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Modeling the Potential Distribution of *Moquiniastrum oligocephalum* (Gardner) G. Sancho (Asteraceae: Gochnatieae) in Brazil

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KAROLINE DE MENEZES REBELLO

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ABSTRACT

Ecological Niche Modeling (ENM) encompasse s mathematical and computational processes guided by algorithms that utilize species occurrence data and environmental variables to establish correlations between distribution and environmental factors. This approach has fundamental implications for the study of biodiversity, decision-making in conservation, and understanding the ecological requirements of species. The application of ENM can aid in comprehending the distribution patterns of species within a biome or ecosystem through regional analysis, and it holds potential for application to other poorly studied tropical species, particularly those under the pressure of logging activities, such as *Moquiniastrum oligocephalum* (Gardner) G. Sancho (Asteraceae: Gochnatieae), commonly known as candeia, in Northeast Brazil. This species typically exhibits an arboreal habit, is ginodioecious, and comprises capitula arranged in reduced axillary panicles, with a biseriate pappus. The objective of this study was to investigate the distribution of Moquiniastrum oligocephalum in Brazil by analyzing the environmental suitability for the occurrence of the species, calculated through ENM. The methodology employed for generating environmental suitability models and analyzing the geographical distribution of *Moquiniastrum oligocephalum* proved satisfactory. The joint analysis focused on climatic conditions (Worldclim), combined with georeferenced occurrence points obtained from databases such as GBIF and speciesLink. The statistical validation of the models was based on the metrics of Area Under the Curve (AUC) and True Skill Statistic (TSS), yielding values of 0.97 and 0.87, respectively. The contribution values of the variables to the models were calculated through Relative Variable Importance, with the most significant variables identified as BIO1 - annual mean temperature (46.5%) and BIO4 - temperature seasonality (44.9%). From the generated models, it was concluded that there is greater suitability (exceeding 50%) for environments in the Caatinga and Atlantic Forest of Northeast Brazil, particularly in the states of Bahia, Sergipe, and Pernambuco. Thus, we can consider the Northeast region as a center for the dispersal of the species, especially in the state of Bahia, where significant environmental suitability was observed in the northern portion of the eastern coast and low environmental suitability in the southern and western areas of the state. For other regions of Brazil, results indicate reduced environmental suitability compared to the Northeast. No records of the species were found in the occurrence databases for the Central-West and Southern regions of Brazil, and there are few records for the Southeastern region. This study has thus expanded knowledge regarding the distribution of the species, providing essential support for conservation efforts in Brazil.

Keywords: Conservation; Ecological Niche Modeling; Environmental Suitability; MaxEnt.

RESUMO

A Modelagem de Nicho Ecológico (MNE), que consiste em processos matemáticos e computacionais guiados por algoritmos que utilizam dados de ocorrência das espécies e variáveis ambientais, para traçar correlações entre distribuição e ambiente. Possui implicações fundamentais para o estudo da biodiversidade, tomada de decisão em conservação e para a compreensão dos requerimentos ecológicos das espécies. O uso de MNE pode auxiliar no entendimento dos padrões de distribuição das espécies de um bioma ou ecossistema em uma análise regional, além de possuir potencial de aplicação para outras espécies tropicais ainda pouco estudadas, sobretudo aquelas que estão sob pressão da atividade madeireira, a exemplo da espécie *Moquiniastrum oligocephalum* (Gardner) G. Sancho (Asteraceae: Gochnatieae), espécie popularmente conhecida como candeia, no Nordeste brasileiro. Esta apresenta-se normalmente com hábito arbóreo, ginodióica, composta por capitulescências agrupadas em panículas reduzidas, axilares e pápus bisseriado. Este estudo teve como objetivo investigar a distribuição de *M. oligocephalum* para o Brasil, a partir da análise da adequabilidade ambiental para ocorrência da espécie, calculado a partir da MNE. A metodologia empregada para a geração de modelos de adequabilidade ambiental e análise da distribuição geográfica de *M. oligochephalum* foi satisfatória. A análise conjunta pautou-se no recorte de condições climáticas (Worldclim), combinado a pontos de ocorrência georreferenciadas, obtidos nos bancos de dados do GBIF e speciesLink. A validação estatística dos modelos foi baseada nas métricas da *Area Under the Curve* (AUC) e *True Skill Statistic* (TSS), com valores de 0,97 e 0,87, respectivamente. Os valores de contribuição das variáveis para os modelos foram calculados por meio da Importância Relativa das Variáveis, sendo consideradas as mais significativas: BIO1 - temperatura média anual (46.5%) e BIO4 - sazonalidade da temperatura (44.9%). A partir dos modelos gerados foi possível concluir que há maior adequabilidade (superior a 50%) para ambientes de Caatinga e Mata Atlântica nordestina no Brasil, principalmente nos estados de Bahia, Sergipe e Pernambuco. Podemos assim, considerar a região Nordeste como centro de dispersão da espécie, especialmente o estado da Bahia onde foi observada significativa adequabilidade ambiental na porção norte da costa leste do estado e baixa adequabilidade ambiental em áreas ao Sul e Oeste baiano. Para demais regiões brasileiras, resultados mostram reduzida adequabilidade ambiental, em relação ao Nordeste. Não foram encontrados registros nos bancos de dados da ocorrência da espécie nas regiões Centro Oeste e Sul do Brasil e há poucos registros da espécie para a região Sudeste. Foi possível, a partir desse estudo, ampliar o conhecimento acerca da distribuição da espécie para fonecer subsídios para as ações de conservação no Brasil.

Palavras-chave: Conservação; Modelagem de Nicho Ecológico; Adequabilidade Ambiental; MaxEnt.

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1. INTRODUCTION

The knowledge about the geographical distribution of species is fundamental for understanding the ecological and evolutionary determinants of biodiversity's spatial patterns and is essential for biological conservation (Ferreira, 2009). The complexity of biological systems follows a series of parameters that enable the survival and development of living beings. For example, abiotic factors such as temperature, humidity, and altitude, together with biotic factors like migration, competition, and dispersal, directly influence the distribution of organisms.

Habitat fragmentation, land-use changes, and climate change threaten the existence and perpetuation of species worldwide. With the intensification of global warming, it is notable that various biomes around the Earth are undergoing transformations, indicating changes that may increasingly lead to desertification processes and the occurrence of extreme events such as severe droughts and intense rainfall (Lacerda *et al*., 2016). Conversely, the growing need for ecosystem protection and restoration demands new technologies, which are being improved and can relate environmental characteristics to species occurrences (Giannini *et al*., 2012; Moreno-Fernández et al., 2016), as environmental changes have especially endangered the distribution of plant species.

Knowledge about species distribution, particularly plants, remains scarce in Brazil (Diniz-Filho et al., 2013; Hortal et al., 2014). One of the challenges faced is the lack of knowledge about the richness and geographical distribution of a considerable number of species. However, there have been significant advances towards a better understanding of phylogenetic relationships within the Asteraceae family.

Moquiniastrum oligocephalum (Gardner) G. Sancho is a species in the Asteraceae family, of economic importance, commonly known in Northeast Brazil as "candeia" or "candeeiro." It typically presents tree-like characteristics, is gynodioecious, and comprises capitulescences grouped in reduced, axillary panicles, shorter than the leaves, rarely bracteate, containing tubular cream-colored flowers and biseriate pappus (Flora e Funga do Brasil, 2023). This species is sought after for its timber potential, highlighting the need for greater efforts in environmental protection to avoid the impacts of population reduction in its niche.

Thus, it is important to invest in and reinforce measures that enable biodiversity conservation, combining efforts to maintain priority areas (Peterson et al., 2011), by identifying likely species occurrence sites and planning management and conservation actions (Funk and Richardson, 2002).

A suitable measure and useful strategy to fill gaps in the knowledge produced about plant species distribution is Ecological Niche Modeling (ENM). ENM consists of a set of modern techniques that use data from various knowledge areas, resulting from the integration of biological knowledge and various technologies (Giannini et al., 2011), to obtain models based on mathematical approximations of the ecological niche (Sillero et al., 2021), allowing discussions about the probabilistic distribution of one or more species in the environment.

The use and application of ecological models related to species distribution have increased. With the growth of scientific research in ecology, computational development, and the use of methods based on geographic information systems, species distribution modeling has gained prominence, mainly due to the availability of algorithms for data analysis, also aiding in understanding species' ecological requirements. This results in fundamental implications for biodiversity studies and determining priority conservation areas (Ferreira, 2009; Anderson, 2013).

The construction of ENM requires the use of environmental variables in conjunction with georeferenced information (Anderson et al., 2003), as well as the use of algorithms that estimate the relationship between this data and map habitat suitability to represent required conditions (Franklin and Miller, 2010). It is a very useful tool for addressing applied ecology, biogeography, and conservation questions due to its ecological and evolutionary foundations (Guisan and Thuiller, 2005). Thus, it provides well-founded responses to current challenges of environmental threats that many species face (Giannini, 2012), and is important in biological analyses, particularly in supporting conservation and management interventions, as it informs about environmental requirements and species distribution, demonstrated in mapping, which are crucial aspects in biological analyses and support for conservation and management interventions. Additionally, knowing plant species and their extinction threat classification is essential for informing conservation policies.

In Brazil, one form of flora protection is the establishment of Conservation Units (UC), aimed at contributing to species conservation and protecting biodiversity (Brasil, 2000). The identification of priority conservation areas in Brazil aims to recognize those locations or regions with unique natural attributes, considered critical for maintaining regional biodiversity (Brasil, 2004). From the development of a technical management plan document, for example, it is possible to establish zoning and guide the actions for the use of UC natural resources (Brasil, 2000). However, selecting priority conservation areas depends on the knowledge of the biodiversity to be conserved.

Considering this information, this unprecedented study was developed to present data on the updated distribution of the species in Brazilian territory. The promising results can be used to guide conservation actions and maintain priority areas in Brazil, especially in the state of Bahia, which has the highest number of species occurrence records.

2. OBJECTIVES

2.1 General

To determine the geographical distribution of *Moquiniastrum oligocephalum* (Gardner) G. Sancho in Brazil, based on occurrence records and the application of the Ecological Niche Modeling (ENM) technique.

2.2 Specific

- ✓ To analyze the geographical distribution of the species and the bioclimatic variables that determine its occurrence in Brazil;
- ✓ Draw up a geographical distribution map of the species in Brazil;
- ✓ Generate Environmental Suitability models based on Ecological Niche Modeling to analyze the geographical distribution of the species in Brazil;
- ✓ Investigate and locate possible priority areas for conservation of the species in Brazil.

3. THEORETICAL BACKGROUND

3.1. The Asteraceae Family in Brazil and Worldwide

Asteraceae Bercht. & J. Presl is one of the most diverse families of Angiosperms (BFG, 2018). It constitutes a monophyletic group, composed of approximately 25,000-30,000 species, grouped into about 1,700 genera (Funk et al., 2009). In Brazil, the family is grouped into 327 genera and about 2,208 species (Flora e Funga do Brasil, 2023). Bremer (1994) divided the family into three subfamilies and 17 tribes. Following the publication of Funk et al. (2009), a classification of Asteraceae was recognized, consisting of 13 subfamilies and 44 tribes, representing about 10% of the world's vascular plants (Funk et al., 2009; Panero et al., 2014).

Asteraceae is characterized by its capitulum inflorescence, with flowers arranged on a receptacle surrounded by bracts. The capitula are composed of sessile flowers, solitary at the apex of the floral peduncle (scape), or usually by few to many capitula in corymbiform, spicate, paniculate, racemose, umbelliform cymose capitulescences (Flora e Funga do Brasil, 2023). The anthers are syngenesious, with secondary pollen exposure, and the ovary is bicarpellate and inferior, with a single ovule of basal placentation that develops into an achene, generally with a pappus (Funk et al., 2005, 2009; Roque and Bautista, 2008).

It has a wide geographical distribution, being present on all continents except Antarctica (Panero, 2008; Roque and Bautista, 2008). It is most abundant in temperate and semi-arid regions of the tropics and subtropics, recorded in open vegetation areas such as fields, high-altitude regions, and low-altitude tropical rainforests (Funk et al., 2009b; GBIF, 2023). However, despite the considerable level of information about Brazilian biodiversity, gaps remain that need to be filled, including those to support conservation actions and improve the understanding of phylogenetic relationships in Asteraceae (Funk et al., 2009).

The efficiency in dispersion confers extreme importance to Asteraceae in understanding the recovery of degraded areas, where they act as pioneers in colonizing degraded environments and occur in clearings and forest edges (Heiden et al., 2007). Distributed in all biomes, the family occurs in Brazil in vegetation formations of Cerrado, Campos, Atlantic Forest, Restinga, Caatinga, swamp areas, riparian forests, and high-altitude forests (Moura and Roque, 2016). Second only to the Cerrado, among the country's phytogeographic domains, the Atlantic Forest is the second richest in Asteraceae, with 187 genera and 961 species (Roque et al., 2020).

Asteraceae exhibits herbaceous, subshrub, shrub, or tree habits, generally terrestrial, rarely epiphytic or aquatic, sometimes succulent. Asteraceae species are extensively studied from botanical, chemical, and pharmacological perspectives (Bremer, 1994; Funk et al., 2009). Research reports the presence of some cytotoxic and anti-inflammatory activities (Funk *et al*., 2009).

The family stands out worldwide for its economic, ornamental, and medicinal importance. Due to the high chemical diversity present and the great bioactive potential, one of the main uses of Asteraceae species is their employment as herbal medicine in popular medicine (Funk *et al*., 2009). Additionally, many plants are edible, and the consumption and cultivation of leaves, stems, seeds for vegetable oil extraction are known, such as Helianthus annuus L. (sunflower); Cynara scolymus L. (artichoke); and Lactuca sativa L. (lettuce). Other species are considered medicinal plants, like the sweetener extracted from Stevia rebaudiana; ointments (*Calendula officinalis* L., *Arnica montana* L.); teas, such as chamomile (*Matricaria recutita* L.) (Panero and Funk, 2008; Moura and Roque, 2014). Phytochemical studies are known among *Moquiniastrum* species, such as *Moquiniastrum argentinum* (Cabrera) G. Sancho, *Moquiniastrum barrosoae* (Cabrera) G. Sancho, *Moquiniastrum blanchetianum* (DC.) G. Sancho, *Moquiniastrum haumanianum* (Cabrera) G. Sancho, *Moquiniastrum paniculatum* (Menos.) G. Sancho, *Moquiniastrum polymorphum* (Menos.) G. Sancho, *Moquiniastrum polymorphum* subsp. *floccosum* (Menos.) G. Sancho, *Moquiniastrum pulchrum* (Cabrera) G. Sancho, from which dozens of special metabolites have been described (Tamayose, 2019).

The production of substances from compound extraction has been reported for the Asteraceae family (Calabria et al., 2007), such as special metabolite classes like flavonoids and terpenoids, with the most common subclasses in Asteraceae being flavones and flavonols, which have been related to the evolutionary success of its individuals (Funk et al., 2009; Tamayose, 2019). Flavonoids generally have great ecological importance for plants, acting as attractants for pollinators, seed and fruit dispersers, signaling in plant-plant and plant-microorganism interactions, and providing UV radiation protection (Funk et al., 2009).

According to Tamayose (2019), experimental procedures with the species *M. oligocephalum* allowed the identification of 20 substances, extracted from samples collected in the Caatinga phytogeographical domain region, in the municipality of Morro do Chapéu, Bahia. This was the first report of the study of epicuticular waxes in Moquiniastrum species, especially in *M. oligocephalum*.

In recent years, several classifications have been proposed for the species of the family. Asteraceae constitutes an easily recognizable and clearly monophyletic group (Judd et al., 2009). Recent molecular studies have proposed arrangements for its classification (Moura and Roque, 2014). Thus, the advent of molecular biology brought new changes to the circumscription of

Asteraceae genera, tribes, and subfamilies, now based on genetic data (Panero and Funk, 2008; Funk et al., 2009).

Despite significant advances in understanding the current phylogenetic relationships in Asteraceae, one of the major problems faced in Brazil is the lack of knowledge about the geographical distribution of a large part of the species and lack of knowledge (inventories) about the richness of genera and species. Additionally, there is high morphological variation and complexity (Roque et al., 2016, 2017). Information gaps hinder the application of conservation actions, and the conservation of the species of interest is limited to areas where it has already been recorded (Moscoso, 2012).

The subfamily Gochnatioideae currently has 103 species and is considered one of the most basal in Asteraceae and a sister group to approximately 96% of the family's species (Panero and Funk, 2008; Sancho and Freire, 2009; Funk et al., 2014). Many morphological studies have not resolved the situation among the sections of the genus Gochnatia, aimed at establishing generic and infrageneric relationships (Funk et al., 2014). Freire, Katinas, and Sancho (2002) published a morphological analysis of Gochnatia species defined by Cabrera (1971), called the "Gochnatia complex."

The genera of Gochnatioideae have characteristics such as an apiculate connective appendage, rounded stylar branches, and dorsally glabrous, with the tribe's apomorphy based on these two characters (Funk et al., 2014). According to the same author, based on phylogenetic studies using molecular and morphological evidence, Gochnatia was reduced to approximately 40 species.

In the 1970s, a revision of the Gochnatinae tribe species led to the redefinition of the Gochnatia genus, grouping 70 species into six sections, one of which was named *Moquiniastrum*. Recent molecular phylogeny studies showed that the species of the *Moquiniastrum* section were very close to each other and different from the other species of the genus, determining its elevation to the genus level (Cabrera and Klein, 1973; Sancho, Funk, and Roque, 2013).

Initially, the tribe consisted of four genera: Cnicothamnus Griseb. (1874), Cyclolepis Gilles ex D. Don (1832), Gochnatia Kunth (1818), and Richterago Kuntze (1891). Currently, the genera included in Gochnatieae vary in their morphology and habitat: Gochnatia, Pentaphorus, Anastraphia, *Moquiniastrum*, Richterago, *Cnicothamnus* (sister group to the *Moquiniastrum* + *Richterago* clade), and Cyclolepis. In the phylogeny of the Gochnatioideae subfamily, the Moquiniastrum and Richterago genera are considered sister groups with statistical support (Funk et al., 2014).

A phylogenetic study of Gochnatieae by Funk et al. (2014) included more than 60% of the tribe's species (represented by 112 samples) and sampled six molecular markers for comparative phylogenetics. This effort confirmed the monophyly and phylogenetic position of Gochnatieae, which currently has seven genera, including the *Moquiniastrum* (Cabrera) G. Sancho genus, and about 80 species, with geographical distribution restricted to the American continent (Funk et al., 2014; Roque et al., 2016; Flora e Funga do Brasil 2024).

In the current classification, the genus is monophyletic and presents differences from Gochnatia, such as gynodioecy; indumentum with 2-5-branched trichomes and usually paniculate capitulescence, actinomorphic corolla deeply lobed, 2–3-seriate pappus, and usually paniculate synflorescence (Sancho, Funk, and Roque, 2013; Freitas, 2014). The sexual complexity of *Moquiniastrum* is unique, with its species essentially classified into five groups according to the sexuality of the flowers: gynomonoecious, gynodioecious, homogamous, hermaphroditic, polygamous (Sancho, 2000). According to Gisele Sancho, the genus is the only one that has functionally female flowers due to the presence of rudimentary anthers (staminodes), considered a model for studying the evolution of the plant sexual system.

The ancestral distribution of *Moquiniastrum* (Cabrera) G. Sancho corresponds to a large area covering eastern South America and the current central Andes, about 32 million years ago (Gostel et al., 2022). The genus is not endemic to Brazil, also occurring in Argentina, Bolivia, Peru, Venezuela, and Uruguay. In its worldwide distribution, Moquiniastrum consists of 22 species, with 20 species occurring in eastern Brazil (Flora do Brasil, 2024), including the new species Moquiniastrum glabrum Roque, Neves & A. Teles (Roque et al., 2019).

In Brazil, the genera *Moquiniastrum* and *Richterago* occur (Funk et al., 2014). The publication by Sancho, Funk, and Roque (2013) provided a nomenclatural rearrangement by segregating *Moquiniastrum* and elevating it to the category of a genus (Freitas, 2014). It is distributed in the phytogeographic domains of the Cerrado (Minas Gerais, Bahia, Goiás, Paraná, São Paulo), Pampa (Rio Grande do Sul), and also in regions of the Atlantic Forest (from the Northeast to the South of the country) (Sancho et al., 2013, 2014; Flora do Brasil, 2023).

Of the 20 species of the genus *Moquiniastrum* that occur in Brazil, nine are found in the state of Bahia: *Moquiniastrum barrosoae* (Cabrera) G. Sancho, *Moquiniastrum blanchetianum* (DC.) G. Sancho, *Moquiniastrum densicephalum* (Cabrera) G. Sancho, *Moquiniastrum floribundum* (Cabrera) G. Sancho, *Moquiniastrum paniculatum* (Less) G. Sancho, *Moquiniastrum polymorphum* (Less.) G. Sancho, *Moquiniastrum discolor* (Baker) G. Sancho, *Moquiniastrum glabrum* Roque, Neves & A.Teles, including *Moquiniastrum oligocephalum* (Gardner) G. Sancho (Sancho et al., 2013, 2014; Roque, 2019; *Specieslink*, 2024).

Moquiniastrum oligocephalum (Gardner) G. Sancho, popularly known in northeastern Brazil as "candeia," is morphologically well-defined within the homogeneous group to which it belongs. The species is distinguished by its typically arboreal habit, tomentose branches, discolorous leaves with branched trichomes, paniculate capitulescence, tubular flowers, and for being gynodioecious (Bremer, 1994; Sancho, 2013; Freitas, 2014; Roque et al., 2019; Flora do Brasil, 2023). According to Sancho, Funk, and Roque (2013), the species has important dispersion centers in Brazil, and the genus also occurs in the following countries according to Flora e Funga do Brasil (2023): Argentina, Uruguay, Bolivia, Paraguay, Peru, Venezuela.

M. oligocephalum has been increasingly sought after for its timber potential, and due to recurring plant extraction, its population tends to be further reduced, especially in Atlantic Forest areas in northeastern Brazil, where local populations are currently threatened with extinction. In northeastern Brazil, this phytodomain presents various physiognomies and according to Tabarelli et al. (2006), more than 46% of the mapped Atlantic Forest remnants are located in the state of Bahia. However, more work needs to be done to increase sampling efforts to enable the recovery of areas and greater promotion of floristic conservation. Woody species, such as *M. oligocephalum*, are especially important in semi-arid regions for protection against desertification and resilience to climate change (FAO, 2016).

3.2. Patterns of Species Distribution

The distribution of organisms across the different environments of the Earth reflects part of the history of geological, ecological, and evolutionary events that have occurred together. Generally, it is known that the geographic distribution of species results from complex ecological relationships involving: soil type, microclimate, macroclimate, altitude, plate tectonics, riverbed narrowing/widening, glaciations, vegetation physiognomies, climate, humidity, ocean currents, salinity, precipitation and day length, food availability, as well as the dispersal capacity of organisms and the influence of geographic and climatic factors such as latitude, altitude, ocean currents, and air masses (Brown and Lemolino, 2006; Soberón, 2010). Additionally, dispersal capacity, species interactions (biotic factors), and anthropogenic impacts are influential (Morellato et al., 2000; Pearson, 2006; Soberón, 2010; Wisz et al., 2013; Wang et al., 2017).

Studies involving dispersal syndromes, for example, have been considered for understanding biogeographic patterns because they are directly related to the distribution of species (Diniz-Filho et al., 2009). Ecologists and biogeographers have been striving over the years to understand the processes involved in the generation and maintenance of the current pattern of biodiversity distribution (Hutchinson, 1959; Diniz-Filho et al., 2009). Some authors emphasize that the distribution of most plant species is mainly controlled by climatic factors such as temperature and precipitation (Bañuelos et al., 2004; Kendal et al., 2012). Regarding neotropical forests, according to Gentry (1983), these environments show patterns in taxonomic composition, diversity, and species dispersal ecology.

According to Neves et al. (2015) and Queiroz et al. (2017), variations in precipitation and temperature can lead to significant changes in species composition and ecological strategies (Santiago et al., 2016). Antonelli (2017) highlights that climate influences species distribution patterns due to its variations, resulting in different scenarios in different periods within the same environment. Thus, biotic and abiotic relationships determinately influence species' geographic distribution (Morellato et al., 2000; Soberón, 2010), and naturally, there are temporal variations in speciation, extinction, and migration rates (Condamine et al., 2018).

Brazil has a great biological diversity (Mittermeier et al., 1998) and a wide variety of environmental factors that operate at different intensities and scales, adjusting the occurrence limits of organisms. The northeastern region of Brazil contains various morphoclimatic domains, rich in ecosystems (Ab'Sáber, 1971, 1977). The coastal forest establishes itself in a narrow strip along the Atlantic coast. This forest encompasses two main vegetation types: Dense Ombrophilous Forest (closer to the coast) and Semideciduous Forest, which forms a narrow belt of drier forest inland (Veloso et al., 1991).

The degree of endemism, according to Gentry (1986), is an important criterion used for selecting priority areas for conservation. Thus, diagnosing probable endemisms and information on the geographic distribution of plant species contribute to promoting identification, diagnosis, and possible recovery programs for areas considered conservation priorities. Diniz-Filho et al. (2009) points out that understanding diversity patterns on large scales and the processes involved in their origin and maintenance are important for establishing more efficient biodiversity conservation programs. Moscoso (2012) emphasizes that knowledge about the distribution of plant species is essential for biodiversity management and conservation planning. Funk and Richardson (2002) assert that understanding biodiversity patterns can be key to conserving the remaining existing species, especially in tropical areas.

There are still many species to be described and cataloged, and knowledge about species identity and distribution is still developing, with gaps in biodiversity study (Cardoso et al., 2011; Hortal et al., 2014). One strategy that can help fill these gaps is to estimate the geographic distribution of species and characterize favorable environmental conditions for species occurrence, possibly locating and identifying how specific environments suitable for the survival of studied organisms are distributed in space (Pearson, 2007).

3.3. Ecological Niche Modeling (ENM)

Ecological niche modeling is defined as the inference of the geographic distribution of one or more organisms through methods or algorithms (Guisan and Zimmermann, 2000; Peterson and Soberón, 2012). According to Siqueira's research (2005), based on biological data (i.e., species occurrence points) and environmental data (i.e., thematic maps), algorithms can be applied in the processes of geographic distribution modeling with the aim of modeling the fundamental niche and estimating probable areas of species occurrence. To do this, they combine species occurrence data with the environmental variables of these locations, seeking to identify areas with suitable environmental conditions for population survival (Elith and Leathwick, 2009; Pearson, 2007; Thuiller, 2007).

Grinnell (1917) described the environment occupied by the bird Toxostoma redivivum, characterizing the niche as the environmental conditions that allowed its survival. In the case of the "Grinnellian" niche concept, interactions between living beings or the influence of environmental resources are not considered, as it focuses on the range of variables and the set of large-scale abiotic components that allow species to exist (Soberón, 2007). Based on Grinnell's niche concept (1917), the areas indicated in the modeling are habitats and satisfactory locations for species occurrence (Phillips, 2008).

Hutchinson (1957) defined the niche as a multidimensional space, within which there are several axes representing different environmental variables, both physical and biological, that allow the survival of a given species and limit its abundance and distribution, such as limiting factors like light, temperature, and food resources. Hutchinson's proposed concept considers the fundamental ecological niche, meaning the one that the species can occupy and encompasses all the conditions and resources that allow a particular species to exist and reproduce in the absence of other species.

Authors such as Soberón and Peterson (2005) mention that niche models provide an approximation to the species' fundamental niche, while others argue that modeling is the spatial representation of the realized niche (Guisan and Zimmermann, 2000; Pearson and Dawson, 2003). Soberón and Peterson (2005) added the dispersal capacity to the interpretation of models and created the Biotic, Abiotic, and Movements (BAM) diagram.

The projection of model predictions onto the geographic space results in environmental suitability maps (Sillero, 2011), which indicate on a continuous numerical scale the similarity of the mapped environments with those where the species under study is present within the domain of the bioclimatic predictor variables used in the modeling. Thus, ecological niche models consist of a simplified approximation of complex processes and assume that the environmental variables of the study area represent an environmental approximation of a particular species' niche (Phillips et al., 2006).

According to Guisan and Thuiller (2005), the interest in computing to study the influence of environmental variables on species distributions was mainly concentrated in the 1970s, 1980s, and 1990s. It offers rapid and well-founded responses to the threats species face (Sillero, 2011; Giannini, 2012), having been used in species distribution analyses, providing information on ecosystems and biomes (Lima-Barreto, 2015; Sobral-Souza, 2018), linked to biogeographic studies (Siqueira and Durigan, 2007); species conservation (Engler, Guisan, and Rechsteiner, 2004), and aiding in the determination of priority areas for conservation (Chen, 2009).

Species occurrence data have been made available by the scientific community in recent years (Trainor et al., 2014). These actions resulted from international initiatives that primarily aimed at standardizing, sharing, and providing primary data from biological collections, museums, and herbaria (Graham et al., 2004), among them the Global Biodiversity Information Facility (GBIF) database on taxonomic information, whose primary goal is to make biodiversity data available. In Brazil, the *speciesLink* network was created in 2002 with the general objective of making data on Brazilian biodiversity available.

Initially, in addition to obtaining species occurrence data and delineating the study area, considering environmental parameters and species biology for statistical analyses, it is necessary to select bioclimatic variables and one or more algorithms to trace potential correlations between the environment and distribution. Phillips (2008) discusses that statistically, the modeling result indicates whether a location is satisfactory for species occurrence and not exactly whether it is being occupied. Thus, the probability of species occurrence can be estimated.

Methodologies using computational algorithms are generally applied to represent primary data, species occurrence of interest, in distribution maps, thus indicating the probable presence or absence (Araújo and Guisan, 2006). These seek to establish non-random relationships between occurrence data and relevant environmental variables for the studied species, such as temperature, precipitation, and topography.

The statistical validation of models uses various techniques to assess the performance of algorithms and the predictive capacity of trained models. Among the methodologies presented in the literature, the Area Under the Curve (AUC) and True Skill Statistics (TSS) metrics (Thuiller et al., 2009) are the most used in the statistical validation of ENMs and ENMs. The closer to 1.0 the AUC value, the better the model's performance (Phillips et al., 2006; Merow et al., 2013).

Regarding modeling procedures, important elements to ensure the quality of the final modeling include the proper definition of environmental layer resolution; accuracy of occurrence points; terrain and species characteristics (Elith and Leathwick, 2009); and the size of the geographic area to be analyzed (Chapman et al., 2005). According to Hernandez (2006), the influence of sample size demonstrates the need to better define a data set based on species biology knowledge and the algorithm's performance used to model it.

MaxEnt is an algorithm capable of estimating the probability of species occurrence, using an optimization procedure based on the principle of maximum entropy, thus relating the presence of species with environmental characteristics (Phillips, 2006) based on Shannon's entropy concept, following what was proposed by Phillips, Anderson, Schapire (2006), Steven et al. (2019), and Dai et al. (2022). This algorithm has a simple user interface and typically performs well, requiring only presence data (Wisz et al. 2008). It is one of the most popular tools for species distribution modeling (Merow et al., 2013) and has proven more effective than other programs in processing small data sets (Elith et al., 2006).

Environmental analysis techniques, using MaxEnt, can indicate environmental conditions similar to those where the species was found, represented on the environmental suitability map scale. Thus, the distribution of occurrences in the geographic space can be estimated from the environmental variables related to both the presence data and the landscape (Lima-Ribeiro and Diniz-Filho, 2012). The model generated for a given species is a continuous surface of values ranging from zero to 100, where high values indicate a greater probability of finding the species under study in the region (Guisan and Zimmermann, 2000). The algorithm execution considers that the species' distribution probability is uniform within the study area (background) (Elith et al., 2006).

According to Carvalho et al. (2019), the performance of each algorithm is related to both the type of species distribution modeled and previous studies by Araújo (2006); Elith et al. (2006) and Pearson et al. (2006). Therefore, the choice of algorithm should be based on the study question and the availability of occurrence data, with no consensus on the best algorithm to use, as the choice should be considered on a case-by-case basis (Ginannini et al., 2012).

There are several types of modeling algorithms, whose classification criteria lie in how they process the data. Due to the complexity of the process concerning reliable predictions, different algorithm and method approaches have been applied, such as bioclimatic envelope algorithms like BIOCLIM (Busby, 1991); statistical fitting ones, like Generalized Linear Model – GLM (generalized linear models) (Wiley & Sons, 2006) and Generalized Additive Model – GAM (generalized additive models); machine learning ones (artificial neural networks) – ANN; support vector machine – SVM, decision trees – CART, random forest – RF and maximum entropy – MAXENT), as observed in the works of (Phillips et al., 2006; Paglia et al., 2012; Merow et al., 2014; Araújo, 2016; Cerdeira et al. 2018).

Understanding species distribution patterns is fundamental for conserving biological diversity (Ferreira, 2009). Thus, species distribution work using Ecological Niche Modeling is relevant for biological analyses, contributing to conservation and management actions, aiding decision-making aimed at biodiversity maintenance and rehabilitation in various contexts.

4. METHODOLOGY

4.1. Study Area

The Brazilian territory was the considered study area, with emphasis on the Northeast region, especially the state of Bahia, for which a modeling projection was carried out after analyzing the distribution data of the species *Moquiniastrum oligocephalum*. For the production of the species' geographic distribution maps, two locations were considered: the entire Brazilian territory and the state of Bahia, as this state has the highest number of occurrence records for the species compared to others. Thus, the geographic coordinates of the species' occurrence points were imported into the QGIS software (QGIS, 2023) and overlaid onto the geographic map of Brazil (IBGE, 2019) for better visualization and analysis of the species' spatial distribution in the Brazilian territory.

Considered the largest country in South America and in biodiversity globally, with a variety of terrestrial biomes (Amazon, Caatinga, Cerrado, Atlantic Forest, Pampas, and Pantanal) (Flora and Funga of Brazil, 2023), Brazil has a predominantly tropical climate (UNDP, 2020), and factors such as surface area, relief, and both latitudinal and longitudinal amplitude result in significant climatic variations throughout the Brazilian territory (Larousse, 2013). Rock outcrops are found in various climatic domains, mainly occurring in the Northeast region, eastern part of the country, both in the semi-arid and the Atlantic Forest domain (Araújo et al., 2008).

In the Brazilian Northeast, it is possible to find some very peculiar geographic mesoregions, whose climates range from the super humid coastal zones to the dry climate of the hinterlands in the region known as the Northeastern Semi-Arid (Zanella, 2014). The Brazilian Northeast is bordered to the North and East by the Atlantic Ocean. Due to its large extension and location (48º 05' W - 35º 02' W and 1º S - 18º 05' S), it is influenced by various atmospheric systems, among which the intertropical convergence zone, eastern waves, cold fronts, and sea breezes stand out (Roucou et al., 1996). The Atlantic Forest phytogeographic domain covers about 15% of the Brazilian territory and is distributed along the entire coast, from the north of the state of Piauí to the south of the state of Rio Grande do Sul, along with isolated areas in Goiás, Mato Grosso, and Minas Gerais (SOS Mata Atlântica, 2018). The Atlantic Forest has been severely impacted by human intervention, usually associated with the massive exploitation of its natural resources (Stehmann et al., 2009). The proximity to the coast provides the Atlantic Forest with constant humidity from the ocean and an important rainfall regime for the maintenance of a significant portion of Brazil's water sources.

The Caatinga phytogeographic domain is the only one genuinely from the Brazilian Northeast and occupies an area equivalent to 11% of the national territory (IBGE, 2019), extending over sedimentary bases, mountains, and plateaus (IBGE, 1985). The vegetation is characterized by seasonality and low rainfall indices (Sampaio, 1995; Rodal and Melo 1999), forming a mosaic of landscapes with high floristic diversity (Sampaio et al., 2002). As for the Cerrado phytogeographic domain, it can be characterized as Brazilian savanna vegetation and once represented about 23% of the national territory, second only to the Amazonian domain (Ratter et al., 1997). It occupies about 25% of the national territory (IBGE, 2019) and is present in all Brazilian regions. The Cerrado features landscapes composing a mosaic of phytophysiognomies, determined by different soil types, climatic conditions, and the fire regime characteristics of each location (Ratter et al., 2003; Durigan et al., 2003a; Ribeiro and Walter, 2008), with only small areas of the Cerrado being legally protected (Bianchi and Haig, 2013).

4.2. Data Collection of *Moquiniastrum oligocephalum*

Moquiniastrum oligocephalum (Gardner) G. Sancho is a species of the Asteraceae family, of economic importance, known locally in the Brazilian Northeast as "candeia" or "candeeiro". The species is distinguished by its typically arboreal habit, tomentose branches, discolorous leaves with branched trichomes, paniculiform capitulescence, tubular flowers, and its gynodioecious nature (Roque et al., 2019; Flora do Brasil, 2023). According to Sancho, Funk, and Roque (2013), the species has important dispersal centers in Brazil, and the genus also occurs in the following countries: Argentina, Uruguay, Bolivia, Paraguay, Peru, and Venezuela.

The construction of an Ecological Niche Model requires the use of environmental variables along with georeferenced information regarding the species' presence in the study area (Soberón, 2010). Thus, in the first stage, proper filtering was carried out using occurrence databases, considering only georeferenced data (i.e., complete occurrences with latitude and longitude records).

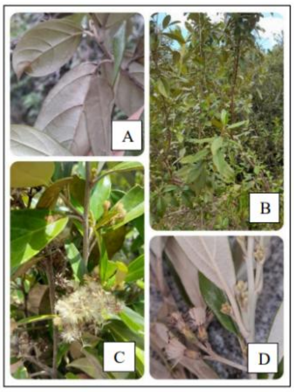
Regarding the global and regional occurrence records data of *Moquiniastrum oligocephalum*, these were obtained from online databases such as *SpeciesLink* (www.specieslink.net) and the Global Biodiversity Information Facility - GBIF (www.gbif.org) in the form of geographic coordinates. The presence records were individually reviewed, and subsequently, duplicates and spatially correlated occurrences were removed to prepare a spreadsheet. The species' occurrences were processed using the tidyverse package (Wickham; RStudio, 2023) to remove duplicates, incorrect and/or missing coordinates, as well as occurrences without location data. All procedures were performed in the R environment version 4.3.0 (R Core Team, 2023). Data related to the geographic distribution and Brazilian phytogeographic domains of *M. oligocephalum* were consulted on the Flora and Funga do Brasil website (http://floradobrasil.jbrj.gov.br/reflora/).

From the consultation of occurrence records of the study species in the databases, a total of 952 occurrence points were obtained. Initially, the occurrence matrix was filtered for the Brazilian territory, resulting in 482 selected points. Subsequently, data cleaning procedures were carried out to construct the definitive occurrence matrix for modeling, which consisted of 173 unique presence points for *M. oligocephalum*, structured in a comma-separated values (CSV) file.

The geographical thinning to remove sampling bias was performed using the spThin package (Aiello-Lammens et al., 2015), considering a radius of 10 km around each occurrence, with this process replicated 100 times by the best sample set selection algorithm.

The voucher material of *M. oligocephalum* was properly collected in the Atlantic Forest environment, within the vegetation complex of UNEB/EBDA, Campus II of the State University of Bahia, in the municipality of Alagoinhas, Bahia, Brazil (Figure 01). The material was herbarized according to standard botanical techniques (Mori et al., 1989) and deposited in the Herbarium of the State University of Bahia (HUNEB). The Atlantic Forest biome in this region is characterized by fragments and remnants, threatened by illegal logging and the advance of silviculture (Alves et al., 2023).

Figura 1 Testimonial material of *Moquiniastrum oligocephalum, in situ* at the EBDA/UNEB Complex, Professor's Trail, Alagoinhas, Bahia (March, 2023). Caption: A - Detail of the whitish, discolored leaves; B - Shrubby habit of *Moquiniastrum oligocephalum, in situ*. C and D - Capitulescence



Source: Authoral, 2023

4.3. Bioclimatic Environmental Variables

To conduct modeling procedures, the environmental variables were clipped to consider the study area, following the methodology of Austin (2007), which refers to the size of the sampling unit where occurrence data are recorded. Thus, the bioclimatic environmental variables were clipped to the specific grid corresponding to the territory of Brazil.

A set of 19 bioclimatic environmental variables were used, extracted in TIFF format from the Global Climate Data - Worldclim database (http://www.worldclim.org/), version 2.1 (Fick and Hijmans, 2017). Following recommendations by Chapman et al. (2005) and Phillips, Anderson, and Schapire (2006), bioclimatic variables (Table 01) composed of temperature, precipitation, isothermality, temperature seasonality, precipitation of the driest month, precipitation seasonality (coefficient of variation), and derivatives thereof were selected. These variables are relevant for studies on the spatial distribution of living organisms (Hijmans et al., 2005) and widely used in Species Distribution Modeling studies (Giannini et al., 2012; Peterson and Soberón, 2012), as well as for Ecological Niche Modeling and Environmental Suitability studies. For climatic data (i.e., temperature and precipitation), the pixel value represents the variable's value in that area.

Table 1 - Identifiers and description of bioclimatic variables

Codes	Variables
BIO_1	Average annual temperature
BIO_2	Average diurnal variation
BIO_3	(monthly average - max. temp. and min. temp.)
BIO_4	Temperature seasonality (standard deviation*100)
BIO_5	Maximum temperature in the hottest month
BIO_6	Minimum temperature in the coldest month
BIO_7	Annual temperature variation (BIO5-BIO6)
BIO_8	Average temperature in the wettest quarter
BIO_9	Average temperature in the driest room
BIO_{10}	Average temperature in the hottest room
BIO_{11}	Average temperature in the coldest quarter

BIO_{12}	Annual rainfall
BIO_{13}	Precipitation in the wettest month
BIO_{14}	Precipitation in the driest month
BIO_{15}	Rainfall seasonality (coefficient of variation)
BIO_{16}	Precipitation in the wettest quarter
BIO_{17}	Precipitation in the driest quarter
BIO_{18}	Precipitation in the hottest quarter
BIO_{19}	Precipitation in the coldest quarter

Source: *WorldClim*, 2020.

Despite the set of bioclimatic variables containing 19 variables (Table 1), a process of correlation analysis was conducted prior to modeling procedures to reduce collinearity effects in the final model. For the selection of variables to be used, the Variance Inflation Factor (VIF) technique was applied with a cutoff factor of 10; variables with VIF values less than or equal to this threshold were considered to have lower correlation within the set, while those with VIF values greater than 10 were discarded. Thus, through VIF calculation, variables with lower collinearity in the set were selected (Warren et al., 2014; Naimi and Araújo, 2016; Lima and Marchioro, 2021).

Based on the analysis of VIF values, variables with the lowest collinearity level were selected for the modeling process (Naimi and Araújo, 2016): BIO3 (Isothermality); BIO4 (Temperature seasonality); BIO7 (Annual temperature range); BIO8 (Mean temperature of wettest quarter); BIO9 (Mean temperature of driest quarter); BIO15 (Precipitation seasonality); BIO17 (Precipitation of driest quarter); BIO18 (Precipitation of warmest quarter); and BIO19 (Precipitation of coldest quarter), with the manual inclusion of BIO1 (Annual mean temperature) and BIO12 (Annual precipitation) due to their biological relevance.

The analysis and selection of the final variables for environmental suitability modeling were conducted using the usdm package (Naimi et al., 2014), also implemented in R 4.3.0 (R Core Team, 2023), with a spatial resolution of 2.5 arc-minutes (approximately 5 km² at the equator).

4.4. Ecological Niche Modeling

To structure the routine of Ecological Niche Modeling and quantify Environmental Suitability, the maximum entropy algorithm (MaxEnt) was utilized, an efficient method for making inferences based solely on spatial presence data of the species in a given area (Phillips et al., 2006).

MaxEnt was chosen for training the ecological niche model of *Moquiniastrum oligocephalum* in Brazil due to its ability to construct models without the need for absence points (Phillips et al., 2017), being frequently applied in studies of ecology, biogeography, conservation, among others. MaxEnt finds the distribution of maximum entropy probability (i.e., closest to uniform) subject to a set of constraints, which should correspond to the averages of the environmental variables observed in the occurrence data set that composes the sample (Phillips et al., 2006; Pearson et al., 2007; Elith et al., 2011).

The MaxEnt algorithm was used in its standard configuration as per the literature: random selection of 10,000 background points across the study area, with cross-validation replication method structured in 30 replicas. For training and testing the models, occurrence data were divided into two sets containing 70% (training) and 30% (testing) of the occurrence data, respectively.

Model validation is an area of research where new techniques have been developed and information has been disseminated through recent publications, such as statistical validation commonly recommended in the literature using AUC (Area Under the Curve) and TSS (True Skill Statistics) metrics (Thuiller et al., 2009), considering AUC values ≥ 0.7 and TSS ≥ 0.4 (Allouche, 2006; Buisson et al., 2010). Based on this, final ensembles can be produced by selecting models based on TSS, maximizing specificity and sensitivity of the models.

Due to internal differences between each generated model, a single map of consensus environmental suitability (ensemble) was created for the studied species, built from selecting the best models using a threshold (TSS ≥ 0.4), maximizing specificity and sensitivity of the adjusted models for the species (Marmion et al., 2009).

To analyze the influence of extreme points in the dataset, two maps of environmental suitability for Brazil were produced, one considering the inclusion of an extreme point (state of Roraima) and another disregarding this occurrence point. The model was adjusted for the Brazilian territory considering the species distribution, and subsequently projected for the state of Bahia (study area with the highest number of occurrence records). For ensemble creation, consensus maps were combined into a single final map using the raster package (Hijmans, 2022), with weighted averaging to structure the final projection. The scale of environmental suitability represents the percentage of environment suitability for the species, considering the gradient represented by the model, measured from 0 to 100%.

Following modeling, to assess and statistically validate the model, the Receiver Operating Characteristics (ROC) curve technique was applied by plotting sensitivity on the y-axis and specificity on the x-axis for the cutoff limits. The ROC methodology is commonly used to evaluate the quality of models generated by MaxEnt (Phillips et al., 2006).

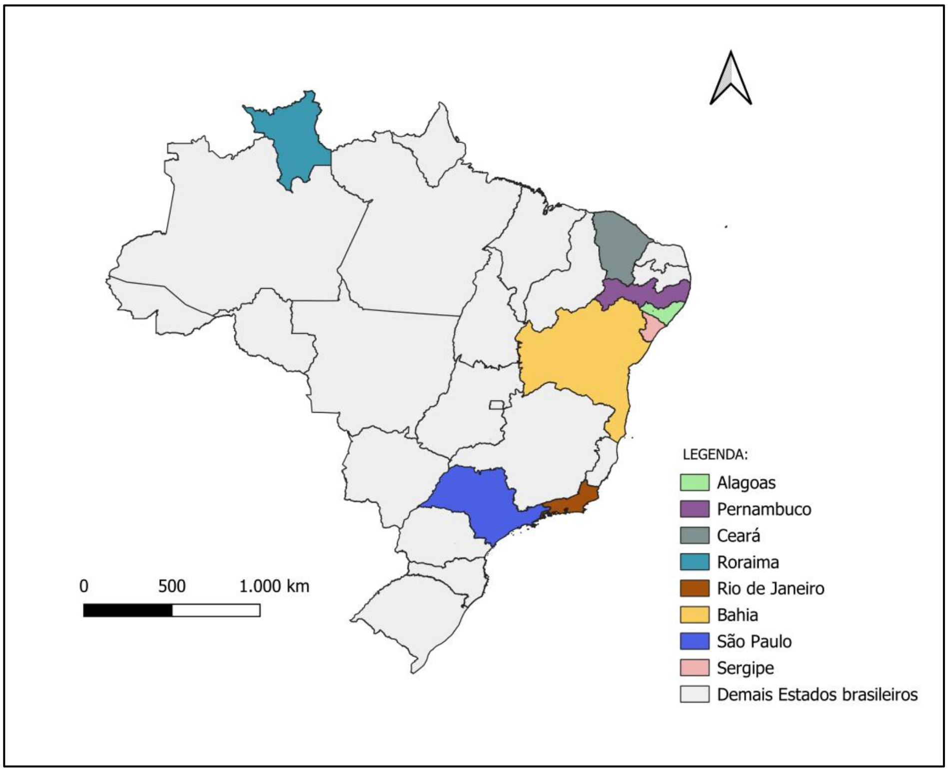
For model accuracy assessment, the Area Under the Receiver Operating Characteristic Curve (AUC) was calculated. This analysis evaluates the model's performance across all possible cutoff limits, generating a single value representing the area under the curve (AUC). It is typically determined by connecting the points with straight lines, and the area value is calculated using the trapezoid method (Phillips et al., 2006). It can be used for comparisons between different algorithms (Phillips, Anderson, and Schapire, 2006). Thus, regardless of the prior choice of a specific cutoff limit, the curve is constructed from various cutoff limits (each cutoff limit corresponds to a point on the curve).

The AUC value ranges from 0 to 1, where an AUC value of 1.0 indicates perfect discrimination. Values closer to 1 indicate higher model performance, while values around 0.5 indicate low performance (Elith et al., 2006). The closer the AUC value is to 1.0, the further the model's result is from random prediction (Phillips, Anderson, and Schariope, 2006), meaning an area equal to 1 represents the best model performance (Phillips et al., 2006; Phillips and Dudik, 2008). AUC is interpreted as the probability that the model will correctly classify a randomly chosen presence location versus any location in the landscape (Merow et al., 2013). Statistical validation was performed by calculating AUC and TSS values as described by Allouche (2006) and Buisson et al. (2010). The selection of the best models considered a TSS value ≥ 0.8, maximizing model sensitivity and specificity.

5. RESULTS AND DISCUSSION

5.1. Geographical distribution of *Moquiniastrum oligocephalum* (Gardner) G. Sancho in Brazil For Brazil, the presence of the species under study in the states of Bahia, Ceará, Pernambuco, Sergipe, Alagoas, Rio de Janeiro, São Paulo and Roraima was verified in the databases (Figure 2). The range of occurrence of the species is necessary in relation to the occurrence of *M. oligocephalum* in Brazil, since there was a record only for the states of Bahia, Ceará and Pernambuco, according to the Flora e Funga do Brasil website, with the addition of the occurrence of the species for the states of Sergipe and Alagoas in the Northeast region and the states of Rio de Janeiro, São Paulo for the Southeast region and for the North region, Roraima.

Figure 2: Brazilian states with records of *Moquiniastrum oligocephalum* (Gardner) G. Sancho (*speciesLink* and GBIF databases, 2023)



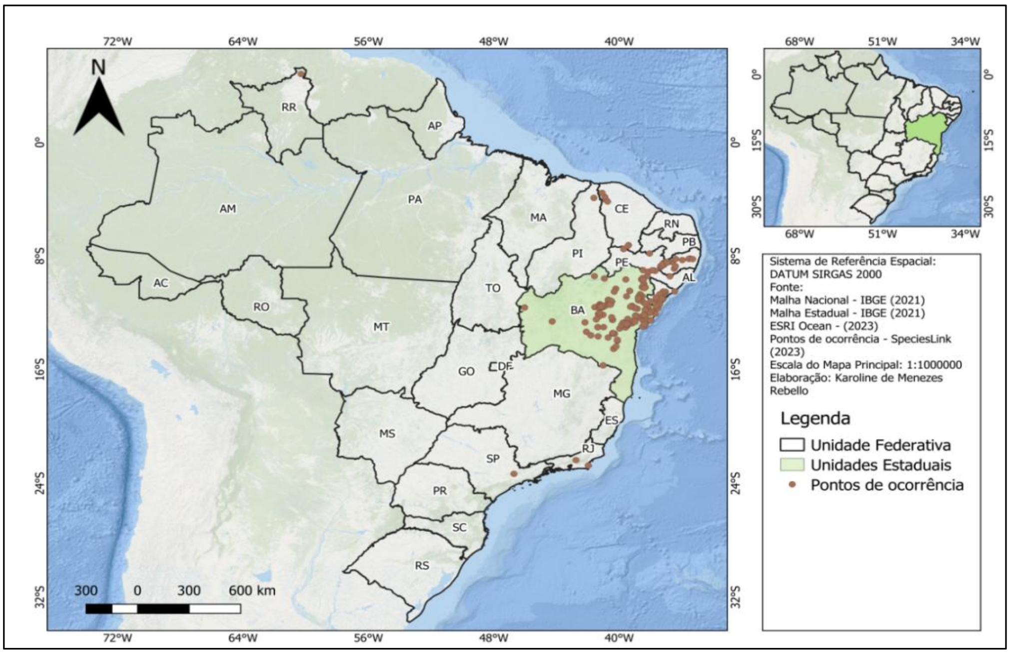
Source: IBGE Mesh, 2022. Survey data, 2024.

In north-eastern Brazil, the species predominantly occurs in drier environments with less frequent irregular rainfall. The species is usually found in arboreal habit, predominantly in environments in the phytogeographic domain of the Caatinga and Atlantic Rainforest in the northeast, as seen in the distribution map for the state of Bahia (Figure 4), where the vegetation forms a mosaic according to the type of soil and humidity.

According to Flora and Funga do Brasil (2023), *M. oligocephalum* is distributed exclusively within the phytogeographic domains of the Caatinga and Cerrado in Brazil. However, the species has been recorded in the GBIF and *speciesLink* databases occurring also in the Atlantic Forest, predominantly in the Northeast region of Brazil (Figure 2). Considering observed occurrence restrictions, it is identified that updates to the geographical distribution and phytogeographic domain in these databases are necessary to support conservation strategies for the species in Brazil.

From the information available on *speciesLink*, out of the 343 georeferenced occurrence records found, which were filtered for Brazil (Figure 3), 241 correspond to the state of Bahia, as presented in Figure 4. In Bahia, the species is more predominantly distributed compared to other states, especially in areas within the Caatinga phytogeographic domain and Caatinga/Atlantic Forest transition areas, influenced by seasonal bioclimatic factors of precipitation and temperature characteristic of the Caatinga region. The species was recorded in approximately 56 municipalities in Bahia (Figure 4) according to the *speciesLink* and GBIF platforms. In other Brazilian states, the records were: 39 for Sergipe; 38 for Pernambuco; 10 for Ceará; 8 for Alagoas; 3 for Rio de Janeiro; 1 for São Paulo; and 1 for Roraima. In the Brazilian territory, *speciesLink* identified 109 records for Atlantic Forest areas, 209 for Caatinga, and 5 for Cerrado. The Northeast region showed a higher number of occurrence records, mainly in Bahia, Pernambuco, and Sergipe.

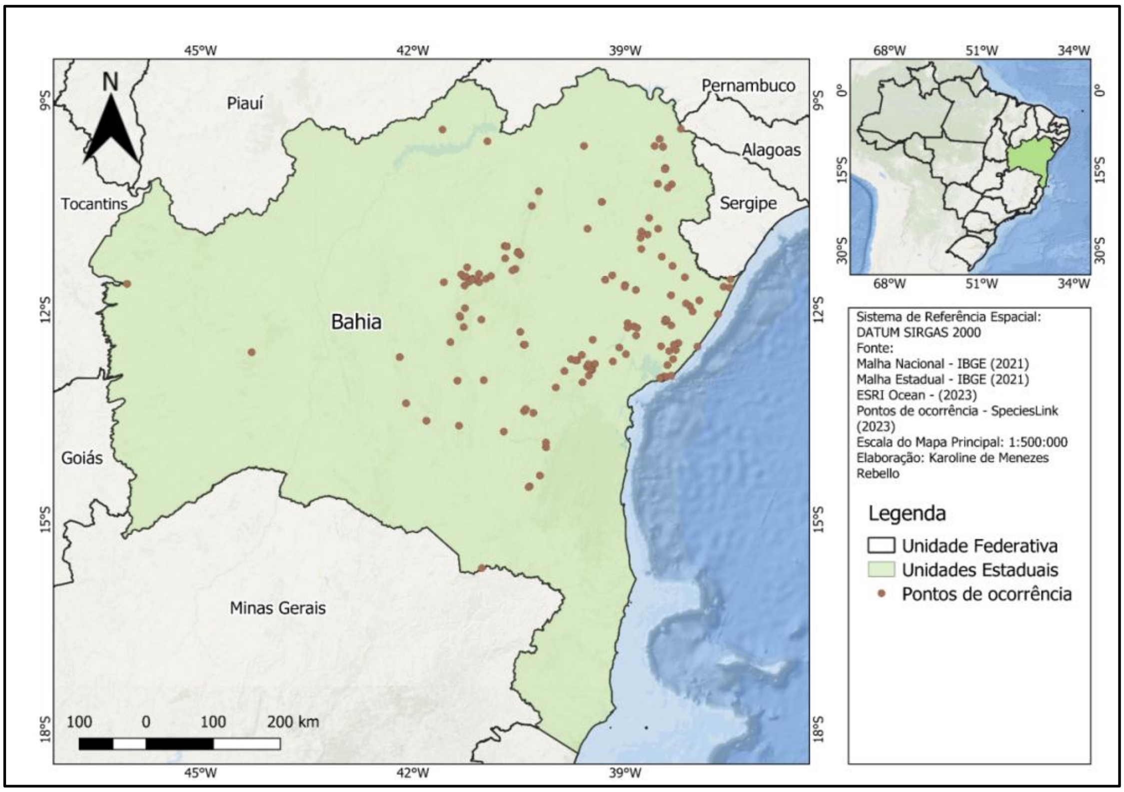
Figure 3 - Distribution map of *Moquiniastrum oligocephalum* Gardner G. Sancho for Brazil.



Source: Research data, 2024 (*SpeciesLink* and GBIF databases).

It occurs in northeastern Atlantic Rainforest environments, where there is a greater influence from the Caatinga, such as the Atlantic Rainforest on the state's northern coast (northern portion of the east coast). There is less suitability (Figure 5) for environments corresponding to the Brazilian Cerrado, where it occurs less frequently according to the databases analyzed.

Figure 4 - Distribution map of *Moquiniastrum oligocephalum* Gardner G. Sancho in the state of Bahia, Brazil.



Source: Research data, 2024 (*SpeciesLink* and GBIF databases).

According to some authors, the Asteraceae family is more prevalent in Cerrado formations and occurs less frequently in areas of Atlantic Forest, Caatinga, restinga, marshes and high altitude forests (Hind and Miranda 2008; BFG, 2015; Roque, 2016). However, this study updates this information about the species' domain of occurrence to areas predominantly in the Caatinga and Atlantic Forest phytodomains in the Northeast. The caatinga is the main vegetation formation in Bahia (SEI, 2009) and is distributed over almost the entire northeastern and central extension of the state (Queiroz et al. 2005).

M. oligocephalum was recorded in the database as occurring in the Espinhaço Chain, a region formed by a series of mountain ranges stretching for around a thousand kilometers in a north-south direction, with its northern limit at Serra da Jacobina, which cuts through the municipality of Jacobina in the state of Bahia. To the south, it reaches the Serra de Ouro Branco, in the state of Minas Gerais (Giulietti and Pitani, 1988). According to Roque et al. (2016), in the municipality of Mucugê in Bahia, *M. oligocephalum* has been collected in areas of Cerrado and campos gerais, such as the locality of Fazenda Caraíbas. Amorin and Bautista (2016) point to *M. oligocephalum* occurring in bloom, in the municipality of Jeremoabo, in the Raso da Catarina, an ecoregion characterized by a marked seasonal climate, hot and dry, of dense shrub-type Caatinga. It comprises portions of the states of Pernambuco and Bahia, and is delimited by the

Tucano-Jatobá sedimentary basin, in the central-eastern portion of the Caatinga domain (Velloso, Sampaio and Pareyn, 2002).

According to the *speciesLink* and *GBIF* databases, there are 40 occurrence records of the species in the state of Sergipe, distributed across more than 13 municipalities. These records show the species typically occurring with arboreal habit in environments that combine vegetation composition characteristic of Caatinga and forests influenced by both Caatinga and Mata Atlântica. The contact between the Mata Atlântica and the semi-arid Caatinga through the agreste establishes a zone of peculiar phytosociological transition, where species from both phytodominions coexist (Carvalho; Villar, 2005; Vicente et al., 2005, Silva et al., 2019).

Occurrences of *M. oligocephalum* are recorded in the Conservation Unit, Parque Nacional Serra de Itabaiana (PARNA), located in the central region of Sergipe (10°40' S, 37°25' W), about 40 km from the coast (Silva, Prata, and Mello, 2019). The PARNA is considered extremely important for the conservation of Mata Atlântica flora (Mendes et al., 2010; *speciesLink*, 2023). It encompasses the municipalities of Areia Branca, Itabaiana, Laranjeiras, Itaporanga D'ajuda, Malhador, and Campo do Brito (Dantas and Ribeiro, 2013).

In this ecotonal region, a considerable number of species common to the Caatinga areas stand out, although they are not endemic to this biome (Mendes, Gomes, and Alves, 2010). There are transitional zones of phytogeographical domains containing endemic species of Mata Atlântica and Caatinga (Vicente et al., 2005, Silva, Prata, and Mello, 2019). It is considered an ecological refuge due to specific substrate formation conditions (Dantas et al., 2010) and harbors a considerable number of species common to the Caatinga areas, despite not being endemic to this biome (Mendes et al., 2010). Local biodiversity is impacted by anthropogenic activities such as recreational trail use (Oliveira, 2008), logging, sand extraction, hunting, wildfires, and waste dumping (Sobral et al., 2007).

According to the *speciesLink* and *GBIF* databases, there are 37 occurrence records of the species in the state of Pernambuco, occurring predominantly in typical steppe vegetation of Caatinga in the state. From a total of 35 records consulted in the *speciesLink* database, these occur in shrub-arboreal Caatinga environments with clay-sandy soil. The remaining 2 records are from Pernambuco's Atlantic Forest. For example, *M. oligocephalum* occurs in the Environmental Protection Area Chapada do Araripe to the northwest of the state and more frequently in the central region, with records in the Catimbau National Park near the Kapinawá indigenous land, in the municipalities of Buípe and Tupanatinga. The Chapada do Araripe has areas where Caatinga and Cerrado zones mix, and there is distinct vegetation known as "carrasco" (Araújo et al., 1998; Giulietti et al., 2002). According to research by Athiê-Souza et al. (2019), although some species have been listed as occurring in other states, out of the 613 species listed for the Catimbau National Park, 34 are new records for the state of Pernambuco, including *Moquiniastrum oligocephalum*.

In Pernambuco, there are important state and federal conservation areas established to ensure the preservation of Brazil's biological diversity (Leão et al., 2011). Among the federal ones are the Catimbau Valley National Park and Chapada do Araripe (CPRH, 2014). There are two records of *M.oligocephalum* occurring at altitudes between 889 to 991 meters in Catimbau, Buíque municipality, an important priority conservation area in the Caatinga phytodomain. Geologically, this park is part of the Jatobá sedimentary basin and is characterized topographically by low mountainous elevations (800 to 1000 m altitude) and open valleys with steep slopes (Rodal et al., 1998, SIGEP 2010). Regarding vegetation, typical of Caatinga, it also presents influences from Brazilian phytodominions of Atlantic Forest and Cerrado (Sales et al., 1998, IBAMA, 2009).

The state of Ceará covers an area of approximately 148,894.757 km², composed of 184 municipalities (IBGE, 2019). Distributed in Ceará, 10 occurrence records of the species were found, located in 5 municipalities: Crato, Viçosa do Ceará, Ubajara, São Benedito, and Guaraciaba do Norte. Remarkably, near the border with the state of Piauí in the northwest portion of the state, 8 of these occurrences of the species, including the region of the Federal Conservation Unit known as Ubajara National Park and Environmental Protection Area Serra da Ibiapaba, both located in the Ibiapaba Plateau. In addition, two records were observed in the south of the state, near the border with Pernambuco. These are located in the Federal Conservation Unit known as Chapada do Araripe Environmental Protection Area, in a region near the municipalities of Crato and Juazeiro do Norte. The Ibiapaba Plateau is the highest-altitude brejo in the westernmost location, bordering the state of Piauí. The region presents microclimates influenced by various environmental factors and species richness, which is benefited by the proximity to the coast and orographic rains (Bezerra et al., 1997; Ivanov et al., 2022).

The vegetation composition of Ceará has different phytogeological units (Figueiredo, 1997; IBGE 2012; Loiola et al., 2020), based on climate, soil types, as well as lithological and topographic characteristics. According to Lima et al. (2000), large geo-environmental compartments are recognized: Coastal Region; Fluvial Plains; Semi-arid Region; Mountainous Region. In southwestern Piauí and on the border of Ceará, there is a complex ecotone where typical Caatinga vegetation meets Cerrado, and various communities occur in these transition zones (Andrade-Lima 1978, Emperaire 1983, Oliveira et al. 1988, Araújo et al., 1999).

The state of Alagoas covers an approximate area of 27,767 km² (IBGE Resolution No. 5 of October 10, 2002). It borders to the north and west with the state of Pernambuco, to the south with the states of Sergipe and Bahia, and to the east with the Atlantic Ocean. According to IBGE (2010), the mesoregions of the state of Alagoas comprise the East, Agreste, and Sertão Alagoano. The east of Alagoas is the largest region in territorial area and includes the Coast and Zona da Mata (North and South). The Agreste is a transition region between wet and dry zones. The Sertão corresponds to areas with arid and semi-arid climatic characteristics.

According to consultations in *speciesLink* and *GBIF*, there are eight occurrence records of the species for the state of Alagoas. These occurrence points are distributed in regions in the center of the state and near the border with the state of Pernambuco. Four records are located in Caatinga vegetation composition, as found in the Serra da Boa Vista region, where granite rocky outcrops with rocky and shrub-arboreal dense Caatinga vegetation were observed in the municipality of Mata Grande.

Other records in the state of Alagoas are located in the municipality of São José da Laje (Serra das Guaribas) and also in the Biological Reserve Pedra Talhada (municipality of Quebrangulo). *M.oligocephalum* occurs in shrub-arboreal habit in fragments of Atlantic Forest in Serra das Guaribas, where part of the Pedra Talhada Biological Reserve is located.

According to Studer (2015), the Pedra Talhada Biological Reserve is considered one of the most important fragments of Atlantic Forest in the northeastern agreste. The forest is characterized as a high-altitude brejo, submontane ombrophilous forest formation (Studer, 1985; Thomas & Barbosa, 2008), where topographical characteristics directly influence rainfall. which is maintained due to the local climate, which is wetter than that of neighboring regions (Studer et al., 2015). It is located in the interior of Alagoas and Pernambuco and preserves important stretches such as the Pernambuco Interior Forests, one of the ecoregions defined by WWF in the Northeast region.

In this protected high-altitude brejo area, there is a submontane ombrophilous forest formation (Studer, 1985; Thomas & Barbosa, 2008), and topographic characteristics directly influence local rainfall, which is maintained due to the climate being wetter than neighboring regions. It is a transition region with Caatinga.

The rainfall regime in the state is directly related to configurations of large-scale atmospheric and oceanic circulation over the tropics. Annual rainfall averages vary from 2,000 mm on the coast to 400 mm in the *sertão*. Thus, distinct areas of the state exhibit different environmental and climatic aspects, such as irregularities in rainfall and little seasonal variation in solar radiation, photoperiod, and air temperature (Barros et al., 2012).

In the southeastern region of Brazil, there are records of *M. oligocephalum* occurring only in the states of São Paulo and Rio de Janeiro. Two occurrence records of the species were found in the mountainous region of the state of Rio de Janeiro. One record was located at 1922 meters altitude in an area known as Morro Branca de Neve, located in the municipality of Teresópolis and included in the Conservation Unit Três Picos State Park. The other record was in an environment characterized as semi-deciduous forest on tabuleiros, in Praia da Gorda, municipality of Armação dos Búzios.

The Serra do Mar is characterized as a geomorphological macro-unit of great importance on the south-southeast Atlantic coast of Brazil, comprising a diversified set of escarpments and plateaus (Freitas et al., 2017). The mountainous region of the state of Rio de Janeiro, where Três Picos State Park is located, consists of granitic and gneissic rocks belonging to the Eastern Terrain of the Ribeira Belt (Heilbron et al., 2000; Heilbron and Machado, 2003). According to Freitas et al. (2017), Três Picos State Park presents conditions of difficult accessibility due to geomorphological factors, such as high altitudes and steep escarpments. Due to the peculiarities of this region, which presents characteristics of mountainous relief, constant planning and monitoring are necessary for the management process (occupation and land use), as it is a priority area for conservation in the state.

Armação de Búzios is located in the region of coastal lowlands, covering an area of 71.7 km² (IBGE, 2010) and borders the municipality of Cabo Frio and the Atlantic Ocean. It presents landscapes of great geological and biological diversity, with ecosystems such as forests, restingas, rocky shores, coral reefs, mangroves, and sandy beaches. Additionally, it holds environmental, social, and cultural importance, as it also houses traditional populations (Barbosa, 2003; Dantas et al., 2009).

For the state of São Paulo, there is a single record in Juquery State Park, in the municipality of Franco da Rocha. Juquery State Park, designated as a priority conservation area, was created by State Decree No. 36,859 of 06/05/1993, originating from Juquery Farm lands (São Paulo, 1993). According to Monteiro (1973), in the semi-mountainous landscape of the area where Juquery State Park is located, the climatic feature is controlled by equatorial and tropical masses, generating tropical climates with alternating dry and wet seasons, according to Köppen's classification (1948). The altimetric gradient ranges from 730 to 950 meters, and the relief is characterized as a "sea of hills" belonging to the Serrania de São Roque, in the Atlantic Plateau region (Ab'Saber, 1978; Dantas, 1990).

The full conservation unit of Juquery State Park - PEJ stands out in the domain of the sea of hills of the Atlantic Plateau, according to Brazil (2006), where the municipalities of Franco da

Rocha and Caieiras are located in the São Paulo metropolitan region. In this region, there are remnants of preserved Cerrado biome, with relic patches, which possibly represents a broader distribution of Cerrado in the past (Ab'Saber, 1963, 2003).

The platforms consulted indicate a single record for the state of Roraima, which is located in an ecoregion known as Guiana Savanna, near the municipalities of Pacaraima and Uiramutã, on the border with Venezuela. This ecoregion is one of the units considered by Borsato et al. (2015) in their study of terrestrial ecoregions of Brazil, based on data from the Ministry of the Environment (MMA) and Wildfinder (WWF).

The states with the highest occurrence records were in the Northeast region: Bahia, Sergipe, and Pernambuco, especially in the state of Bahia. This predominance of the species indicates that the Northeast region is the center of dispersion of the species in Brazil. No records were found in the databases in the Central-West and Southern regions of Brazil, and the few records of the species for the Southeast region, in the mountainous region of the Rio de Janeiro coast and in São Paulo, show the need to expand sampling efforts and studies in the states of the Southeast region and Roraima to confirm the occurrence and distribution of the species in these states. From this study, therefore, it is known that it is necessary to carry out better analyses and invest in floristic surveys, as well as field expeditions where *Moquiniastrum oligocephalum* can be collected in various Brazilian states.

Although it is somewhat suited to occurring in an Atlantic Forest environment, it is a species that probably does not need high rainfall to survive and there is a preference for Caatinga areas, since it has adaptive morphophysiological characteristics that allow it to survive in these environments. Thus, even though it occurs in forest environments, it is possible to see that it is more suited to areas influenced by the Caatinga, i.e. those with low rainfall throughout the year.

The species has been recorded in protected areas such as Catimbau National Park, Morro do Chapéu State Park, Pedra Talhada, Junquerey Park, Serra do Mar and others. Regarding the ecoregions of the Caatinga Biome, there are records of the species occurring in the Chapada Diamantina, Raso da Catarina and the Ibiapaba-Araripe Complex. Even though it has been recorded in some protected environmental areas, there is still a lack of floristic surveys in these and other areas that have not yet been studied.

This study draws attention to the need for investment in projects aimed at floristic studies with the species, for the states of the northeast region with few or no records, especially Paraíba and Rio Grande do Norte.

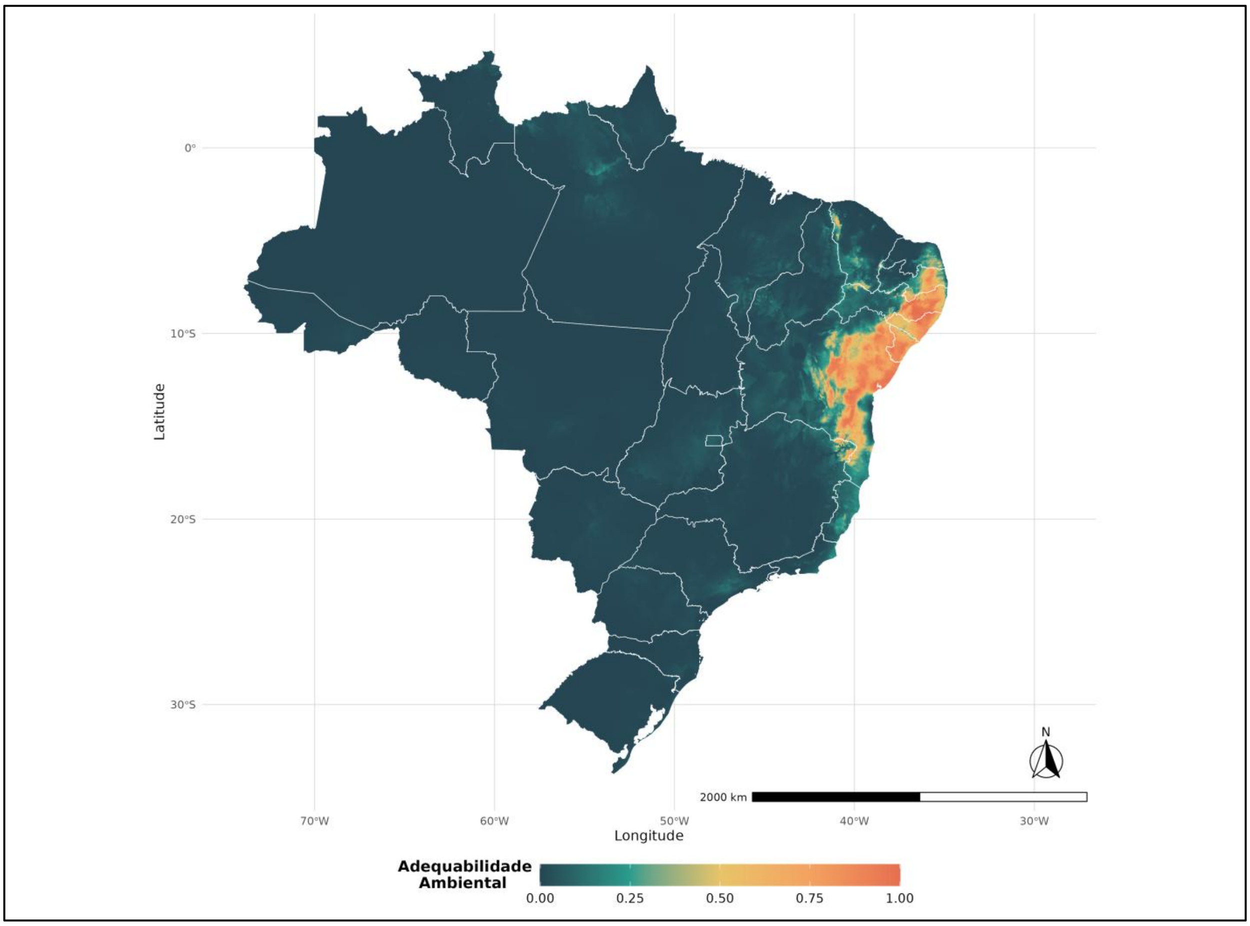
5.2. Ecological Niche Model of *Moquiniastrum oligocephalum* (Gardner) G. Sancho for Brazil

The modeling conducted corroborates information about the species distribution and indicates the Brazilian Northeast, especially the state of Bahia (Figure 6), as the center of dispersion for the species in Brazil. The probability of species occurrence can be estimated based on environmental suitability, with the percentage scale indicating how suitable or unsuitable the environment is for the species occurrence (representing potential geographic niches it may occupy).

Thus, the modeling conducted (excluding the extreme point in Roraima from the analyses) allowed visualizing regions with higher environmental suitability for Brazil. For statistical validation of the models, values of AUC ≥ 0.7 and TSS ≥ 0.8 were considered; the results obtained in the modeling showed AUC = 0.97 and TSS = 0.87, which are considered valid for projection.

The areas indicated with higher percentages (suitability ≥ 50%) of environmental suitability (Figure 5) for the occurrence of *Moquiniastrum oligocephalum* correspond to the northern portion of the East Coast, Brazilian Northeast, including mainly areas of the geographical domains of Caatinga and Mata Atlântica, predominantly in the state of Bahia. However, for the Central-West, South, North, and Southeast regions, the percentage of environmental suitability was lower (around 30% to 00%), indicating the need for updating databases and further investigation as an incentive for more field expeditions, where the species can be collected and taxonomically identified accurately.

Figure 5 - *Ensemble* modeling of *Moquiniastrum oligocephalum* (Gardner) G. Sancho projections for the Brazilian territory based on the occurrence matrix

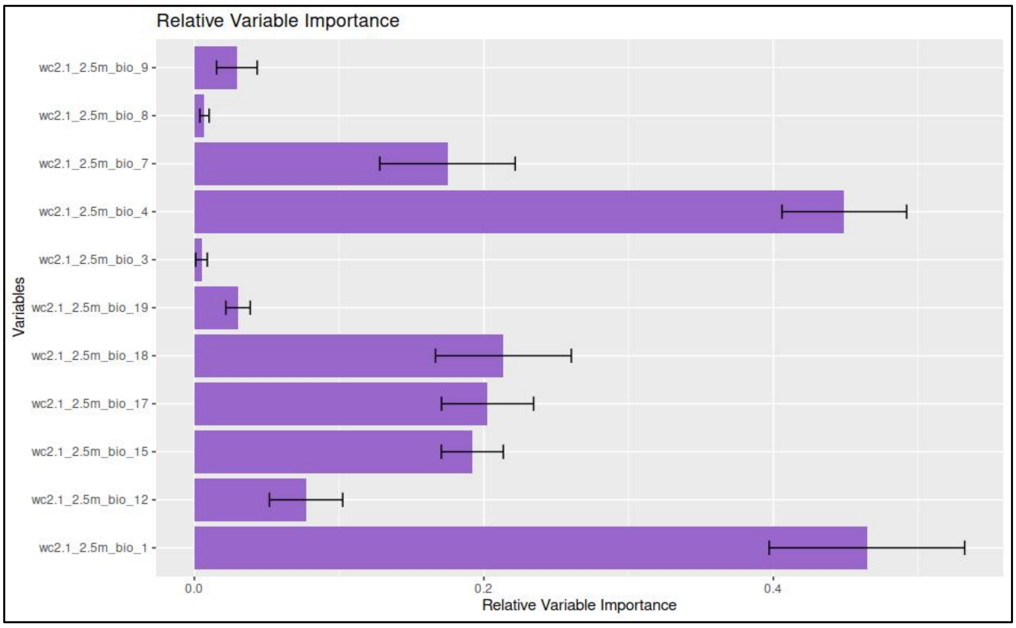


Source: Survey data, 2024

The model is satisfactory for analyzing the distribution of *M. oligocephalum* habitat suitability. Thus, it was possible to better understand that the species develops preferentially in environments with marked environmental seasonality, where there is periodic regular rainfall and temperatures characteristic of a tropical to semi-arid climate (as seen in strips comprising the Caatinga and the Atlantic Rainforest).

The relative importance values of the variables with the greatest contribution to Ecological Niche Modeling were: BIO1 - average annual temperature (46.5%); BIO4 - temperature seasonality (44.9%); BIO18 - precipitation in the hottest quarter (21.4%); BIO17 - precipitation in the driest quarter (20.3%); BIO15 - precipitation in the wettest quarter (19.2%) (Figure 6). This data shows the direct influence of these variables on modeling (Figure 5) and the limits of the geographical distribution of the species.

Figure 6 - Relative importance of bioclimatic environmental variables in the Environmental Suitability Modeling of *Moquiniastrum oligocephalum* (Gardner) G. Sancho



Source: Research data, 2024.

The modeling (Figure 5) represents, in an approximate manner, environmental conditions suitable for the occurrence of the species and presents relevant biological sense, corroborated by information regarding the investigated geographic distribution in databases. It was verified the important influence of highlighted bioclimatic variables: BIO1 - mean annual temperature (46.5%); BIO4 - temperature seasonality (44.9%); BIO18 - precipitation in the warmest quarter (21.4%) for the development and occurrence of the species in the areas shown on the species distribution map for Brazil (Figure 3). Regarding the influence of precipitation (represented by variable BIO18) and significant annual temperature fluctuations (BIO07), spatial-temporal variabilities can be perceived, where the mechanism of precipitation formation is directly related to the accumulation of water vapor volume, condensed in the air, as stated by Tucci (2000).

Amissah et al. (2014) identify precipitation as a key factor in the distribution of tree species. Additionally, according to Albuquerque et al. (2012), precipitation (rainfall) is considered the most controlling and dominant climate element for life in dry lands, such as in the Caatinga biome, where rain initiates and concludes several eco-physiological processes such as phenology and seed germination. According to Carvalho e Silva (2006), atmospheric humidity, especially due to evapotranspiration, and the mechanism of air cooling (due to the ascent of humid air) are some of the elements necessary for precipitation formation.

According to Frankie et al. (1974), Gentry (1982, 1988), and Bullock (1995), one of the main ecological differences between dry and wet tropical forests is related to the difference in the amount and seasonality of annual precipitation. Therefore, the relevance of environmental factors such as temperature seasonality and precipitation throughout the year (especially after periods when temperatures are higher), which allows for the increase in necessary humidity for species flowering, followed by a drier period, allowing for fruit development and dispersion.

The species has characteristics that favor dispersion in different environments where it can be found. For example, there is the biological characteristic of the species to produce dry fruits of the cypsela type, with a tufted dispersal structure (pappus), which are dispersed by anemochoric events (influence of the movement of air masses) after periods of significant rainfall and suitable warm temperatures during the reproductive period.

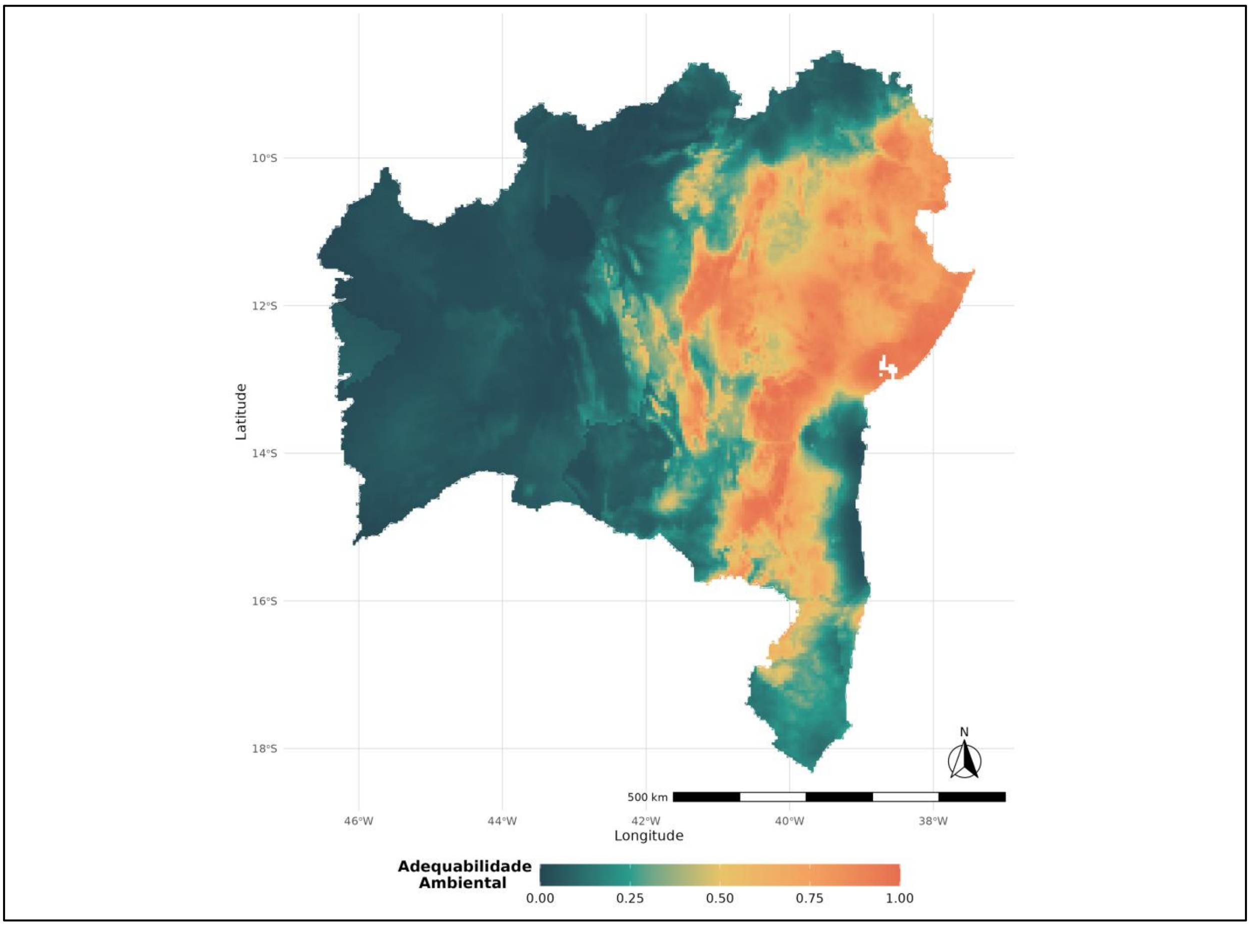
Studies in the ecology of plant species dispersion constitute an important foundation for understanding the structure and functioning of forest communities in the Neotropics (Gentry, 1983). Dispersion allows for the establishment of new individuals in a population and/or colonization of new sites, influencing the floristic composition and functioning of forest communities. In dry environments, anemochory is the predominant syndrome (Howe and Smallwood, 1982; Lopes et al., 2010). The dispersal of anemochoric diaspores is favored during drier periods in regions with seasonal climates (Croat, 1975; Morellato and Leitão-Filho, 1990), as environmental factors such as increased temperature, along with low humidity, help in fruit opening and weight reduction, as well as in the dispersal of diaspores, with reduced vegetation cover increasing exposure to wind (Souza et al., 2012).

According to Frankie et al. (1974), Bullock (1995), anemochory is the dominant mode of dispersion, characteristic of dry tropical forests. It is generally assumed that seeds dispersed by the wind prevail in "dry forests" (Gentry, 1983, 1995). Regarding the mode of dispersion of woody plants, it is assumed that the frequency of various seed dispersal strategies differs between wetter and drier locations, both at the continental and local scales, as well as between sympatric perennial and deciduous tree species (Gentry, 1995).

The information presented as a result of the highlighted bioclimatic variables (Figure 6) corroborates the environmental preference of *M. oligocephalum*, which has adaptable phytomorphological aspects that allow it to survive especially in environments characteristic of the Caatinga and Atlantic Forest under semi-arid influence, where there is marked seasonality and low rainfall. The species was recorded occurring less frequently in Cerrado environments.

According to the projection results for the state of Bahia (Figure 6), a high environmental suitability (suitability ≥ 50%) for *Moquiniastrum oligocephalum* was observed in areas of the state with predominantly tropical and semi-arid climates, as well as high temperatures and high rainfall in some periods. However, it showed low values of environmental suitability (suitability ≤ 25%) in areas of the southern East Coast, western Bahia, and Cerrado belts (Figure 7).

Figure 7 - *Ensemble* projections of *M. oligocephalum* for the state of Bahia from the complete Brazilian model, based on the complete occurrence matrix



Source: Author's elaboration (2024).

The species is notably distributed across the phytogeographical domains of the Caatinga in Bahia and the Atlantic Forest, where it is concentrated in the northern portion of eastern Bahia, as well as in the transition zones between the Caatinga and the Atlantic Forest. The analysis of the generated model can support environmental conservation actions for the species in the Atlantic Forest areas of the Northern Coast and in the Caatinga of Bahia (Figure 6).

It is evident that the biodiversity in the state of Bahia is substantial, with the potential to increase further with more extensive sampling efforts, as a large part of the floristic inventories are concentrated in the southern portion of the state, in ombrophilous forests or transitional areas (Amorim et al., 2009; Thomas et al., 2009; Coelho and Amorim 2014). Additionally, according to authors such as Tabarelli et al. (2006), more than 46% of the mapped remnants of the Atlantic Forest in the Northeast are located in Bahia.

In the state of Bahia, areas with high precipitation are primarily found in the eastern part of the state (Figure 7), where remnants of the Atlantic Forest are located. The protection of significant environments poses a challenge, and the promotion of scientific actions contributes to this process (Sanquenta, 2008).

For the states of Minas Gerais, Espírito Santo, Rio de Janeiro, and São Paulo (with recorded occurrences in São Paulo and Rio de Janeiro), the modeling showed reduced environmental suitability (≤ 40%) compared to the states of Bahia, Sergipe, and Pernambuco.

This research emphasizes the need to expand sampling efforts through floristic surveys, identification of areas, and management of priority conservation actions for Brazilian biomes, particularly in northeastern states such as Piauí, Paraíba, and Rio Grande do Norte, as these states, for example, contain considerable portions of Caatinga ecoregions (Appendix A), and no records of *M. oligocephalum* have been found in the consulted databases.

In the northern region of Brazil, there is a predominance of Amazonian forests. In the state of Roraima, reduced environmental suitability was observed (suitability ≤ 25%), indicating that this is not the preferred niche for the species to occur. Regarding the single occurrence record found in the databases, which was disregarded in the latest modeling analyses, it is possible that the species was introduced in the region, as it is known that the species is not endemic to northern Brazil.

These findings corroborate what is currently known in the literature regarding the global distribution of the *genus Moquiniastrum*. Following the publication by Sancho et al. (2013), there was a nomenclatural rearrangement, elevating Moquiniastrum to the rank of genus. The species are limitedly distributed to South America (Appendix B) and occur mainly in Brazil (Sancho, 2000; Funk et al., 2014). However, despite efforts, there is a scarcity of studies on the taxonomy, ecology, and geographical distribution of the group, necessitating further compilation and updating of data.

In the analyses, the preferred niche for the occurrence of the species was considered to be locations with higher percentages of environmental suitability (suitability ≥ 50%) as indicated in the modeling. Thus, the combination of occurrence data with selected bioclimatic environmental variables allowed for the development of a representation of the probabilistic conditions necessary for the survival of *M. oligocephalum*. Nonetheless, further analyses need to be conducted.

In the research by Carvalho et al. (2019), using machine learning algorithms, the results showed a greater influence of the environmental variable precipitation compared to temperature. A study of the distribution of ten tree species in the Caatinga region, most abundant in a subbasin of the São Francisco River (MG), evaluated three machine learning methods (J48 decision tree, random forest, and artificial neural networks).

According to the study by Araújo et al. (2004), this type of modeling is an important tool for selecting priority areas for conservation, reinforcing the importance of maintaining the species for the preservation of the environments where it occurs. Thus, the data presented on the geographical distribution of *M. oligocephalum* enable the expansion of biogeographic studies necessary for the development of conservation strategies for species in the local flora.

5.3. Priority Areas for Species Conservation in Brazil

Brazil is the country with the highest diversity of species in the world, spread across six terrestrial biomes, as well as the coastal and marine zones. However, the biological richness, endemism, and diverse phytophysiognomies of Brazilian biomes require more efficient tools to aid environmental conservation (MMA, 2023). Since 2004, the Ministry of Environment and Climate Change has adopted the Priority Areas for Conservation, Sustainable Use, and Distribution of the Benefits of Brazilian Biodiversity.

The Priority Areas serve as an informative tool guiding the definition of environmental public policies and providing a database with information on action priorities in each area, considering biological importance and various uses of natural resources (MMA, 2023). The tool also supports already established protected areas, such as conservation units, indigenous lands, and quilombola territories, which harbor various endangered species and special environments.

Furthermore, it supports measures to be implemented in the new Priority Areas for Biodiversity. These measures contribute to actions such as research, biodiversity inventory, recovery of degraded areas, environmental licensing, monitoring, identification of areas with potential for creating conservation units, among other actions aiming at connectivity of areas through ecological corridors, promotion of sustainable use, and environmental regularization (MMA, 2023).

According to data from various databases, *M. oligocephalum* occurs in protected areas such as: National Park (PARNA) in the Serra de Itabaiana in Sergipe; Raso da Catarina on the border between Pernambuco and Bahia; Morro do Chapéu State Park in Bahia; Pedra Talhada in Alagoas; Vale do Catimbau in Pernambuco; and the Araripe Plateau located in Ceará, Pernambuco, and Piauí. Additionally, the Second *SpeciesLink* (2024) reports the species' presence in the Serra das Guaribas in Alagoas. In Ceará, *M. oligocephalum* has been recorded in federal conservation units like the Serra da Ibiapaba Environmental Protection Area, Araripe-Apodi National Forest, and Ubajara National Park.

Regarding biodiversity identification and conservation priority areas discussed by Olson et al. (2001), the global ecoregion map provides a useful framework for conducting biogeographic or macroecological research. These are largely based on the biogeographic realms of Pielou (1979) and Udvardy (1975). A team of biologists convened by the World Wide Fund for Nature (WWF) developed a system of eight biogeographic realms (ecozones) as part of their delineation of over 800 terrestrial ecozones worldwide.

According to Borsato (2015), an important approach for defining conservation priorities is the Terrestrial Ecoregions in Brazil. This involved overlaying the geographical delineation of the ecoregions (WWF) on vegetation cover maps showing remnants of the Atlantic Forest in Brazil (MMA, 2005). Locations with the lowest proportion of remaining vegetation are considered of utmost importance for conservation. The ecoregional biodiversity vision, as conceived by WWF-Brazil, is a planning tool aimed at guiding biodiversity conservation actions to identify priority areas to maintain a representative sample of biodiversity across an entire ecoregion (Borsato, 2015).

Highlighted ecoregions and the percentage of remaining Atlantic Forest, in descending order, are: Guianan Savanna (8.3%); Bahia Coastal Forests (11.9%); Bahia Interior Forests (14.8%); Caatinga Enclaves Moist Forests (25.6%); Pernambuco Coastal Forests (27.6%); Serra do Mar Coastal Forests (29.1%); Atlantic Coast Restingas (30.2%); Pernambuco Interior Forests (33.8%); Caatinga (57.1%); Atlantic Dry Forests (66.5%) (Borsato et al., 2015).

M. oligocephalum has been recorded in the ecoregions listed above. Verified records in the consulted databases, in the Atlantic Forest environment, indicate the need for priority conservation actions in these ecoregions and other localities in Brazil.

Significant advances in conservation have been made over recent decades, such as the enactment of Law No. 11,428 of December 22, 2006, the Atlantic Forest Law, which regulates the use of Atlantic Forest remnants. However, only 9% of the remaining forest cover is within protected areas (Ribeiro et al., 2009), and these do not necessarily correspond to areas of vegetation remnants. Protected areas do not always represent the region's biodiversity. Therefore, since it is not possible to preserve all remaining natural areas, it is necessary to prioritize them, aiming to adequately represent existing biodiversity (Durigan et al., 2009).

Despite being reduced and highly fragmented, it is estimated that the Atlantic Forest hosts about 20,000 plant species (about 35% of Brazil's species), including many endemic and endangered species. The coverage of protected areas in the Atlantic Forest has significantly increased over the years, with contributions from federal, state, and more recently, municipal governments and the private sector. However, most native vegetation remnants remain unprotected (MMA, 2020).

The development of Brazil's main humid forest blocks, the Amazon and the Atlantic Forest, is still under discussion. These two formations were possibly connected in the past, either directly, as suggested by fossil pollen grain studies (Behling et al., 2000), or indirectly, through a tangled network of corridors and forest galleries (Oliveira-Filho and Fontes, 2000). It is believed that both originated from small independent forest formations and probably developed due to favorable climate. During the Tertiary, a xeric corridor possibly established between both forest formations, and due to climatic variations, more humid formations than those observed today would have developed.

Thus, the Atlantic Forest region was likely covered by a seasonal arboreal formation during most of the Pleistocene, with riparian forests interconnecting it with the Amazon forest during the wetter interglacial periods (Costa, 2003; Percequillo et al., 2011). Such climatic oscillations, acting in both areas and especially with numerous local and punctual variations, would have influenced the distribution of taxa and the current relationships between the two largest neotropical forest blocks (Costa, 2003).

Due to the combined effects of altitude and moist oceanic air currents entering the continent, there are enclaves of mountain forests in the Caatinga, known as Brejos de Altitude or Brejos Nordestinos. The brejos-nordestinos (or brejos-de-altitude, humid mountain ranges, enclaves), a term coined by Andrade and Lins (1964) and Andrade-Lima (1964), develop in the semi-arid region of Northeast Brazil (Câmara, 2005) and present an integration of different morphoclimatic types of the Atlantic Forest and Caatinga, mainly in the state of Ceará.

In Pernambuco, these enclaves are located much closer to the eastern northeast coast (Coimbra-Filho and Câmara 1996; MMA 1993, 2000). They constitute disjunctions of the evergreen tropical forest, with altitudes ranging from 600 to 1100 meters, occurring on the tops and upper windward slopes of mountains in the Borborema Plateau (Andrade-Lima, 1960; Rodal et al., 1998). The mountain forests in Pernambuco have been more intensively studied concerning the location and conservation of remnants (Rodal et al., 1998) and floristics (Sales et al., 1998).

M. oligocephalum has been recorded in altitude brejos only in the states of Pernambuco and Alagoas, in the Borborema Plateau. According to Velloso et al., 2002, this region encompasses Caatinga ecoregions and includes parts of the states of Rio Grande do Norte, Paraíba, Pernambuco, and Alagoas. There are rock formations with particular vegetational compositions, contrasting with the Caatinga of the semi-arid interior regions of Northeast Brazil. Borborema has a large vegetational diversity, ranging from the low caatingas of Cariris Velhos and Curimataú in Paraíba to forests very similar to coastal ones (defined as Atlantic Forest), and the mountain forests of altitude brejos (Giulietti et al., 2002).

Many areas with rocky outcrops, such as the Pedra Talhada Biological Reserve (municipality of Quebrangulo, Alagoas), are recognized for having a highly specialized flora with high levels of diversity and endemism (Correia et al., 2021). Thus, mountainous areas deserve special attention for biodiversity conservation due to the degree of endemism found (Hind, 1995; Rapini et al., 2002), and floristic inventories are needed in these regions, as the significant relevance of the information provided is essential for recognizing the local flora of such areas and their proper conservation (Moura and Roque, 2014).

In semi-arid regions, the function of Conservation Units goes beyond biodiversity conservation, representing an essential front to curb or reduce the effects of degradation and desertification of new Caatinga areas (Barbosa et al., 2005). Seasonally dry tropical forests are densely populated and have undergone intense transformations (including desertification) over the last five centuries, increasing their vulnerability to climate change (Silva et al., 2019). A recurring challenge is to develop functional strategies that help species survive in threatened environments and understand how plant distribution will be, given climate change, as rocky outcrops or inselbergs harbor various endemic species (Gomes and Alves, 2009, 2010).

The Caatinga is considered a high priority for conservation due to the complexity of its biota and the considerable number of endemic species it harbors (Andrade-Lima, 1982; Rodal, 1992; Sampaio, 1995; MMA, 2002). This is attributed to its climate and parent rock composition (Oliveira Filho et al., 2006; Giulietti et al., 2002). Conservation efforts in the Caatinga are closely linked to combating environmental degradation, desertification, and improving the quality of life for local populations. However, it remains underprotected in conservation units (Tabarelli et al., 2000; Teixeira et al., 2021; MMA, 2022), with limited scientific literature compared to other Brazilian vegetation domains (Tabarelli and Silva, 2003).

Moreover, preservation of permanent and remaining rivers is crucial in these areas, as they harbor a significant number of rare and endemic taxa, and water availability is a limiting factor for the diverse vegetation types in the Caatinga. Conservation of these forests is particularly critical, depending on the protection of their headwaters, found in regions such as swamps or mountain forests in Borborema, Serra do Araripe, among others (Giulietti et al., 2002).

Enhanced knowledge of the geographic distribution of *M. oligocephalum* and other species across Brazil is necessary, particularly in poorly protected areas like the Indigenous Territory Kiriri (Banzaê municipality), UNEB/EBDA Vegetational Complex in the North Coast (Alagoinhas municipality), Baixa dos Quelés and Povoado Casinhas (Jeremoabo municipality), as well as less known areas within Federal and State Conservation Units and others located in states within the "Polígono das Secas" in Northeast Brazil (Andrade-Lima, 1981).

There is a pressing need for increased investment in maintaining existing Conservation Units and establishing new ones, especially in the identity territories of North Coast and Agreste of Bahia; Northeastern Semi-arid region; Metropolitan region of Salvador; Portal do Sertão; Itaparica; Sisal; Recôncavo; and Chapada Diamantina, particularly in Bahia state, to enhance preservation of threatened biodiversity and ensure adequate conservation of flora.

6. FINAL CONSIDERATIONS

Brazil is a country of continental dimensions where the increasing use of natural resources is causing a gradual loss of biological diversity at various levels. Therefore, it is of utmost importance to map and develop strategies so that the quality and quantity of data can also be evaluated.

The Northeast region can be considered as the species dispersion center. The states with the highest occurrence records were in the Northeast region: Bahia, Sergipe, and Pernambuco, especially in Bahia where significant environmental suitability was observed for the Caatinga and Atlantic Forest in the northern portion of the eastern coast of the state, and low environmental suitability in areas to the south and west of Bahia. For other Brazilian regions, the ensemble map showed reduced environmental suitability at a scale of less than 25%. No records were found in the databases for the Midwest and South regions of Brazil, and the few records of the species for the Southeast region, in the mountainous coastal region of Rio de Janeiro and São Paulo, indicate the need to expand sampling efforts.

The statistical indicators (AUC and TSS) evaluated classify the model as valid, being satisfactory in estimating the habitat suitability distribution of *M. oligocephalum*. Thus, it was possible to better understand that the species preferably develops in environments with marked seasonal variability, where there are periodic regular rains and characteristic temperatures ranging from tropical to semi-arid climates (as seen in areas encompassing the Caatinga and Atlantic Forest). This study suggests the constant updating of databases, especially in support of the work developed by Flora and Funga of Brazil, since there are records in the Caatinga, Atlantic Forest, Cerrado, and transition zones between these phyto-domains.

Although showing some suitability to occur in Atlantic Forest environments, it is a species that likely does not require high rainfall to survive. It is noted that there is a certain preference for Caatinga areas in northeastern Brazil, as it presents morphophysiological adaptive characteristics that allow it to survive in these environments. Thus, even occurring in forest environments, it is known that there is higher environmental suitability ($\geq$ 60%) for areas influenced by Caatinga, i.e., areas with reduced rainfall throughout the year.

There are still gaps regarding the knowledge and distribution of the species that need to be filled concerning the Brazilian flora. Ecological Niche Modeling and the estimation of environmental suitability corroborated the species distribution pattern, proving to be an excellent methodology for studying the biogeography of other species, thereby expanding knowledge of Asteraceae diversity and distribution in Brazil. Moreover, it provides support for the recovery of areas considered conservation priorities, contributing to strategies in creating other priority areas for conservation and environmental preservation in Brazil.

It is known that protected areas such as conservation units, indigenous lands, and quilombola territories are fundamental for maintaining representative and viable samples of biological and cultural diversity, sheltering several threatened species in special environments, which can even serve as a starting point for defining new priority areas for conservation.

This study suggests increased investment in collection expeditions and floristic surveys of *Moquiniastrum oligocephalum* in various states of Brazil. Despite its vast extent and considering the importance of the Caatinga phyto-domain for northeastern Brazil, there is still a lack of ecological information, with a scarcity of publications. Consequently, due to being poorly studied, poorly protected, and undergoing constant processes of alteration in floristic composition and vegetation physiognomy, the landscape has been profoundly altered, and areas have been reduced to small fragments. Additionally, even with some public policies in place, they often lack coordination with the interests and knowledge of the communities they are intended to serve. Therefore, the restoration of dry forests and the adoption of best practices to prevent further degradation are urgently needed to aid in the recovery of ecosystem productivity and resilience.

This study also suggests increased sampling efforts in priority areas for the conservation of Caatinga biological diversity, which are of extreme importance and are located around some marshlands, humid mountainous areas formerly covered by forests, such as Planalto da Ibiapaba do Norte/Jaburuca, Chapada do Araripe, and in the central region of Bahia in Morro do Chapéu and Raso da Catarina. For these reasons, the perpetuity of native species from the Caatinga must be ensured through projects that use, for example, morphological descriptions, gathering information on flowering and fruiting, phytosociological and floristic data in degraded areas, the use of analytical keys, distribution maps of species, ecological niche modeling, and providing habitat information to assess conservation status.

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