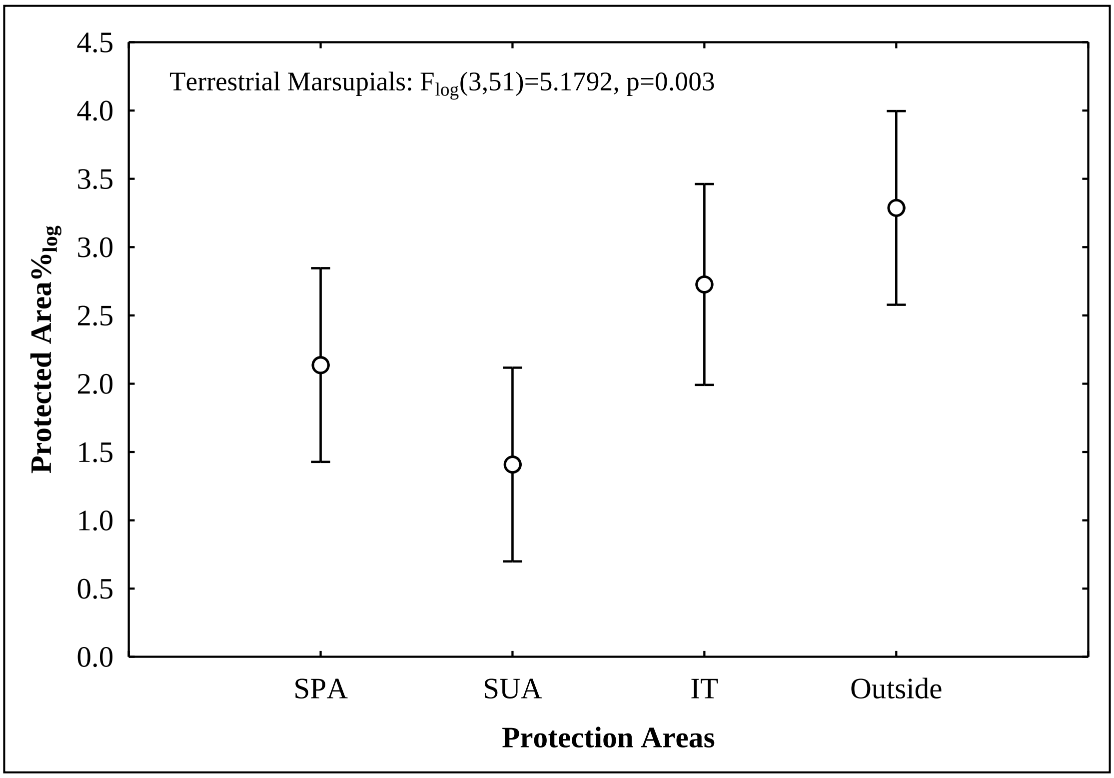


Figura 010. Range plots of the One-Way Anova test for marsupial species (Didelphimorphia: Didelphidae) without habitat information for the Brazilian Amazon.

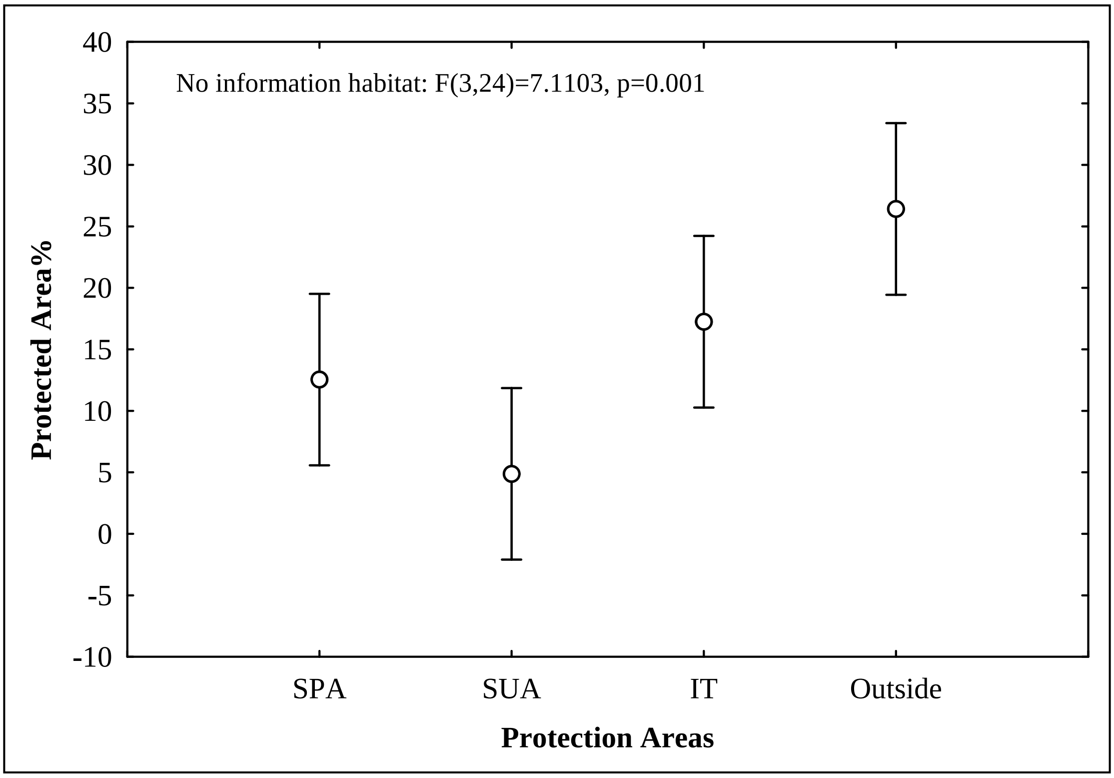


Figura 011. Range plots of the Anova One-Way test of marsupial species (Didelphimorphia: Didelphidae) considered to have a threat factor of Least Concern (LC) by the IUCN for the Brazilian Amazon.

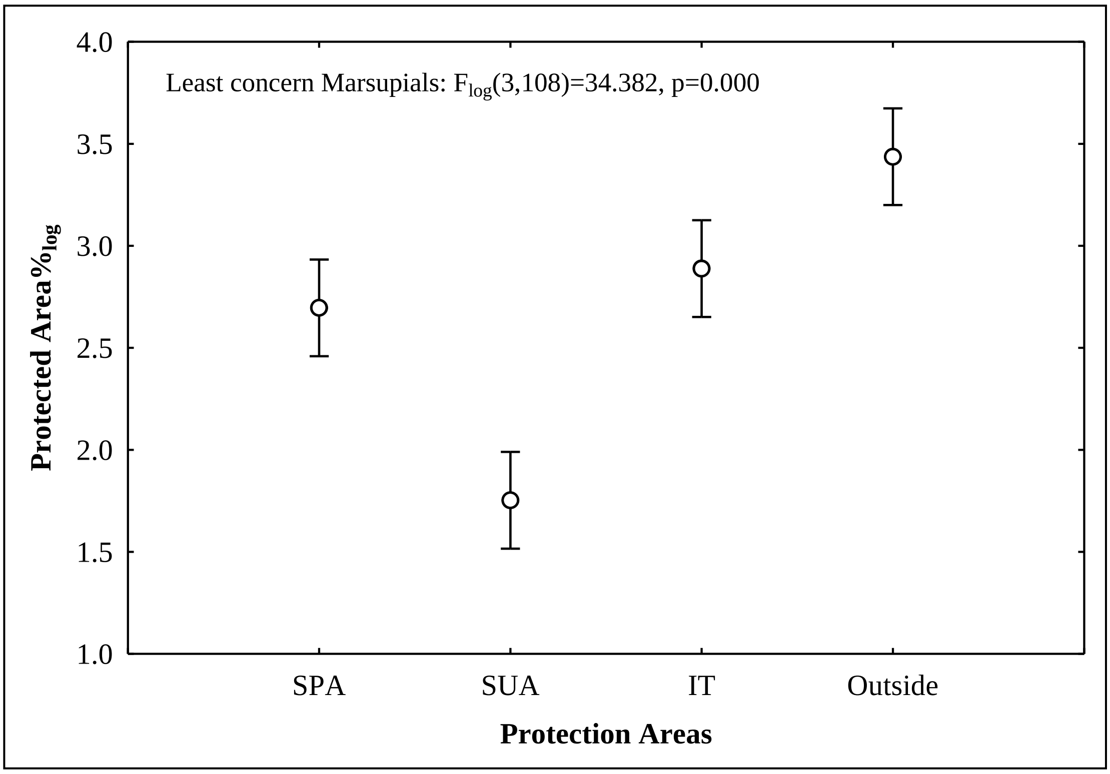


Figura 012. Range plots of the non-parametric Kruskal-Wallis test of marsupial species (Didelphimorphia: Didelphidae) considered with a Vulnerable threat factor (VU) by the IUCN for the Brazilian Amazon.

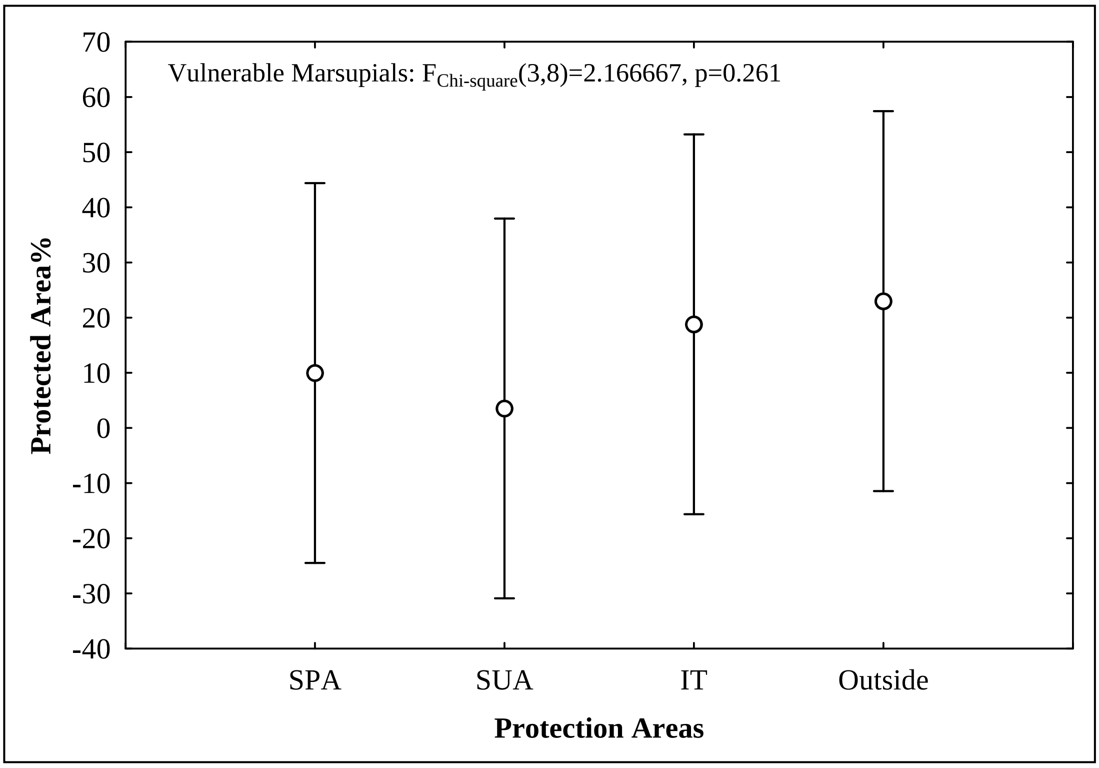
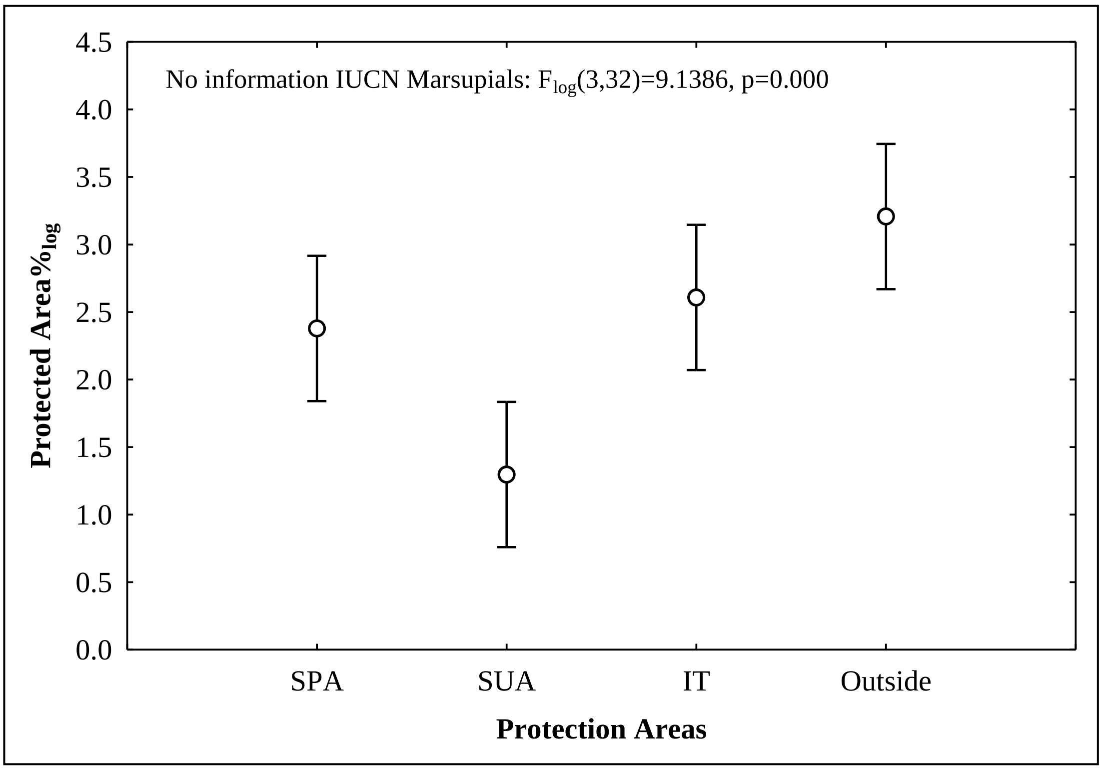


Figura 013. Range plots of the One-Way Anova test of marsupial species (Didelphimorphia: Didelphidae) considered without information on the threat factor by the IUCN for the Brazilian Amazon.



Appendix 04 – Rodents Range-plots.

Figura 01. Range plots of the One-Way Anova test of total rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon.

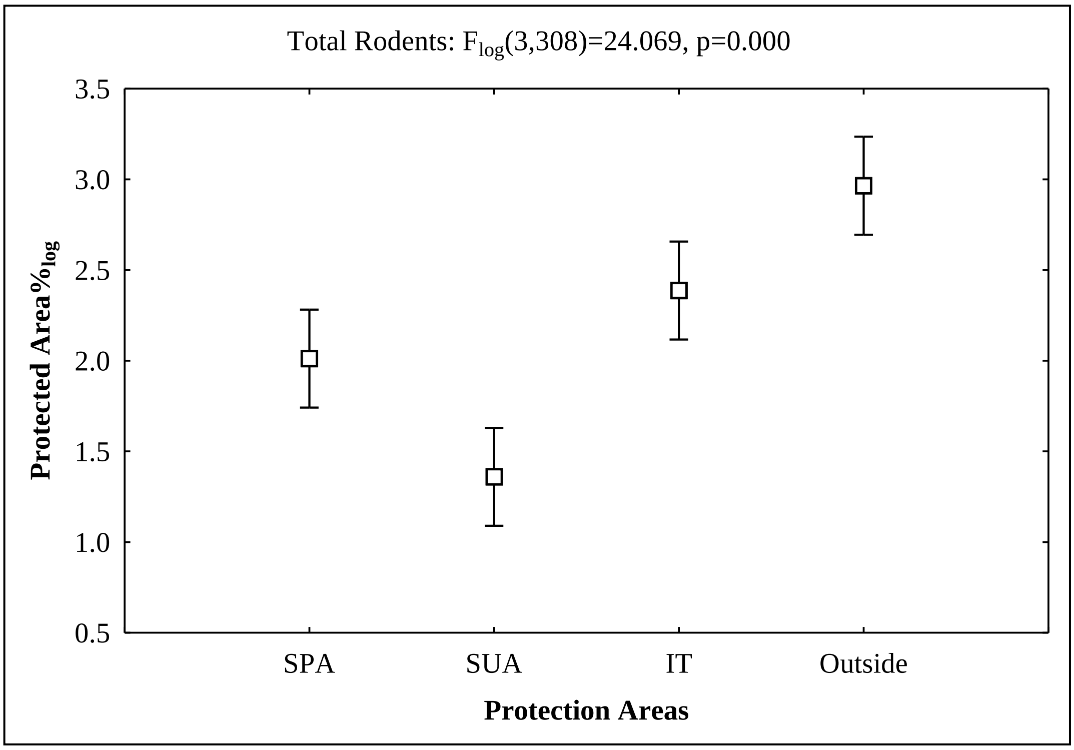


Figura 02. Hierarchical range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon.

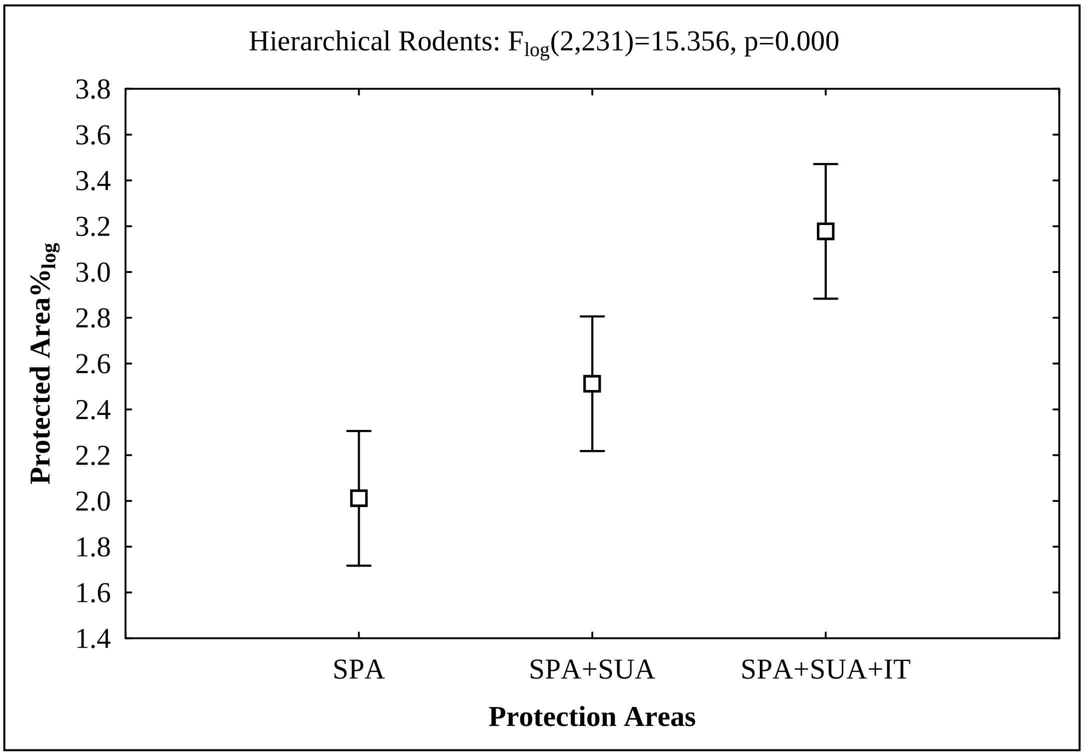


Figura 03. Range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Foliphagous Guild for the Brazilian Amazon.

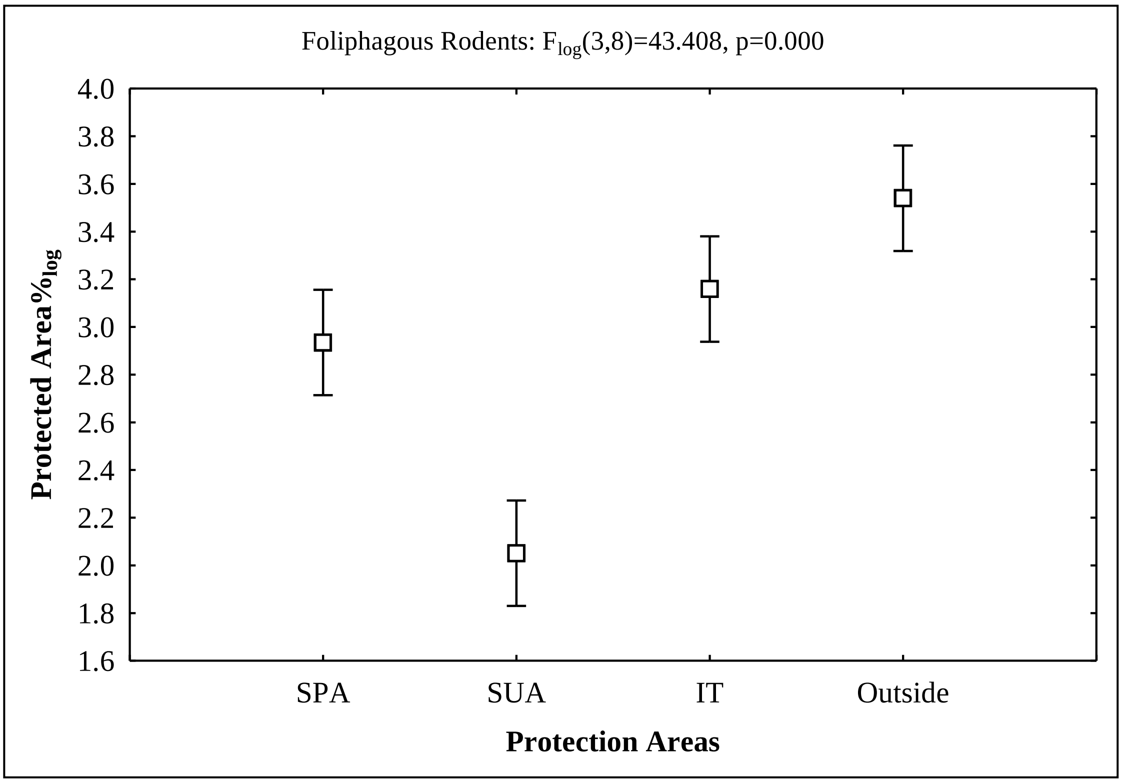


Figura 04. Range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Frugivore Guild for the Brazilian Amazon.

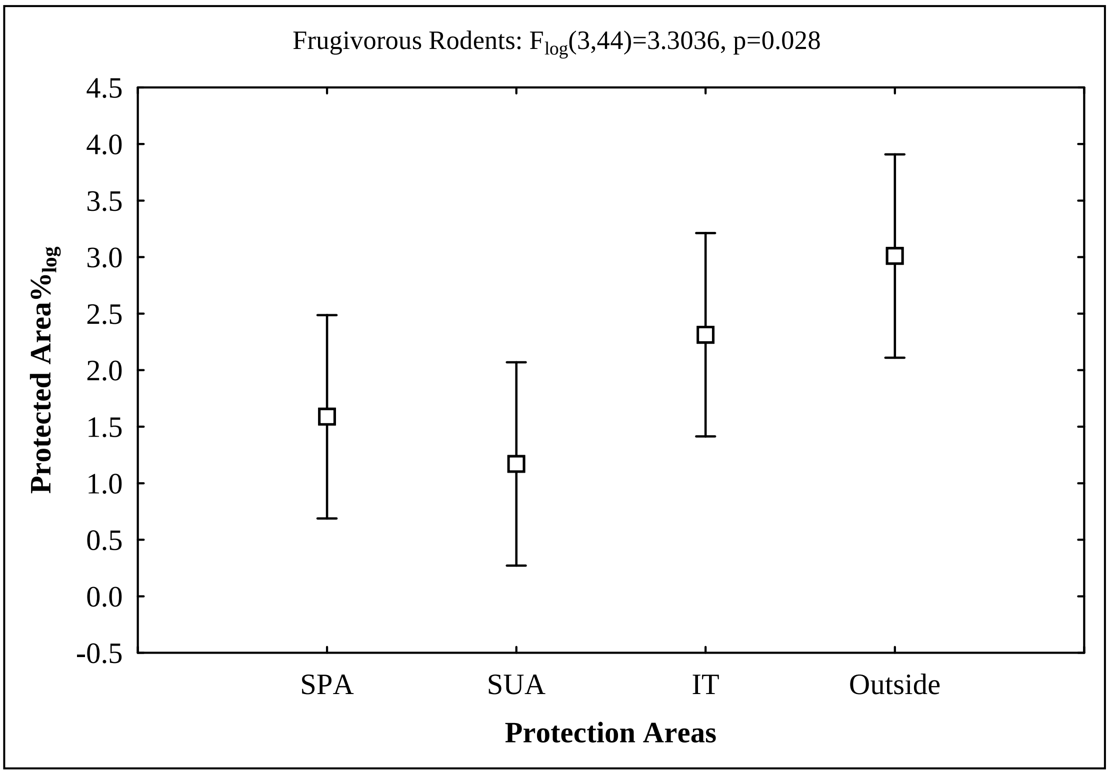


Figura 05. Range plots of the non-parametric Kruskal-Wallis test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Granivore Guild for the Brazilian Amazon.

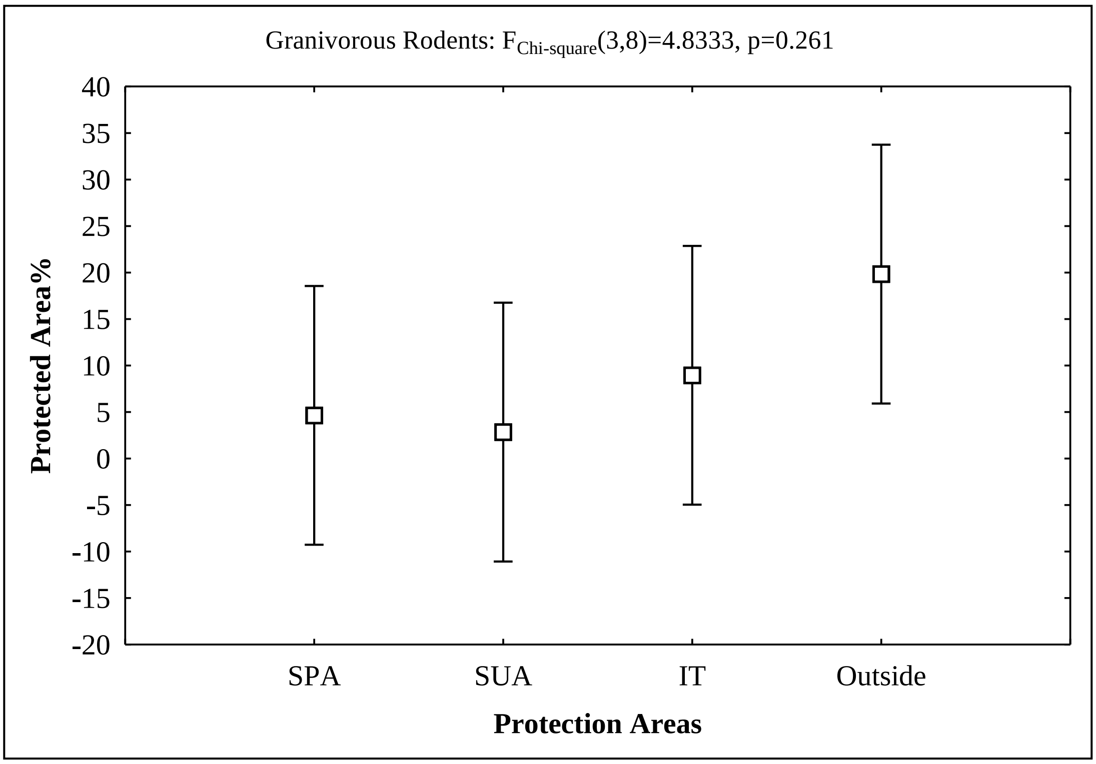


Figura 06. Range plots of the non-parametric Kruskal-Wallis test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Insectivore Guild for the Brazilian Amazon.

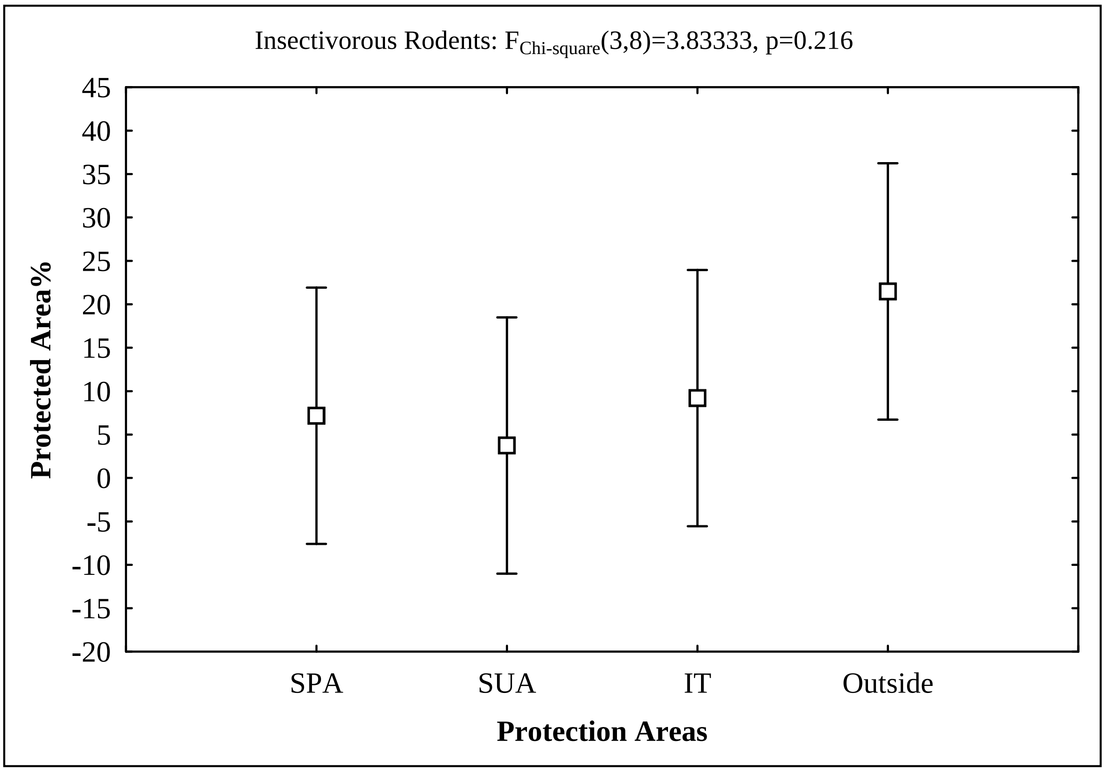


Figura 07. Range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Omnivorous Guild for the Brazilian Amazon.

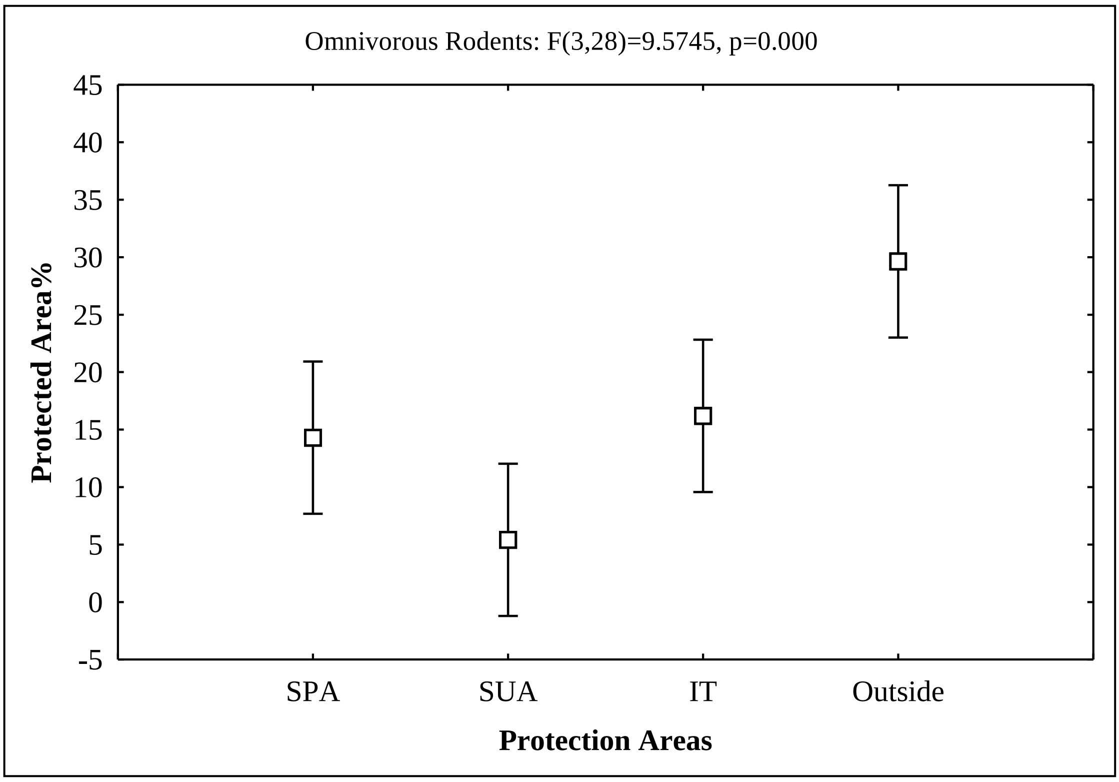


Figura 08. Range plots of the One-Way Anova test for rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) without information on trophic guild for the Brazilian Amazon.

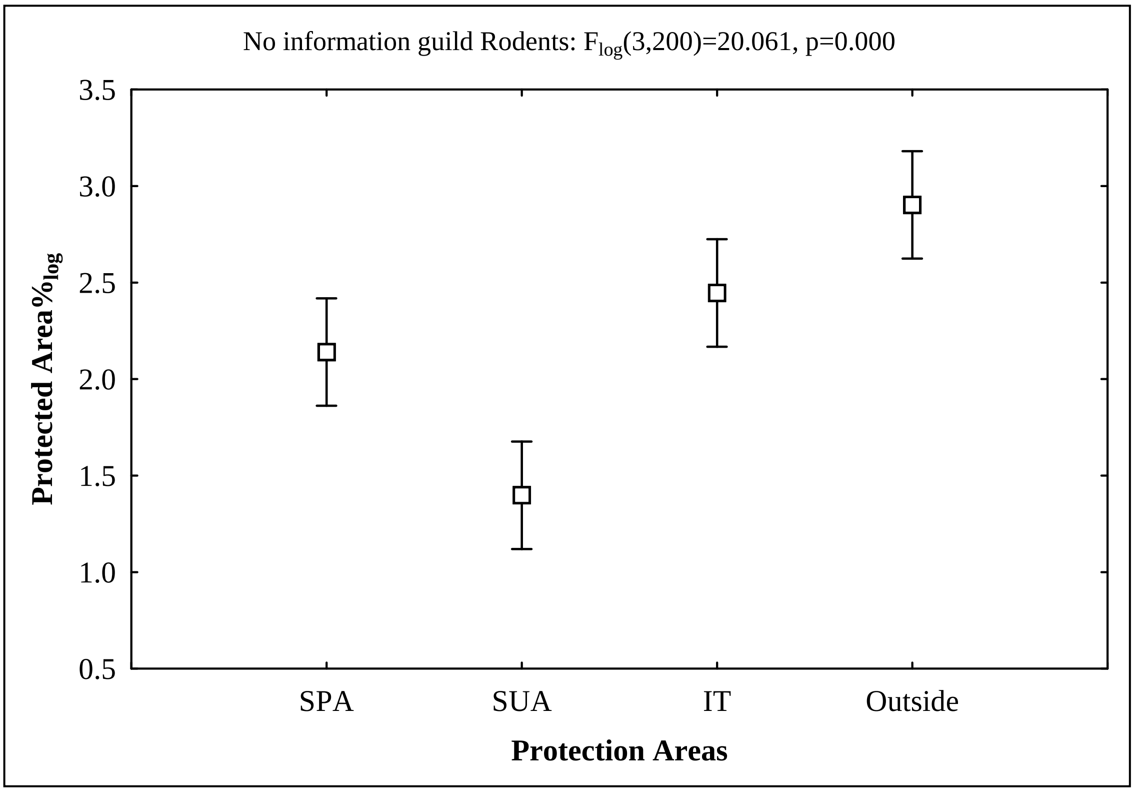


Figura 09. Range plots of the One-Way Anova test of Arboreal rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon.

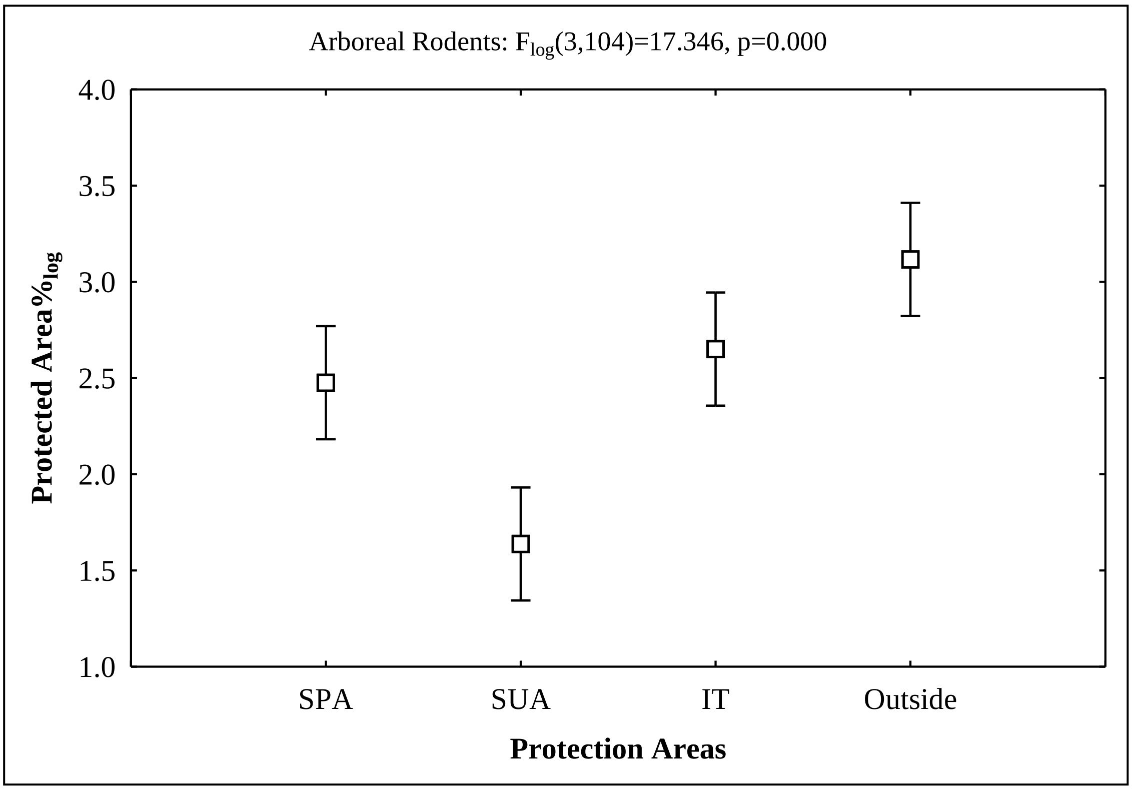


Figura 010. Range plots of the One-Way Anova test of Semiaquatic rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon.

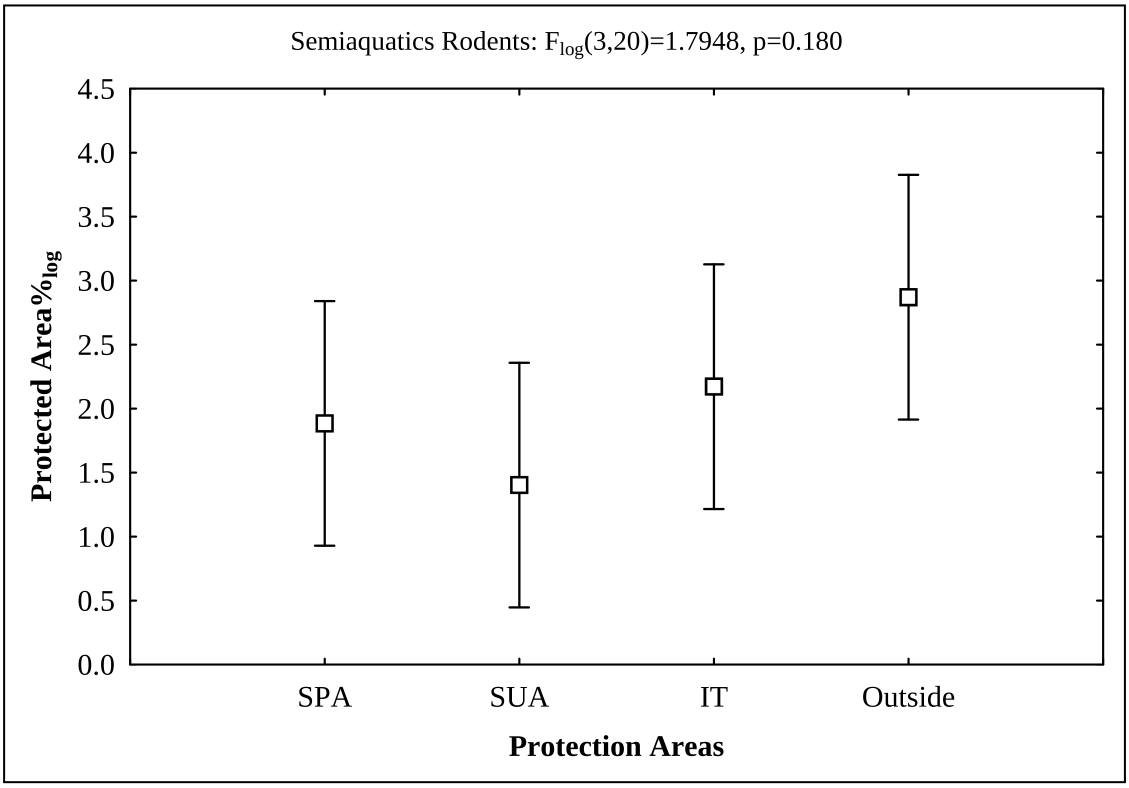


Figura 011. Range plots of the One-Way Anova test of Terrestrial rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) for the Brazilian Amazon.

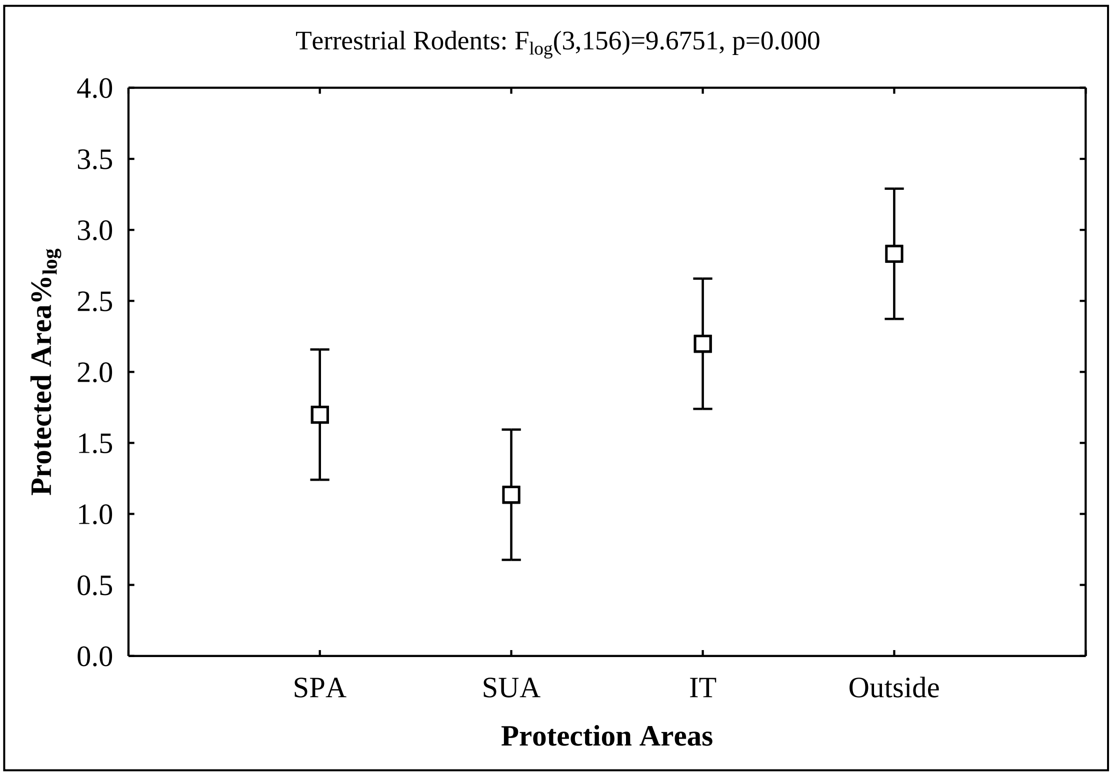


Figura 012. Range plots of the non-parametric Kruskal-Wallis test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) without habitat information for the Brazilian Amazon.

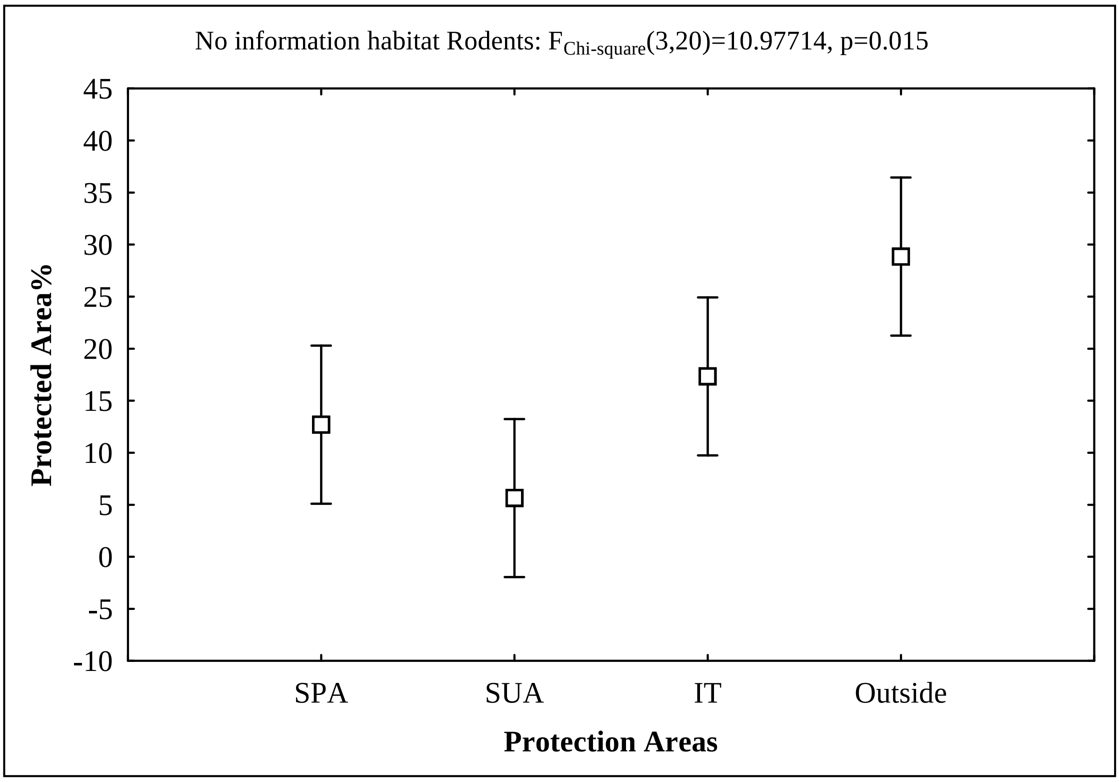


Figura 013. Range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) with Deficient Data (DD) regarding the IUCN threat factor for the Brazilian Amazon.

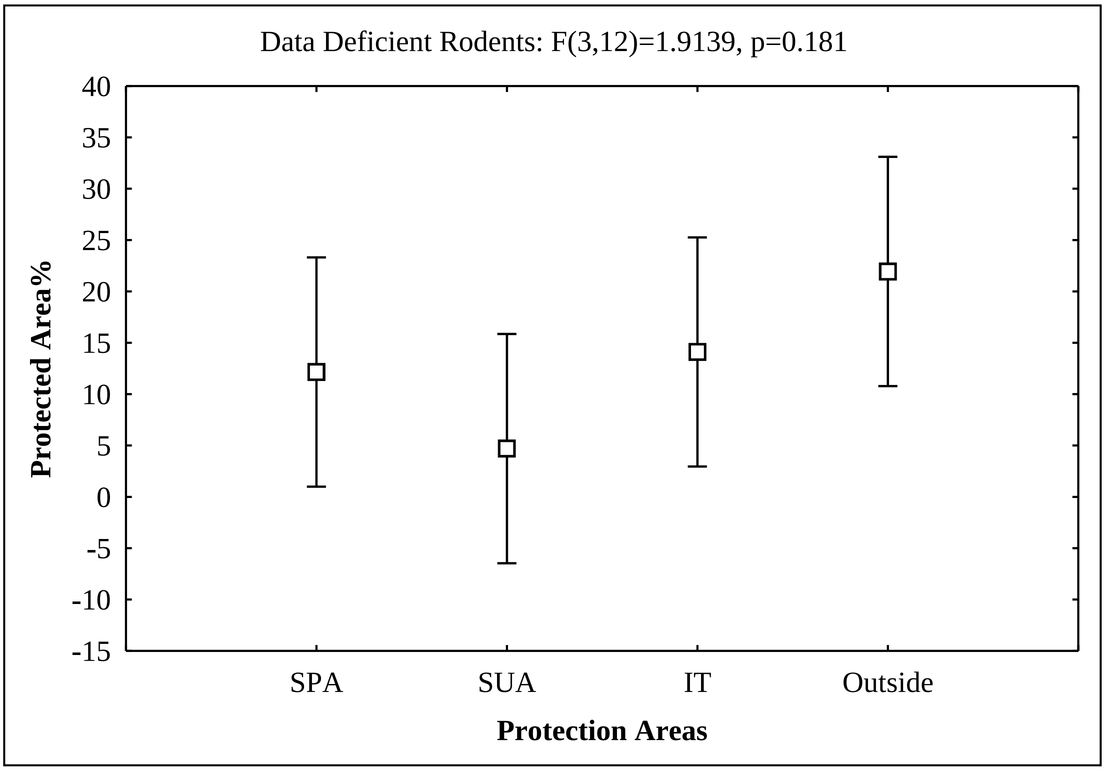


Figura 014. Range plots of the One-Way Anova test of rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) considered to have a threat factor of Least Concern (LC) in the IUCN for the Brazilian Amazon.

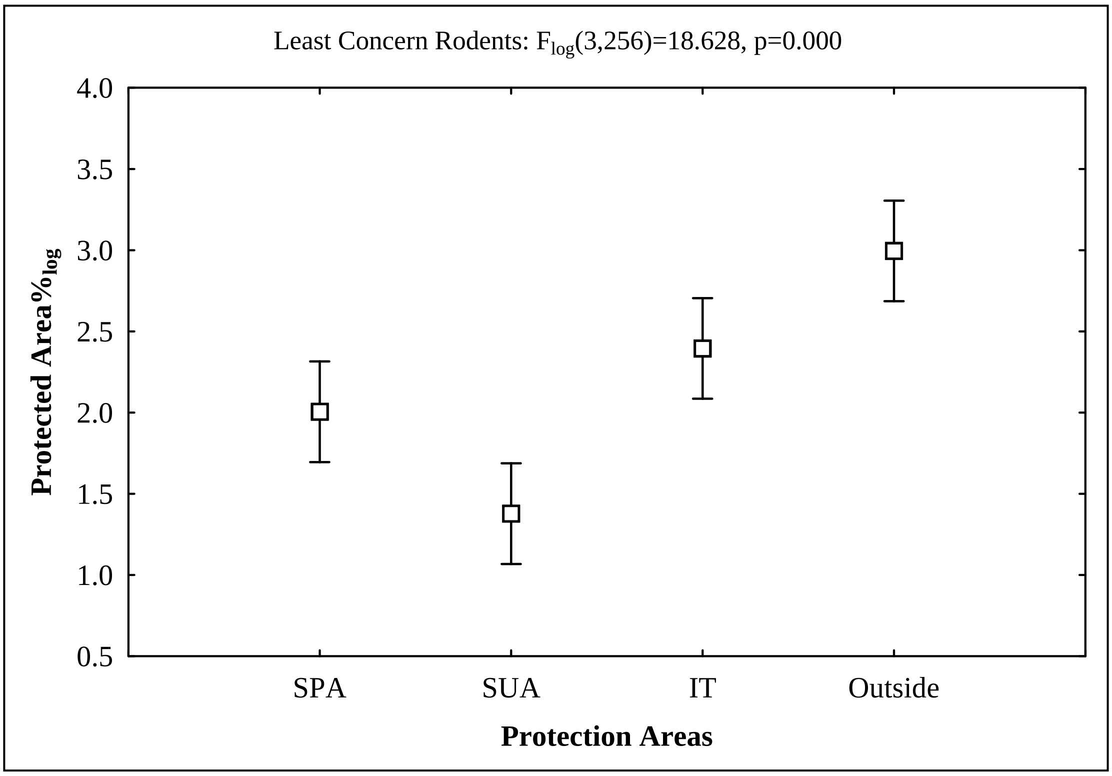
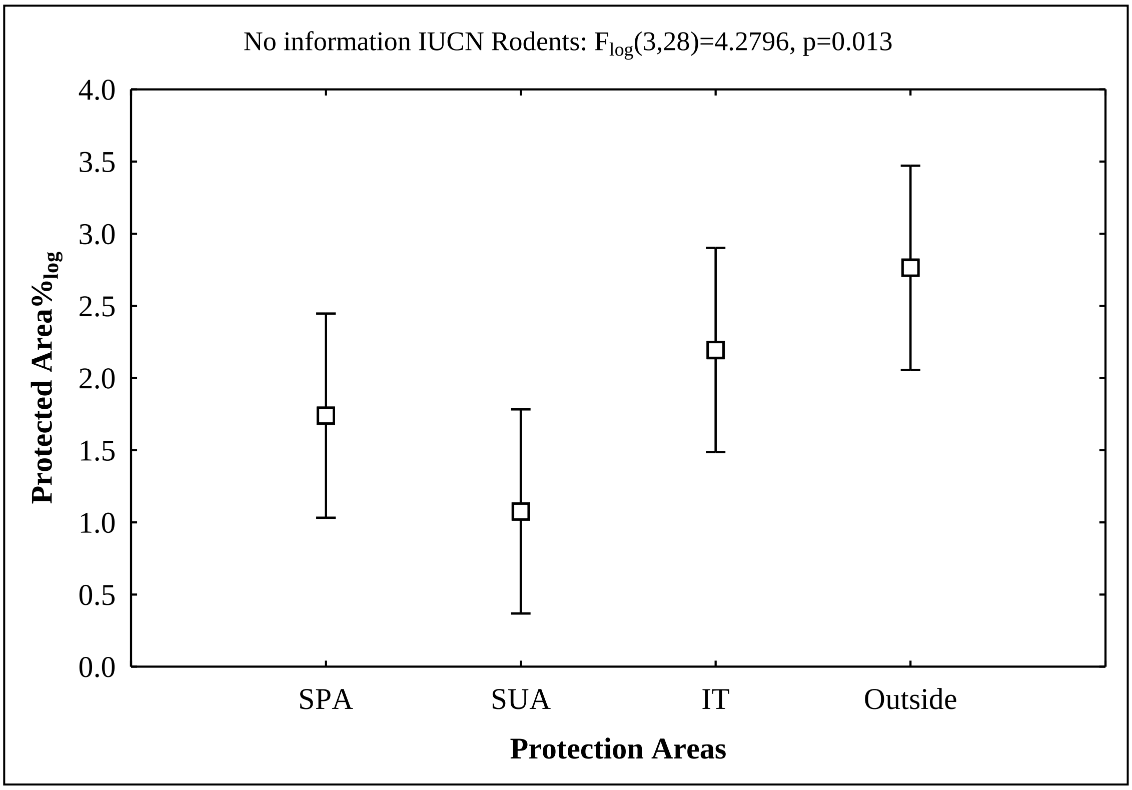


Figura 015. Range plots of the One-Way Anova test for rodent species (Rodentia: Cricetidae, Echimyidae and Caviidae) without information on threat factor in the IUCN for the Brazilian Amazon.



Capítulo 3

Appendix 01 – Details on the small mammal potential distribution model's protocol.

Occurrences data and species modeling

We used primary species collection and occurrence data from 1900 onwards, restricting ourselves to the Neotropics, to prevent the original data from being incompatible with the range of the environmental dataset present in the SpeciesLink digital collections (https://specieslink.net/), GBIF – Global Biodiversity Information Facility (www.gbif.org) and AMNH – American Museum of Natural History (https://www.amnh.org/research/vertebrate-zoology/mammalogy/collection-information/database). In addition to digital databases, such as ISI Web of Knowledge (http://www.webofknowledge.com), Scopus (https://www.scopus.com) and Google Scholar (https://scholar.google.com.br/), using a set of keywords ("small mammals"; "non-volant"; "Rodentia"; "rodents"; "rodent"; "Didelphimorphia"; "marsupials"; "marsupial"; "Amazon"). Records of doubtful and exotic species were excluded, as well as data without coordinates. To consult digital mastozoological collections, we used data collected through the Brazilian Biodiversity Information System - SIBBR (https://collectory.sibbr.gov.br/collectory/?lang=pt_BR). We created potential distribution models – SDMs, with spatial restrictions and without restrictions, following the recommendations of Pimenta et al. (2022), using the occurrence points from the entire Neotropical region for species with confirmed occurrence in the Brazilian Amazon. The modeling was carried out without land use and cover data so that it could be assessed which areas should be recovered.

Environmental variables

We used 19 bioclimatic variables (resolution 9.4 x 9.4 km) for the entire Neotropical region obtained from the WorldClim database (http://www.worldclim.org/) (Hijmans et al. 2005) as a basis for creating of ecological niche models. They are: Average annual temperature; Monthly average daytime temperature; Isothermality; Seasonality temperature; Maximum temperature of the hottest month; Minimum temperature of the coldest month; Annual temperature range; Average temperature of the wettest quarter; Average temperature of the hottest quarter; Average temperature of the coldest quarter; Annual precipitation; Precipitation of the wettest month; Precipitation of the driest month; Seasonality precipitation; Precipitation from the driest quarter; Precipitation from the wettest quarter; Precipitation from the warmest quarter; Precipitation of the coldest quarter.

These variables belong to a group of climate variables derived from monthly temperature and precipitation values sampled over 1970-2000 from the WorldClim 2.1 version (Fick and Hijmans 2017). These data are often used for Species Distribution Modeling (SDM) to assess the potential distribution of species (Lee et al. 2012). To reduce multicollinearity in our dataset, we performed a Principal Component Analysis (PCA) (Legendre and Legendre 2012) and used the eigenvalues as environmental variables. We then selected only the axes that represent an explanation equal to or greater than 95% (De Marco and Nóbrega 2018), using these axes as model variables. Only data from species that had more than 5 occurrence points were modeled, thus avoiding high spatial correlation between occurrence points (Figure 2; Chapter 2).

Algorithm

We adjusted the models, according to Pimenta et al. (2022), using four algorithms: Support Vector Machine (SVM, Guo et al. 2005), Random Forests (RDF, Prasad et al. 2006), Maxent, using only linear and quadratic features (MXS, Anderson and Gonzalez 2011; Phillips et al. 2017) and Gausian-Bayesian (GAU, Golding and Purse 2016), so that an ensemble combining the final fitness maps was generated by the four algorithms (Araújo and New 2007; Diniz-Filho et al. 2009; Marmion et al. 2009). These algorithms were chosen because they cover different theoretical bases for fitness estimates and are widely applicable in species distribution modeling (Beeman et al. 2021; Ingram et al. 2020; Lemes et al. 2019; Sillero et al. 2021 Velazco et al .2019). The RDF and SVM algorithms require species absence data.

To minimize model uncertainty, we consider an ensemble as the final model (Velazco et al. 2019, Pimenta et al. 2022). This model consists of the average adequacy of models whose Jaccard threshold value (Pimenta et al. 2022) were greater than the average threshold for each species (Velazco et al. 2019). The Jaccard threshold was selected with the aim of minimizing omission and overprediction (commission) errors in the models (Pimenta et al. 2022).

Additionally, we evaluate ENMs (Ecological Niche Models) and perform spatial restriction on the models, thus minimizing excessive prediction (overprediction) in distribution models (Mendes et al.

2020; Pimenta et al. 2022), so that the metric used in order to capture the specific characteristics of a set of species (mainly for species that will have many points), that is, a more restrictive threshold. Subsequently, only the pixels in which the species was predicted and have a record of the species or pixels in which the species was predicted and are close to pixels with prediction and points of occurrence, were maintained in the species' potential distribution map (Pimenta et al. 2022). As a partitioning method, we used the work of Pimenta et al. (2022) who developed specific modeling protocols for the different taxonomic groups: Block (for species > 30 occurrence points) **-** map partition using the checkerboard method (De Andrade et al. 2020) and Bootstrap (for species < 30 points) **-** Random selection of a percentage of points for modeling and another for evaluation, with 70% of the points selected for the model and 30% for evaluation (Pimenta et al. 2022).

As the spatial restriction generates more conservative maps, restricting the occurrence areas to locations close to or with the occurrence of the species, we carried out a second modeling, without the spatial restriction. In this way, we have a more restrictive and conservative model (model with spatial restrictions) and a smaller conservative model, containing areas with environmental suitability without considering the occurrence or not of the species. All procedures were performed with the *Enmtml* function implemented in the ENMTL package (Andrade et al., 2020) for the R environment (R Development Core Team 2010). The processing of georeferenced data, reclassifications and creation of maps will be carried out using the Qgis 3.28.3 software (https://www.qgis.org/pt_BR/site/forusers/download.html). For the final model, the ENMs were adjusted using all occurrence records, with this procedure being applied to each algorithm within each species, adjusting the main components and specific layers (Brasil et al. 2021).

In the pre-modeling phase, we first converted the predictor variables to the "*.asc*" format, then cut this information to the study region (mask). Subsequently, we extracted environmental information for each point of occurrence of small non-flying mammal species. After this extraction, we selected the predictor variables to reduce the redundancy of information. The selected variables were evaluated regarding their importance for the study groups. In the modeling phase, we use "presence and absence" data and classifications for trophic guild, behavioral guild and threat level according to the IUCN, for all species present and for the potential distribution of species, always differentiating them between marsupials and rodents. The conservation units were differentiated into Full Protection Areas (SPA's), Sustainable Use Areas (SUA's) and Indigenous Lands (TI's). For data on sun use and coverage, data from MapBiomas 8.0 was used (https://storage.googleapis.com/mapbiomas-public/initiatives/collection_8/iclu/coverage/brasil_covarage_2022.tif). Regarding illegal mining, data from the Amazon Socio-Environmental Information Network - RAISG (www.raisg.org) was used, which updated data from 2020 and mapped illegal mining locations and their impact on ITs and protected natural areas in the Amazon.

Model evaluation

The evaluation was carried out using operating characteristic curves (ROC), and the efficiency of each model was evaluated using the True Skill Statistics - TSS (True Skill Statistic) analysis test, which has been widely defended as an adequate discrimination metric. which is independent of prevalence (Allouche et al. 2006; Shabani et al. 2018). TSS is an intuitive method for measuring the performance of DEMs, which calculates sensitivity (true positive fraction) and specificity (true negative fraction) values, in which predictions are expressed as presence-absence maps. This test restricts the area of occurrence a little more, leading to a less inclusive map, considering errors of omission in the distribution of species (false negative) and commission (false positive), with a variation between -1 and +1 (Sensitivity + Specificity) to indicate the predictive capacity of the models. Models with TSS values close to +1 reflect the good predictive capacity of the model, models with TSS of 0.2 – 0.6 are considered regular and/or moderate and models with TSS close to 0 and negative indicate low capacity. We then measure the model's predictive ability by its value for True Skill Statistics (TSS), True Positive Rate (TPR), and True Negative Rate (TNR). This procedure is considered appropriate in studies on the geographic distribution of species (Allouche et al. 2006).

7. ARTIGOS PUBLICADOS DURANTE O PERÍODO DO DOUTORADO

Artigos 2022

1. Vieira, T. B., Sánchez-Botero, J. I., Garcez, D. S., Lima, S. M. Q., Pavanelli, C. S., Casatti, L., Smith, W. S., Benedito, E., Mazzoni, R., Pompeu, P. S., Agostinho, C. S., Montag, L. F. A., Zuanon, J., Aquino, P. P. U., Cetra, M., Pena, S. A., Alexandre, R. J. R., Oliveira, A. S. Q. A., Tejerina-Garro, F. L., Duboc, L. F., Pérez-Mayorga, M. A., Brejão, G. L., Mateussi, N. T. B., Leitão, R. P. and Júnior, P. De Marco. (2022). *Spatial non-stationarity in the distribution of fish species richness of tropical streams*. **Community Ecology** 24, 35-45. DOI: https://doi.org/10.1007/s42974-022-00121-7

2. Pena, S. A., Alencastre-Santos, A. B., Da Silva, J. B., Correia, L. L., Urbieta, G. L., Graciolli, G., Palheta, L. R. and Vieira, T. B. (2022). *Bats (Mammalia, Chiroptera) and bat flies (Diptera, Streblidae) from the Cazumbá-Iracema and Chico Mendes Reserve, Western Brazilian Amazon*. **Parasitology Research** 122, 451-459. DOI: https://doi.org/10.1007/s00436-022-07741-y

Artigos 2023

1. Vieira, T. B., Correia, L. L., Pena, S. A., Gomes-Almeida, B. K., Urbieta, G. L., Graciolli, G., Palheta, L. R., Caçador, A. W. B. and Aguiar, L. M. S. (2023). *Bats (Mammalia, Chiroptera) and bat flies (Diptera, Streblidae) found in the largest sandstone cave of Brazil*. **Mammalia** 87 (4). DOI: https://doi.org/10.1515/mammalia-2022-0105

2. Pena, S. A., Torres, N. R., Silva, C. R. and Vieira, T. B. (2023). *State of the art on the knowledge: a scientometric analysis of small non-volant mammals from Brazil (Didelphimorphia and Rodentia)*. **Brazilian Journal of Mammalogy** (91), e91202277. DOI: https://doi.org/10.32673/bjm.vi91.77 (Capítulo 1 da tese).

Artigos em avaliação

1. De Carvalho, E. S., Pena, S. A., Alexandre, R. J. R., Dias-Silva, K., Bastos, R. P., Oprea, M., Brito, D., Da Silva, J. C. and Vieira, T. B. *Chiropterofauna (Mammalia: Chiroptera) from Altamiro de Moura Pacheco State Park, Goiás, Brazil*. **Revista Biología Colombiana**.

2. Oliveira, A. S. Q. A., Alexandre, R. J. R., Pena, S. A., Vieira, T. B. and Gomes, F. B. R. *Can the morphological variation of Amazonian Bufonidae (Amphibia, Anura) be predicted by their habits and habitats?* **Revista South American Journal of Herpetology.**
3. Ferreira-Silva, S. K., Alexandre, R. J. R., Pena, S. A., De Lucena, M. D. L., Vieira, T. B. and Gomes, F. B. R. *Associations between morphological attributes and food resources in frogs from the Middle Xingu region, Pará, Brazil.* **Revista Brazilian Journal of Biology.**
4. Vieira, T. B., Alexandre, R. J. R., Dias, S. V., Pena, S. A., da Silva, Z. D., Correia, L. L., da Silva, J. B. and Graciolli, G. *Association between bats (Mammalia: Chiroptera) and ectoparasite diptera (Streblidae, Hippoboscoidea) in forest fragments in southwest Pará*. **Revista Mastozoologia Neotropical**.
5. Pena, S. A., Da Silva, C. R., Vieira, T. B. *Where are the small non-volant mammals (Didelphimorphia and Rodentia) of the Brazilian Amazon and who will protect them?* **Revista Biodiversity and Conservation** (Capítulo 2 da tese).
6. Pena, S. A., Da Silva, C. R., Vieira, T. B. *Priority enclaves of the Amazon Cerrado for the conservation of small non-volant mammals (Didelphimorphia, Rodentia) in the Brazilian Amazon.* **Revista Ecology and Evolution** (Capítulo 3 da tese).