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How much do we know about the Amazonian flora of Maranhão?

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ABSTRACT

Priority areas for conservation are largely defined based on information about biodiversity. However, the available information on species richness is heavily biased due to low sampling density, especially in hard-to-reach areas such as the Amazon region of Brazil. Here, we quantified the efforts to inventory the flora of the Amazonian region of Maranhão, evaluating the evolution of collection records, and presenting the data on the collections. Thus, we explore the hypothesis that, despite being located in a marginal area of the Amazon, the Amazonian region of Maranhão stands out for its uniqueness and richness, but it is under-sampled and under-represented in scientific studies. We retrieved 20,181 collection records from 89 out of 108 municipalities comprising this region. The vast majority of collection records (~48%) come from São Luís Island and the municipality of Buriticupu, the former an exception in terms of sampling density when compared to other regions/municipalities possibly due to the higher number of projects and well-structured collections. Angiosperms, especially legumes, represent the largest group, with collections distributed throughout the studied region. It is urgent to fill in the gaps identified here for the future establishment of conservation units and the recognition of the Brazilian biodiversity.

KEYWORDS: databases, sampling gaps, diversity, embryophyte

Quanto conhecemos sobre a flora amazônica do Maranhão?

RESUMO

As áreas prioritárias para conservação são definidas, em grande parte, pelas informações sobre a sua biodiversidade. Entretanto, as informações disponíveis sobre a riqueza de espécies tornam-se enviesadas pela escassez amostral, especialmente em áreas de difícil acesso como as que ocupam a região amazônica do Brasil. Aqui nós quantificamos os esforços no processo de inventariar a flora da Amazônia maranhense, demonstrando a evolução dos registros nos bancos de dados, e apresentando os dados sobre as coletas. Assim, exploramos a hipótese de que, apesar de estar localizada em uma área marginal da Amazônia, a região amazônica do Maranhão se destaca pela sua singularidade e riqueza, mas é subamostrada em termos de pesquisas e estudos científicos. Recuperamos 20.181 registros de coleta de 89 dos 108 municípios que compõem a Amazônia maranhense. Os primeiros registros foram feitos em meados do século XIX, mas se intensificaram apenas na década de 60 do século XX. A grande maioria dos registros de coleta (~48%) provém da Ilha de São Luís e do município de Buriticupu, sendo a primeira uma exceção em termos de densidade amostral quando comparada às demais regiões/municípios possivelmente pelo maior número de projetos e coleções bem estruturadas. Angiospermas, especialmente as leguminosas, representam a maior amostragem, tendo coletas distribuídas por toda Amazônia maranhense. É urgente preencher as lacunas aqui identificadas para o futuro estabelecimento de unidades de conservação e o reconhecimento da biodiversidade brasileira.

PALAVRAS-CHAVES: banco de dados, lacunas de amostragem, diversidade, embriófitas

INTRODUCTION

Priority areas for conservation are largely defined by information on their biodiversity. However, the available information on species richness is hampered by low sampling density, leading to the false impression of low species richness (Preston 1948; Magnusson et al. 2016). Investment in projects focused on scientifically unexplored areas has partially mitigated the problem of sampling biases. The implementation of floristic studies is relevant not only to improve sampling efforts and species richness assessment but

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also because the floristic composition itself is a good indicator of the current preservation conditions of these areas. This is particularly important within the context of continuous floristic degradation (Dias 2005).

Increasing sampling density is mainly recommended considering the dimension and complexity of the studied environments. For example, plants have a much lower sampling density in Brazil than what is considered adequate to fully study a flora (i.e., three herbarium specimens/km²) or assess regional richness (one herbarium specimen/km²) (Cielo-Filho et al. 2009). As a country with continental dimensions and mega biodiversity, Brazil still has floristically unexplored areas, especially in hard-to-reach areas such as its Amazon region (Costa et al. 2020; Stropp et al. 2020).

Proper sampling density allows biodiversity analysis, as well as contributing to other factors, such as the dissemination of local flora supported by the information gathered over time during efforts to inventory species (Cancela 2021). The records of this information, obtained through botanical collections, hold regional historical value, spanning from the earliest works of naturalists to current taxonomic research. In the context of deforestation, these data are essential for preserving the history of this environment and enabling comparisons between past and present information (Nualart et al. 2017; Shweta et al. 2024).

Some of these areas have a history of land conflicts and illegal resource exploitation, which are factors that significantly limit our understanding of local biodiversity (Carvalho et al. 2023). Therefore, it is essential to conduct studies in these regions. One example is the Amazonian region of Maranhão, located in "arc of deforestation" (Nepstad et al. 1995), which encompasses the frontiers of the Brazilian Legal Amazon with the Cerrado and Pantanal domains of Mato Grosso State. This region has significant biodiversity from both the Amazon and Cerrado domains, including several rare species, some of which are already threatened with extinction (Martins and Oliveira 2011).

Furthermore, the Amazonian region of Maranhão constitutes an important part of the Belém Endemism Center, characterized by expressive plant biodiversity including various vegetation types associated with watercourses such as the Tocantins, Gurupi, and Pindaré rivers (Almeida and Vieira 2010; De Oliveira Santos 2014). The Belém Endemism Center extends from the eastern State of Pará to the western State of Maranhão and is home to thousands of indigenous people of various ethnicities (Celentano et al. 2018) as well as rare or endangered animal species.

The ecotonal nature of Maranhão contributes to its wide biodiversity and creates an ambiguous space for the application of laws designed to protect specific phytogeographic domains. The major challenges in conserving the Amazonian region of Maranhão are wildfires, illegal hunting, and conflicts related to timber extraction, agriculture, and livestock (Celentano et al. 2018; Pinheiro et al. 2020). These factors directly impact the region, which has the lowest percentage of protected areas within the Brazilian Legal Amazon and the situation is aggravated due to its vulnerability to deforestation and forest fragmentation (Martins and Oliveira 2011). Only 17.66% of the total area of the Amazonian region of Maranhão is protected by two conservation units: the Baixada Maranhense Environmental Protection Area and the Gurupi Biological Reserve (REBIO Gurupi), the latter an integral conservation unit (BRASIL, 2000). REBIO Gurupi preserves about 20% of the primary forest and is under imminent threat of habitat loss/environmental crimes (Cardoso da Silva et al. 2005, Almeida and Vieira 2010).

Understanding how the flora of the Maranhão Amazon is represented in its different environments can contribute to the planning of conservation actions. Therefore, this study aims at quantifying efforts to inventory its flora over time, tracking the evolution of records in databases, and analysing the collection data, including the main collectors and the sampled environments. We investigate if the Amazonian region of Maranhão is under-sampled, despite being in a marginal area of the Amazon.

MATERIAL AND METHODS

Study area

The State of Maranhão (331,938.29 km²) is in Northeast Brazil bordering the North and Midwest regions. It encompasses a transitional region between the Amazon and Cerrado domains and is part of the states comprising the Brazilian Legal Amazon (IBGE 2002). The extent of the Amazon rainforest in Maranhão is 136,875 km² (Figure 1), representing 24.46% of the state's territory and encompassing 108 municipalities (IBGE 2019; De Sá Araújo 2020). The region has varied topography ranging from hills, inselbergs, flattened surfaces, river plains, and plateaus (Feio et al. 2013). Is located on the eastern border of the Amazon domain, adjacent to the dry forests of the Brazilian Cerrado. In the north, unlike much of the Amazon Basin, the Maranhão Amazon is bordered by an extensive area of coastal vegetation, such as restingas, dunes, and mangroves, which give the area unique characteristics (Martins and Oliveira 2011) The average temperature in the Maranhão Amazon is above 26°C and the climate is tropical with monsoons of the Am type according to the Köppen classification (Alvares et al. 2014).

Data sampling and sorting

The data were compiled from the speciesLink platform (2022) and Reflora virtual herbarium (https://floradobrasil.jbrj.gov.br/reflora/herbarioVirtual/), using the filters "Plantae" and "Maranhão" for all groups of embryophytes (i.e., bryophytes *s.lat.*, pteridophytes *s.lat.*, gymnosperms, and angiosperms). The generated spreadsheet contained the collector's name, collection number, year of collection, kingdom, phylum, family, genus, city, locality, and general description. The data

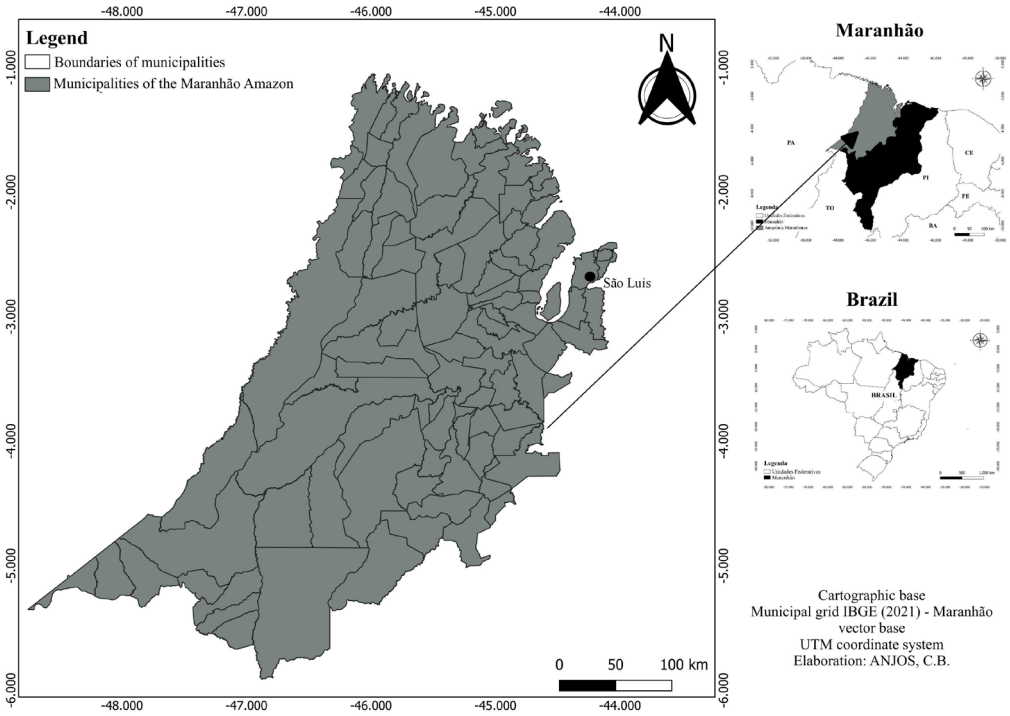

Figure 1. Location of the Amazonian region of the Maranhão state, Brazil.

were screened for exclusion based on the following criteria: a) records of algae or fungi; b) collections made in municipalities that do not correspond to the Maranhão Amazon; c) records without collection numbers; d) records without the year of collection; e) duplicate records; f) records without municipality names; g) not validly published names. Only the municipalities having vegetation coverage entirely within the Amazon rainforest were considered. The spreadsheet with the filtered data is available on the Figshare online repository (https://doi.org/10.6084/m9.figshare.26093623.v1).

Data analyses

The records obtained after the filtering process were analyzed considering: 1) The number of samples accumulated along the last 30 years and up to the present year of 2024 (Figure 2), thereby identifying the evolution of records; 2) The number of samples per collector, acknowledging the oldest collectors and those with the highest number of collections conducted in the region (Table 1); 3) The number of samples/sampling proportion per municipality and 4) The number of samples per taxonomic group.

To calculate the number of samples, we performed a count of the records of herbarium specimens by municipality. The values for each municipality were listed and categorized into four groups, as illustrated in Figure 3a, with colours differentiating the value ranges: ≥ 1,000 (black), ≥ 500 (medium grey), ≥ 100 (dark grey), and < 100 (white), excluding duplicates. Then, the proportion of samples in the regions was calculated considering the size of each municipality and the number of samples relative to the municipality with the highest number of records, to determine the relationship between the number of collections and the size of the municipality. The following steps were carried out in the calculation: 1) Average value of the municipalities' area (MVMA), calculated by dividing the total area of the Amazonian region of Maranhão (136,875 km²) by the number of municipalities (108); 2) The MVMA value was divided by the area of each municipality in the region, resulting in a correction factor (CF) (municipalities

Table 1. List of botanical collectors with the highest number of herbarium specimens collected in the Amazonian region of Maranhão.

Collector's name	Year of the first sampling	Number of herbarium specimens collected	Description of the environments covered in sampled areas
Froés, R.L.	1905	1,678	Upland regions, capoeiras, rocky islands, gallery forests, campinaranas, restingas
Muniz, F.H	1985	1,202	Restingas, humid tropical forests locally named as "Pre-Amazonia"
Daly, D.C	1980	627	Anthropized areas, secondary forests, forests dominated by palms, capoeiras, dry slopes, areas with partially disturbed vegetation, gallery forests
Lima, G.P	2013	580	Restingas, upland forest, secondary forests
Amorim, G.S	2015	388	Restingas (beaches and dunes), secondary forests, forest border areas

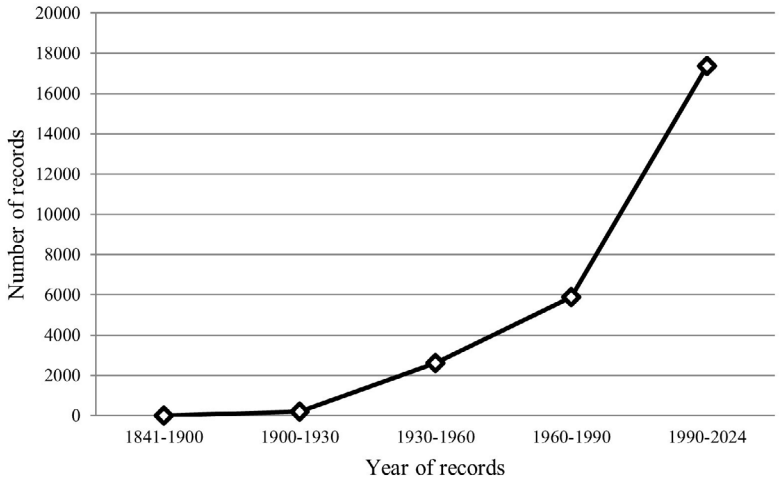

Figure 2. Evolution of collection records in the Maranhão Amazon between 1841 and 2024.

smaller than the MVMA presented CF values > 1); 3) The number of samples was multiplied by the respective FC of each municipality, resulting in its proportional sampling rate (PSR), which varies according to the size of the municipality. The PSR for each municipality was normalized to the highest PSR value (considered 100%). Municipalities were colored from black (= 100%) to white (1-20%), according to their relative PSR value to produce the map of sampling proportion. Maps were constructed using QGIS software version 3.16.14. The shapefiles of the Maranhão state and its municipalities were downloaded from the IBGE website (2021).

RESULTS

Number of records and collectors

We retrieved 122,856 herbarium specimens, of which 102,675 were excluded. Most of the excluded records were from collections made in municipalities outside the Maranhão Amazon or from records without clear information about the collection site.

Additionally, many records were eliminated for being duplicates, identified by the collector's number. Thus, 20,181 collection records were included in our analysis of the Amazonian region of Maranhão flora. The earliest records date back to 1841, marking the beginning of exploration in the area by naturalists (Figure 2). The number of collections remained constant until 1931, when the records significantly increased, especially from the 1960s onwards.

The first collection records in Maranhão were made in the mid-19th century by George Gardner (1812-1849), who sampled many species throughout Brazil between 1836 and 1841 (Stafleu and Cowan 1976). The sampling numbers of Gardner, ranging from 5,981 to 6,103, are collections made in Maranhão, mainly in forests around São Luís. According to the author, part of the collected samples was lost on the way back to England. Other significant collectors in the Maranhão Amazon and their respective number of herbarium specimens collected are listed in Table 1.

Sampling areas and sampling proportion

Most collections were made in forest areas, gallery forests, secondary forests, Amazon/Cerrado transition zone, and restingas of the São Luís Island. Botanical records were found for 89 out of 108 municipalities comprising the Amazonian region of Maranhão (Figure 3a). The darkest area in the northeast of the map on Figure 3a represents the São Luís Island, composed of the municipalities of Paço do Lumiar, Raposa, São José de Ribamar, and São Luís. Together with Buriticupu in the central-south region, these areas account for 10,092 samples, approximately 50% of the records. However, only the state capital São Luís has a collection record proportional to its size (Figure 3b, black areas), showing that in general municipalities of this region are under-sampled. Even in municipalities considered relatively well-sampled such as Buriticupu, Bacabal, Maracaçumé, Santa Luzia, Alcântara, and Turiaçu, the sampling density was about 60% (Figure 3b, dark gray areas).

Additionally, 57 municipalities (approximately 60% of the municipalities in the Amazonian area of Maranhão) have less than 100 collection records (Figure 3a, light gray areas), and 27 municipalities have less than 10 (Figure 3a, white areas). Bela Vista do Maranhão, Centro do Guilherme, Porto Rico do Maranhão, São João do Carú, and Satubinha do not have any herbarium specimens collected (Figure 3a, white areas). For municipalities with low sampling, the collection density ranged from 1% to 15% (Figure 3a, white areas).

Taxonomic groups

The majority of the collection records are of angiosperms, with 19,523 herbarium specimens distributed across 193 families, Leguminosae being the most abundant with 3,612 records. Bryophytes were the second major group with 403 collection records corresponding to 26 families (Calymperaceae was the

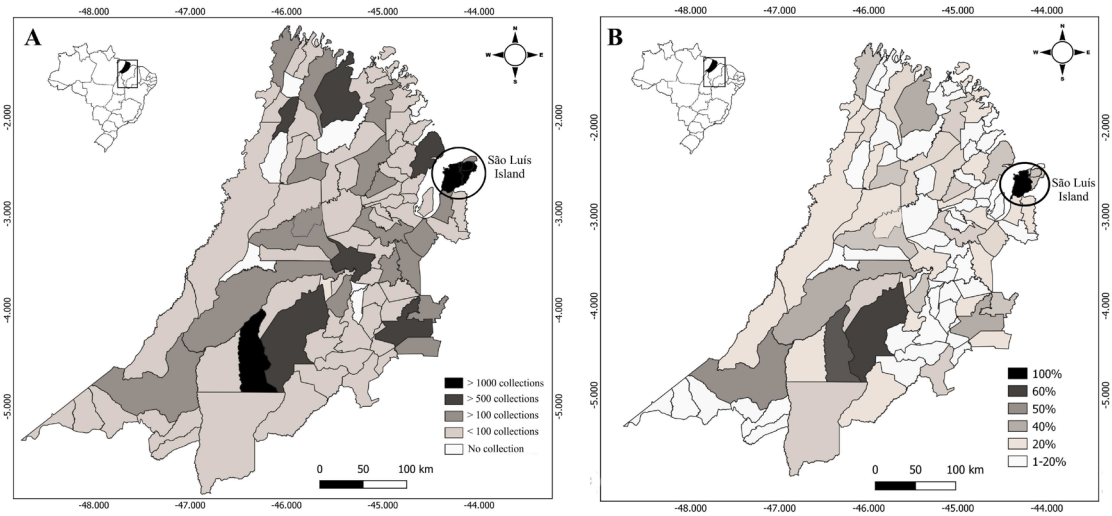

Figure 3. Maps showing: **A.** the number of herbarium specimens collected, and **B.** the sampling proportion (i.e., proportion between the number of records and the size of the municipality) per municipality of the Amazonian region of the Maranhão state, Brazil.

most abundant with 171 records). Pteridophytes, including lycophytes and ferns, accounted for 254 collection records distributed among 19 families. Pteridaceae and Polypodiaceae were the most abundant families with 26 records each. Gymnosperms were the most under-sampled group with only one record from the Gnetaceae family.

DISCUSSION

The search for the quantification of the Amazonian flora of Maranhão, through records in databases, enabled the discussion of historical aspects of the documentation of this flora, such as the exploration of less-studied areas and the taxonomic groups collected. One of these historical aspects dates to the visit of the first naturalists to the state, highlighted by the first collection made in the region by the naturalist George Gardner. Gardner visited São Luís in the last year of his journey and, besides collecting samples, he documented cultural and historical aspects of Maranhão in his book "Travels in Brazil" (Gardner 1942). Since then, the collection records remained modest until the mid-20th century when technical and higher education institutes started to be established in Maranhão. The creation of these institutions attracted local researchers and those from other states to collect plants from the forests of Maranhão, especially near major cities such as the capital São Luís.

Indeed, São Luís Island holds the highest sampling effort in the Maranhão Amazon, where approximately 50% of the samples were collected. This information was previously highlighted by Pinheiro (2020) when investigating the flora of coastal formations in Maranhão. The vegetation on the island is strongly influenced by the ocean, forming a true mosaic of plant communities with Amazonian species, some elements of Cerrado, and species commonly distributed along the Brazilian coast (Ewerton-Silva et al. 2023). Numerous recent floristic studies conducted on the island (e.g., Araújo et al. 2016; Dos Santos Amorim et al. 2016; Lima et al. 2017; Guterres et al. 2020; Dias and Almeida Jr. 2021; Caldas et al. 2023; Garcia et al. 2023) have revealed new distribution records (e.g., Castro and Almeida Jr. 2016; De Almeida Jr et al. 2018; Salazar-Ferreira et al. 2024) and new species (e.g., Scatigna et al. 2021). The concentration of collection near the state capital is possibly due to the higher number of projects and well-structured collections. The island is home to the largest herbaria in the state (MAR and SLUI) and serves as the main hub for training new botanists. However, within the island, only São Luís has a significant number of collections to comprehensively understand its flora, taking into account the size of the municipality and the number of collections.

Buriticupu also shows a high number of collection records. Differently from São Luís, almost all records from Buriticupu come from Muniz's studies (1998, 2008) when investigating the structure and dynamics of the Pre-Amazon forest in the Buriticupu Forest Reserve. Unlike other municipalities, the vegetation of this area is dominated by a mosaic of dense and open liana forests (Golfari 1980). However, considering its extension, these collection records are still insufficient to fully understand the flora of Buriticupu.

Besides São Luís Island and Buriticupu, other information has been published as part of broader floristic studies (e.g., Silva Jr. et al. 2020; Lima et al. 2022; Silva et al. 2022) or as a result of individual collection expeditions (e.g., Guarçoni et al. 2018; Ferreira et al. 2019). In general, the remaining municipalities in the Amazonian area of Maranhão have been sparsely sampled, with sporadic and small-scale collections. Floristic and physiognomic studies are limited, contributing to the sampling deficit and lack of knowledge about the biodiversity of this region. Therefore, increasing the sampling

density is necessary to enhance our understanding of the local flora and assist conservation status assessments (Dias 2005).

From a taxonomic perspective, the result obtained is similar to that found regarding the Brazilian flora, leguminosae was the most significant family, with 3,612 records. Some floristic studies in Amazon regions and other domains in Northeast Brazil have also reported similar results such as Freitas and Matias (2010) and Silva (2015) for Ceará and Rio Grande do Norte, respectively. In addition, the diversity of plants in ecotonal regions of the Amazon has already been explored in previous studies (Oliveira-Filho and Ratter 2002; Wittmann and Junk 2003), with results comparable to those found in the Amazon region of Maranhão. Leguminosae is particularly prominent in these transition zones in Brazil (e.g. Araújo et al. 2017).

The second most collected group was the bryophytes, the Amazon region has a wide range of bryophyte species and studies in Maranhão Amazon attested to the biodiversity of this group (Da Silva Brito and Ilkiu-Borges 2014; Monteiro 2018; Silva 2018). It is estimated that the Brazilian Amazon region hosts approximately 600 species of bryophytes distributed across 67 families, while in Maranhão, around 70 species of this group are known, distributed across 28 families (Flora do Brasil 2020). In the records evaluated here, 26 families were identified. When comparing these data, we see that almost all of the known species in Maranhão have already been collected in the study region. However, when compared to the number of species known for the Brazilian Amazon, a sampling deficit can be identified. Ferreira et al. (2023), in their study, discussed that there is still a knowledge gap regarding the diversity of bryophytes in Maranhão, especially in the southern region of the state, which was confirmed by our results, where we identified the need for greater collection efforts.

A sampling deficit was identified for lycophytes and ferns, aligned with conclusions of Silva Junior et al. (2024), who recognized 18 families in Maranhão, compared to the 19 families identified in our records. Recent studies indicate that knowledge about this group in Maranhão has been advancing (Fernandes et al. 2022; Ribeiro da Silva Junior et al. 2023).

Gymnosperms were represented here by only one record, and a low representation is also observed in other floristic surveys conducted in the state (Melo 2024). This pattern is expected, as gymnosperms are the least diverse group of plants in Brazil (Flora do Brasil 2020).

CONCLUSION

The information and availability of biodiversity databases, especially speciesLink and REFLORA, were crucial for assessing historical information on regional floristic composition and identifying under-sampled regions in the Maranhão Amazon. Based on our results, we recommend conducting collection expeditions, especially in areas with low sampling effort, such as the southern and southeastern regions of the Maranhão Amazon. The existing information on species richness in these municipalities is hindered by the lack of sampling, creating a false impression of low species richness. As priority areas for conservation are largely defined based on biodiversity information, it is urgent to fill in the gaps identified here. The path to conservation is long and begins with training qualified personnel and funding projects focused on under-sampled regions. The results of these actions may not be immediate but are essential for the future establishment of conservation units and the recognition of Brazilian biodiversity.

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