Projections of suitable habitat loss and its implications in conservation for endemic non-pseudantial Euphorbioideae (Euphorbiaceae) species in Northeastern Brazil under climate change scenarios

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Abstract

Climate change has intensified negative impacts on biodiversity through changes in precipitation patterns and rising global average temperatures. Semi-arid regions, such as parts of Northeastern Brazil, are particularly susceptible to these changes, with projections indicating that they will become hotter and drier, reducing the climatic suitability of several plant species. In this context, endemic and restricted-range species may be highly vulnerable. In this study, we used distribution modeling to estimate potential changes in the geographic distribution and conservation of 12 endemic Euphorbiaceae species from Northeastern Brazil, to inform conservation strategies. We found that climate change will have distinctly different impacts on the suitable habitat areas for the analyzed taxa. Projections indicate that in the optimistic scenario (SSP126), *Sapium sceleratum* could expand its suitable range by approximately 80%, while *Microstachys uleana* and *Actinostemon appendiculatus* will experience limited gains (< 14%), and other species will experience losses exceeding 40%. In the pessimistic scenario (SSP585), five taxa lose areas of suitability above 40%, but *Sapium sceleratum* and *Algernonia bahiensis* could expand by 76% and 100%, respectively. We also documented a reduction in species richness in all future climate scenarios analyzed. Furthermore, in both climate scenarios, a general trend toward increasing extinction risk is observed for most species. Thus, this study clearly demonstrates that most endemic species in the family are highly vulnerable to various future climate change scenarios and that conservation measures such as the creation of protected areas within the species' climatically suitable concentrations should be established.

Introduction

Climate change significantly influences species population dynamics (Zhao 2021) and may modify climate suitability and precipitation patterns in natural ecosystems (MMA 2018). This, in turn, may increase the risk of large-scale extinction events (Pillet et al. 2022), as has been recorded several times throughout the geological period (Elewa and Abdelhady 2020). Currently, the possibility of a new extinction event caused by the increase in Earth's temperature, driven by the intensification of anthropogenic activities, is being discussed (Schmidt 2021; IPCC 2023). These environmental changes can accelerate the decline in plant health in both natural environments and agricultural systems (Pautasso et al. 2012), negatively impact the distribution of endemic species (Manes et al. 2021) and increase vulnerability to extinction (Qian and Qian 2024).

The subfamily Euphorbioideae (Euphorbiaceae) comprises representatives of the tribes Euphorbieae, Hippomaneae, Hureae, Pachystromateae, and Stomatocalyceae (Wurdack et al. 2005). The group referred to as non-pseudantial Euphorbioideae includes the tribes that lack pseudantial inflorescences of the cyathium type (Hippomaneae, Hureae, Pachystromateae, and Stomatocalyceae), and is characterized by more conventional flowers, usually arranged in racemes, thyrsus or panicles. The subfamily is predominantly composed of species producing toxic latex and defensive chemical compounds (García-Saldaña 2024), with recognized potential for cancer treatment (Souza et al. 2025a), biological control (Vaz et al. 2010), rubber production (Guerra et al. 2021), traditional medicine (Agra et al. 2008; Ramos et al. 2024), and pharmaceutical applications (Silva et al. 2024). In Brazil, the Euphorbioideae subfamily is represented by 219 species, of which 100 are endemic and 26 are restricted to the Northeastern region, including 15 belonging to the non-pseudantial group (Flora e Funga do Brasil 2025). These species occur mainly in the Atlantic Forest and Caatinga (Flora e Funga do Brasil 2025), many of them with extremely restricted geographic distributions (Oliveira 2010; Esser 2012; Athiê-Souza et al. 2015). Approximately one third are classified in some category of threat (Athiê-Souza et al. 2015; Fernandez and Rosa 2018; Fernandez and Moraes 2020; Amorim and Fernandez 2021).

The Northeastern region is home to more than 11,900 species of angiosperms, making it the third most diverse region in the country in terms of flora (Flora e Funga do Brasil 2024). In contrast, it is also one of the most vulnerable to current climate change, subject to changes in the distribution of extreme temperature and rainfall events (Araujo and Willians 2000; Suarez-Contento et al. 2024). According to the Brazilian Panel on Climate Change (PBMC 2013), a reduction of up to 20% in precipitation and an increase of approximately 1°C in average air temperature are projected by 2040, with these trends progressively worsening by the end of the century, which could accelerate processes such as the desertification of the Caatinga. Furthermore, in recent decades this region has suffered a high degree of deforestation associated with the loss of habitats for agricultural activities (Araújo et al. 2023), resulting in a high proportion of locally threatened species, including endemic ones (Leal et al. 2005).

In this context, studies that associate climate change and its future projections with the population dynamics of plant species are essential, especially for developing conservation strategies and contributing to elucidating the impacts of environmental changes on the biodiversity of semiarid regions (Cavalcante et al. 2020). Furthermore, investigating the potential distribution of species is an essential tool for identifying priority areas for conservation, helping to direct management efforts and reduce the limitations associated with the creation of new conservation units (Diniz-Filho et al. 2009). Applying spatial analyses with a research approach, such as those based on diversity metrics (Bullong et al. 2024), can deepen the understanding of the population dynamics of endemic species, especially those with restricted and regionalized geographic distributions (Echternacht et al. 2011; Costa et al. 2024). The use of species distribution models (ENM) has also proven effective in elucidating spatial patterns in specific regions and ecosystems (Siqueira and Durigan 2007), such as Northeastern Brazil.

The potential effects of climate change on the distribution of species have been widely investigated in regions such as Asia and Europe (Qazi et al. 2022). In contrast, in Neotropical countries, particularly Brazil, which harbors one of the largest portions of global biodiversity, including a high number of endemic species, such studies remain relatively scarce. In Brazil, most research has been concentrated in the Southeastern and Southern regions (Duarte et al. 2019), while other areas that are highly vulnerable to climate change, such as the Northeastern, have received less attention. This gap is particularly evident in arid and semi-arid regions, where ecological niche modeling studies face additional challenges due to the scarcity of occurrence data (Vasconcelos et al. 2024). Nevertheless, recent studies have indicated severe habitat losses for many animal and plant species, especially within the Caatinga biome (Rodrigues et al. 2015; Simões et al. 2019; Moura et al. 2023a; Suarez-Contento et al.

2024), with the most critical impacts predicted for endemic species (Simões et al. 2019; Almeida et al. 2024; Suarez-Contento et al. 2024).

In this study, we analyzed the impacts of climate change on the distribution of endemic non-pseudantial Euphorbioideae species in Northeastern Brazil, projecting their potential distribution under different climate scenarios until the year 2100. Furthermore, we identified the areas of greatest species richness and estimated the extinction risk of these taxa in the face of predicted environmental changes.

Materials and Methods

Study area

The Northeastern region is in Brazil's tropical belt (1°02' N, 18°20' S, 34°47' W, 48°45' W) and comprises the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, and Bahia. It is the third-largest region in the country in terms of territorial extension, with 1,561,177.80 km², corresponding to approximately 18.26% of the national territory (IBGE 2006). Its vast spatial dimension is reflected in significant physical, cultural, and climatic variations, which led to its subdivision into four subregions: the Mid-North, characterized as a transition zone between the Semiarid and the Amazon; the Sertão, located in the interior of the region; the Agreste, a transition zone between the Sertão and the Zona da Mata; and the Zona da Mata, located in the coastal strip that extends approximately 200 km inland (IBGE 2006). Due to the region's remarkable environmental heterogeneity, areas of high rainfall are found along the coast, where annual precipitation can exceed 2,000 mm, in contrast to the semiarid Sertão, where annual rainfall is often less than 400 mm and droughts are recurrent. Temperatures also vary: while the coast has annual averages between 24°C and 28°C, the Sertão experiences high daytime temperatures, often above 30°C.

In terms of vegetation cover, the Northeast is home to formations belonging to four major domains: the Atlantic Forest, restricted to small areas near the coast; the Cerrado, present in western Bahia and southern Maranhão; the Caatinga, predominant in the semiarid interior; and the Amazon, represented by the Mata dos Cocais in portions of Maranhão, Piauí, Rio Grande do Norte, and Ceará (Rizzini 1963). Each of these domains presents distinct biological, hydrographic, climatic, and topographic characteristics, offering a wide range of ecological niches and environmental conditions that contribute to the region's high biodiversity.

Database – species occurrences

The occurrence data of the endemic species of non-pseudantial Euphorbioideae of Northeastern Brazil were compiled from specific literature (e.g., Wurdack et al. 2005; Oliveira 2010; Athiê-Souza et al. 2015; Pscheidt 2015; Cordeiro 2018), where 15 taxa were identified (14 spp. and 1 subspecies), of which 12 were evaluated in this study (Table 1). Subsequently, collection occurrence records were extracted from 46 indexed herbaria (ALCB, ASE, CEN, CEPEC, CEPLAC, CESJ, CSTR, EAC, ESA, F, FUEL, FURB, G, HDELTA,

HFC, HPL, HRCB, HTSA, HUEFS, HUESB, HURB, HVASF, IAN, IBt, IPA, JPB, MAC, MBM, MCCA, MCMG, MN, MO, MOSS, NY, PEUFR, MNHN, SORO, SP, SPF, UB, UEC, UEFS, UFBA, UFP, US, USP -- acronyms follow Thiers 2025, continuously updated) and HST herbarium (not indexed) through the virtual platforms SpeciesLink (https://specieslink.net/) and Reflora (https://reflora.jbrj.gov.br/reflora/herbarioVirtual/), totaling 1077 specimens. The data were then screened to eliminate duplicate specimens, those with non-georeferenceable information, and/or uncertain identification. Specimens identified by experts in the Euphorbiaceae family were used to validate identification. After screening, the database totaled 421 records sampled here.

Table 1
Minimum and maximum elevation of the sampled species endemic to Northeastern Brazil

Species	Minimum elevation (m)	Maximum elevation (m)
Ac_appendiculatus	12	350
Al_bahiensis	13	225
Gr_franciscana	119	120
Ma_f_bahiensis	372	770
Mi_heterodoxa	4	1206
Mi_revoluta	888	1269
Mi_uleana	777	1531
Op_parviflorum	360	360
Op_pedunculare	16	474
Se_jacobinensis	50	860
Se_macrocarpa	18	853
Se_trinervia	607	607
Sa_sceleratum	153	887
St_loranthacea	839	1074
St_trapezoidea	170	1129

Table 2
Extent of Occurrence (EOO) and Area of Occupancy (AOO) based on the current distribution of endemic species of Northeastern Brazil

Species	**EOO (km²)**	**AOO (km²)**
Ac_appendiculatus	169,959.304	114
Al_bahiensis	8,230.618	28
Gr_franciscana	00	6
Ma_f_bahiensis	35,387.887	28
Mi_heterodoxa	226,.694.344	356
Mi_revoluta	146.963	24
Mi_uleana	31,357.204	132
Op_parviflorum	0	4
Op_pedunculare	4,363.019	24
Se_jacobinensis	328,437.8540	116
Se_macrocarpa	442,805.7598	336
Se_trinervia	0	4
Sa_sceleratum	212,176.014	32
St_loranthacea	634.365	52
St_trapezoidea	599,044.629	232

Environmental Variables and Distribution Modeling

A set of 19 bioclimatic variables for the different scenarios were obtained from WorldClim 2.0 (Fick and Hijmans 2017), with a 30-second resolution (using the boundaries of the Northeastern region of Brazil). To avoid multicollinearity problems and improve model robustness, a 70% correlation threshold was applied to the selection of environmental variables (Booth et al. 2014). After this analysis, the variables were: bio2, bio3, bio4, bio8, bio14, bio16, bio18, and bio19.

Modeling of the potential distribution of species was performed using the Maxent algorithm (Phillips et al. 2017), implemented through the modleR package (Sánchez-Tapia et al. 2020) in R software (v. 4.4.0, R Core Team 2023). Of the 15 taxa initially considered, only 12 were modeled, as three of them have only the type locality. Maxent is a maximum entropy method that models species distribution based on presence data and environmental variables. It is particularly advantageous for species with few occurrence records—a minimum of 5 to 10 unique occurrence points is recommended for robust analyses (Phillips et al. 2006). Its effectiveness with small sample sizes is due to the exclusive use of presence data and the incorporation of regularization techniques that prevent overfitting (Wisz et al. 2008; Phillips et al. 2006; Hernandez et al. 2006). The accuracy and robustness of the models were assessed using cross-validation techniques, with performance measured by the Area Under the ROC Curve (AUC) (Boria et al. 2014, 2016; Cobos et al. 2019). The calibration area for each species was defined by a minimum convex polygon encompassing 100% of the occurrence points, expanded by a 1.5° buffer. The model projection area corresponded to the geographic limits of Northeastern Brazil, as this is the region where the study species are present.

Future projections (2080–2100) were performed using four General Circulation Models (GCMs) representing the full range of climate sensitivity (ECS 2.9–5.5°C): BCC-CSM2-MR, CMCC-ESM2, HadGEM3-GC31-LL, and IPSL-CM6A-LR (Boucher et al. 2020; Cherchi et al. 2019; Williams et al. 2018; Wu et al. 2021; Zelinka et al. 2020). These GCMs were selected based on their robust historical performance in South America (Eyring et al. 2016; Hodnebrog et al. 2022; Scafetta 2023; Zelinka et al. 2020), allowing for contrast between the Shared Socioeconomic Pathway scenarios: SSP126 (optimistic) and SSP585 (pessimistic).

The area of environmental suitability was calculated from the distribution models using the cellStats() function of the raster package (Hijmans 2012) in R software (v. 4.4.0, R Core Team 2023). A suitability threshold of 0.6 was applied to generate binary maps, considering cells with values above the threshold as suitable. Based on the suitability area indicated in the ecological niche modeling, the extent of the protected territory (km²) was calculated using the mask_thr_projs_mscn_b function from the ENMwizard package (Heming et al. 2019). Data on protected areas were obtained from the UNEP-WCMC and IUCN databases (UNEP-WCMC and ShareAction 2024 & IUCN 2023). All analyses were conducted in R software (v. 4.4.0, R Core Team 2023).

To assess the taxonomic diversity of endemic species under different climate scenarios, we used distribution models for each species. The metric was calculated using a tree-based approach and raster data (Mota et al. 2023). Alpha diversity was obtained using the spat.alpha() function from the divraster package (Mota et al. 2023). This function is suitable for raster data and optimizes calculations for large datasets. Taxonomic diversity was defined as the species richness in each raster cell, where each species is connected to the tree root by an edge of unit length (Mota et al. 2023). All these analyses were performed in R software (v. 4.4.0, R Core Team 2023).

Risk of species extinction

For the current conservation status, the area of occupancy (AOO) of the species was used as follows: CR < 100 km², EN < 5,000 km², VU < 20,000 km², NT < 30,000 km², and LC > 30,000 km². Conversely, for future scenarios, the conservation status analysis was performed based on the potential distribution and projections for future scenarios, using the values of the extent of the areas of suitable occurrence and area of occupancy, according to criterion A3(c) (IUCN 2024). Criterion A3 considers the "projected or estimated future population reduction," and subcriterion (c) considers the decline in area of occupancy (AOO), extent of occurrence (EOO), and/or habitat quality. Therefore, we classified species according to the percentage of habitat loss as follows: Extinct (EX) – 100%; Critically Endangered (CR) – above 80%; Endangered (EN) between 50% and 80%; Vulnerable (VU) – between 30% and 50%; Near Threatened (NT) – slightly below 30% (Pomoim et al. 2022). All analyses were performed using R software (v. 4.4.0, R Core Team 2023).

Results

All taxa exhibited changes in their areas of climatic suitability in both projected scenarios (Figs. 1 and 2). Although the optimistic scenario (SSP126) indicates more significant reductions in the loss of climatic suitability for a greater number of species (over 25%), the pessimistic scenario (SSP585) proves more critical, as the reductions occur primarily in species with already restricted areas of suitability, resulting in greater susceptibility to inclusion in threatened categories.

In SSP126, *Sapium sceleratum* could expand its area of suitability by approximately 80%, while *Microstachys uleana* and *Actinostemon appendiculatus* will experience gains of no more than 14%. The opposite trend was observed for other taxa, such as *Mabea fistulifera* subsp. *bahiensis*, which experienced a 75% loss in area, followed by *Ophthalmoblapton pedunculare*, *Microstachys heterodoxa*, and *Sebastiania jacobinensis*, which had the most critical losses above 40% (Fig. 3A). Regarding the SSP585 scenario, a 40% loss was observed for *Mabea fistulifera* subsp. *bahiensis*, *Ophthalmoplapton pedunculare*, *Microstachys heterodoxa*, and *Stillingia loranthacea*. On the other hand, *Sapium sceleratum* could gain 76% in area, and *Algernonia bahiensis* could double its area of suitability (Fig. 3B).

The environmental suitability analysis revealed significant differences among species regarding the proportion of their potential habitats protected by conservation units, considering the current scenarios, SSP126, and SSP585. Overall, most species have a low level of protection. Less than 20% of the suitable area for these species overlaps with protected areas. Species such as *O. pedunculare*, *M. revoluta*, and *M. uleana* stand out for having high percentages of protection in some scenarios, but have relatively small potential areas of occurrence. This suggests that, despite their limited distribution, much of their projected habitats are within conservation units, which may benefit their conservation in the future. On the other hand, widely distributed species such as *Sp. sceleratum* and *Se. macrocarpa* maintain large areas of environmental suitability, but with low relative protection, representing a potential risk in the face of climate change, especially in the most pessimistic scenario (SSP585) (Fig. 4).

In general, the analyzed taxa exhibit higher richness values in southern Bahia, Chapada Diamantina, and the Atlantic Forest areas on the east coast of the Northeast. These regions, although experiencing reductions in both future scenarios, still concentrate the greatest richness (Fig. 5). In the current scenario, the regions with the highest species richness are concentrated primarily in southern Bahia and northern Minas Gerais, reaching values of up to five species per pixel. Cores/secondary areas of species richness were also identified in elevated areas of Pernambuco, Alagoas, and Paraíba. Under the SSP126 scenario, a general reduction in species richness is observed. Although some higher elevation areas in Bahia and Pernambuco maintain some suitability, the extent of zones with high richness (values ≥4) decreases. In the pessimistic scenario (SSP585), the effects of climate change are more pronounced. Species richness declines drastically, and areas that previously had high suitability now show low or intermediate values (1–3 species per pixel). Only small regions in southern Bahia and Pernambuco retain moderate levels of richness. These results indicate a trend toward a loss of climatic suitability for the studied species, with potential consequences for regional biodiversity conservation, especially in the most extreme scenarios.

The conservation status of the 12 endemic taxa of the Northeastern shows a predominantly increasing trend without risk of extinction (Fig. 6). Our results indicate that in the current scenario, 10 species (83%) are classified as Least Concern (LC) and two (16.66%) are classified as Near Threatened (NT). In both future scenarios, *A. pendiculatus* maintains its Least Concern (LC) status, demonstrating some resilience of its potential habitats. In the optimistic scenario (SSP126), 75% of the species migrated to higher risk categories, with specific species classified as Near Threatened (NT), Endangered (EN), and Vulnerable (VU). Similarly, in the pessimistic scenario (SSP585), the majority of species (75%) were found in some threat category. The increase in risk is most pronounced for *O. pedunculare*, which changes from Least Concern (LC) to Near Threatened (NT) in SSP126 and subsequently to Endangered (EN) in SSP585; and for *St. loranthacea*, which jumps from Least Concern (LC) to Endangered (EN) in SSP126. The most critical case is that of *Mabea fistulifera* subsp. *bahiensis*, which changes from Least Concern (LC) to Endangered (EN) in SSP126 and, in the worst-case scenario, reaches Critically Endangered (CR) status. In contrast, *A. bahiensis* exhibits an atypical pattern, worsening from Least Concern (LC) to Near Threatened (NT) in SSP126 but returning to Least Concern (LC) in SSP585.

Discussion

Our results highlight complex and worrying patterns in the potential distribution and conservation status of non- pseudantial endemic Euphorbioideae species in Northeastern Brazil under climate change scenarios. A generalized contraction of areas of climatic suitability was observed for most taxa (75%) under both scenarios, resulting in a significant increase in extinction risk. Furthermore, we observed that the effects of climate change can vary distinctly across areas of suitability, thus being species-specific. These results corroborate recent evidence that many endemic plant species are sensitive to climate change, primarily because they often have restricted distributions and fragmented habitats, which represent barriers to the colonization of new climatically suitable areas in the future (Suarez-Contento et al. 2024). Furthermore, seasonally dry tropical forests, such as the Caatinga, are highly sensitive to climate change, as they are already close to their tolerance limits in terms of temperature and water availability (Allen et al. 2017). Thus, rising temperatures and reduced engineering standards can significantly reduce suitable habitats for many species (Marengo et al. 2011; Andrade et al. 2017).

Moura et al. (2023) used ENMs to assess potential changes in the distribution of non-volant mammals in the Caatinga and observed that 85% of mammal species will lose suitable habitats, with a quarter of species projected to completely lose their suitable habitats by 2060. A similar result was found in the study by Silva et al. (2019), which demonstrated that habitats in the Caatinga with a high probability of occurrence (> 80%) of endemic species will be reduced (up to ~ 10% for trees, ~ 13% for non-trees, 10–28% for species with any pollination/breeding system), with the largest reductions recorded for species with specialized reproductive traits.

In this study, expansions into suitable areas were observed in both scenarios only for *S. sceleratum* and *A. appendiculatus*, indicating that some species can withstand extreme climate events, as they possess morphophysiological adaptations capable of withstanding prolonged droughts (Bongers et al. 2017). According to Cordeiro et al. (2018), S. *sceleratum* is commonly found on rocky outcrops and in environments subject to seasonal water deficit in the Caatinga. According to Souza et al. (2025b), the areas surrounding inselbergs in the Caatinga serve as ecological microrefugia and create exceptional wetlands within these dry forests, as runoff is largely directed down the inselberg slopes. Therefore, these environments are potentially important for the persistence of many species under increasing aridity. Additionally, the presence of abundant laticifers, common in Euphorbiaceae and confirmed for species of the genus *Sapium*, may contribute to the rapid sealing of injured tissues, reducing water loss through transpiration in wounds and offering a physical barrier in hot and dry environments (Demarco et al. 2013).

Actinostemon appendiculatus is widely distributed in the Atlantic Forest, occurring from the state of Bahia to Paraíba in both dense and open seasonal and ombrophilous forests. This range of occurrence may explain the species' tendency toward greater resilience to climate change, given that, as discussed by Leão et al. (2021), widespread species tend to be less vulnerable, as they encounter favorable climatic conditions in different regions. On the other hand, *A. bahiensis* showed a different pattern. Despite its distribution restricted to the Atlantic Forest of Bahia and its preferential occurrence in open and dense ombrophilous forests, as well as in deciduous and semideciduous seasonal forests (Sátiro and Sales 2014), the species showed projections of significant expansion of suitable areas only under the most pessimistic climate scenario. This seemingly contradictory result may be related to changes in the availability of phytophysiognomies, since, according to the MMA (2018), most forest types in the Atlantic Forest are likely to lose climatic suitability in future scenarios, except for open ombrophilous forest and transition areas, which have potential for expansion. Therefore, the projected increase in areas of suitability for *A. bahiensis* should be interpreted with caution, as it is associated with specific habitat changes and not necessarily with greater safety for the species.

Several studies have shown that, in certain cases, climate change can favor some plant species, expanding the areas considered environmentally suitable for their occurrence. One example of this is the study by Gülçin et al. (2021), which highlighted the likely expansion of potential areas for *Carpinus betulus* in Northern Europe under the new climate conditions. Meanwhile, in China, modeling for *Magnolia officinalis* indicated a significant increase in areas of high and medium suitability by the end of the 21st century, with projected increases of more than 300,000 km² under moderate and pessimistic scenarios (Ren et al. 2025). A similar trend was observed for species of the genus *Epipactis*

(Orchidaceae) in Europe, where future suitability increased in more than half of the species studied, in addition to showing northward latitudinal shifts, accompanying changes in temperature regimes (Evans and Jacquemyn 2022). A similar trend was recorded for three specialist tree species associated with seasonally dry tropical forests (SDTFs) in Brazil, where modeling indicated an increase of approximately 18% in suitable areas by 2080, especially in the Midwestern and Northern regions of the country (Rodrigues et al. 2015).

Meanwhile, the remaining taxa studied, that is, more than half of them, could be impacted in both scenarios. However, more intense and negative impacts on suitable habitats are expected for *M. fistulifera* subsp. *bahiensis*, *O. penduncular*e, *M. heterodoxa*, and *S. jacobinensis*, whose habitats will shrink by more than 45%. Similarly, Suarez-Contento et al. (2024) predicted a decrease in ranges for approximately half of the endemic species of the genus *Manihot* (Euphorbiaceae) in Northeastern Brazil. The authors also observed that most species are found in regions that are extremely fragmented and degraded by human action.

Furthermore, most of these species occur in Chapada Diamantina, Bahia, an area predominantly characterized by rocky fields and Caatinga vegetation. For example, *Microstachys revoluta* is exclusive to the Sincorá mountain range (Esser 1998), and *Stillingia loranthacea* is restricted to the municipality of Morro do Chapéu (Athiê-Souza et al. 2014), while *Microstachys uleana*, in turn, grows from the south to the central portion of the Chapada (Pscheidt 2015). The rocky fields of Chapada Diamantina are high-altitude ecosystems with high endemism and a small continuous area, making them extremely vulnerable to climate change (Bugado et al. 2025). According to Bitencourt et al. (2016), this area will nearly disappear, losing more than 98% of its habitat due to climate change. Furthermore, it is currently highly threatened by deforestation for agricultural activities (Funch et al. 2005, 2008), and between 2019 and 2021 it suffered the loss of more than 100,000 hectares of natural territory (Silva et al. 2023).

According to Evans and Jacquemyn (2022), species with broader niche ranges (generalists) experience greater changes in habitat range in response to climate change than specialists. Similar studies have demonstrated a recurring pattern of reduced areas of climatic suitability for many Brazilian plant species. In the Brazilian semiarid region, *Ceiba glaziovii*, an endemic species of the Caatinga, showed significant losses of climatically suitable range in all scenarios analyzed, with the disappearance of areas of high suitability in more pessimistic scenarios (Almeida et al. 2024). Furthermore, in the Caatinga biome, other endemic cactus species, such as *Brasilicereus phaeacanthus* and *Pereskia aureiflora*, showed significant losses of climatically suitable range, and in future scenarios, these species face considerable challenges in maintaining their current distributions (Simões et al. 2019). Furthermore, in other specific biomes, such as the Cerrado, the genus *Lessingianthus* (Asteraceae), which comprises numerous threatened species, also showed significant reductions in its future distribution ranges in both optimistic and pessimistic scenarios for 2050 and 2070 (Angulo et al. 2021). Thus, these studies highlight both the intrinsic vulnerability of endemic and restricted species and the urgent need for robust conservation strategies, including the expansion of protected areas and the identification of climate refugia, to ensure the maintenance of plant biodiversity in the face of future climate change.

Furthermore, these findings indicate the need to reassess the representativeness of protected areas, prioritizing both species with widespread distributions that are poorly protected and those with restricted distributions, even when currently well protected.

Despite the identification of areas of high biodiversity value in the current scenario, future projections point to a significant reduction in these biodiversity hotspots. Furthermore, analysis of overlap with protected areas also reveals that, although some species may find partial refuge in already protected areas, current coverage is insufficient to ensure the maintenance of most potential habitats in the face of predicted severe climate change. Similar patterns are observed in other regions, indicating that, even with the expansion of protected areas, their capacity to guarantee suitable habitats may prove limited in the face of future climate conditions (Lombo-Sanchez et al. 2025).

In this study, we found that nine taxa are considered within some threat category in both future scenarios, notably *Stillingia loranthacea*, which is restricted to a single municipality and in the projections showed a decline in its area of suitability in both scenarios, in addition to going from the category of Least Concern (LC) to Vulnerable (VU). For the conservation of these taxa to be effective, it is necessary to create new Conservation Units in the areas of greatest richness and diversity, with emphasis on Chapada Diamantina and Sul Baiano, which presented the highest diversity indices, as well as in regions with extremely restricted species, such as *Gradyana franciscana*, as well as areas that are suitable refuges for wider species, such as the fragments of the East Northeast, which present a refuge for *Actinostemon appendicullatus*.

A recent survey of biodiversity protection in Brazil's protected areas, covering vertebrates, arthropods, and angiosperms, indicates that, despite the country's exceptional biological wealth and its status as a global conservation priority, these areas still offer insufficient protection. Many endemic species and lineages remain unprotected, highlighting significant gaps in the coverage and effectiveness of currently established areas (Lopes, 2010).

Although restricted species known only from type material (*Ophthalmoblapton parviflorum*, *Sebastiania trinervia*, and *Gradyana franciscana*) were not included in the distribution modeling, they are likely at high risk of threat due to their microendemism and extremely small populations (Qian & Qian, 2024). Furthermore, they are highly vulnerable to human impact. A striking example is *Gradyana franciscana*, recorded on the banks of the Lower São Francisco River, an area heavily impacted by human activity and subject to intense modifications of the riverside landscape, with consequent alterations to associated ecosystems (Araújo, 2015).

Conclusion

The study of endemic Euphorbioideae taxa in Northeastern Brazil highlights the importance of assessing their potential distribution, vulnerability, and adaptation in the face of climate change. The results, which indicate both gains and losses in suitable areas, reveal the complexity of climate impacts and the need to expand collections and population studies, especially for rare species underrepresented in scientific collections. Furthermore, the current configuration of Protected Areas (PAs) in Northeastern Brazil does not guarantee the conservation of the studied species against future climate change. Therefore, we emphasize the need for conservation strategies to protect biodiversity in Northeastern Brazil's ecosystems.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

All authors contributed to the concept and design of the article. Database compilation and preparation were carried out by J.C.R.M. & T.O. All analyses developed in the study were performed by T.O., K.Y.S.C., Y.J.L.S., and V.R.S.L. with supervision by S.M.A.S. Graphical production of the maps in QGIS was performed by T.O. The scope of this manuscript was written by T.O., A.M.T., and S.M.A.S., and the other authors contributed comments and suggestions throughout the writing process. All authors read and approved the result.

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Figures

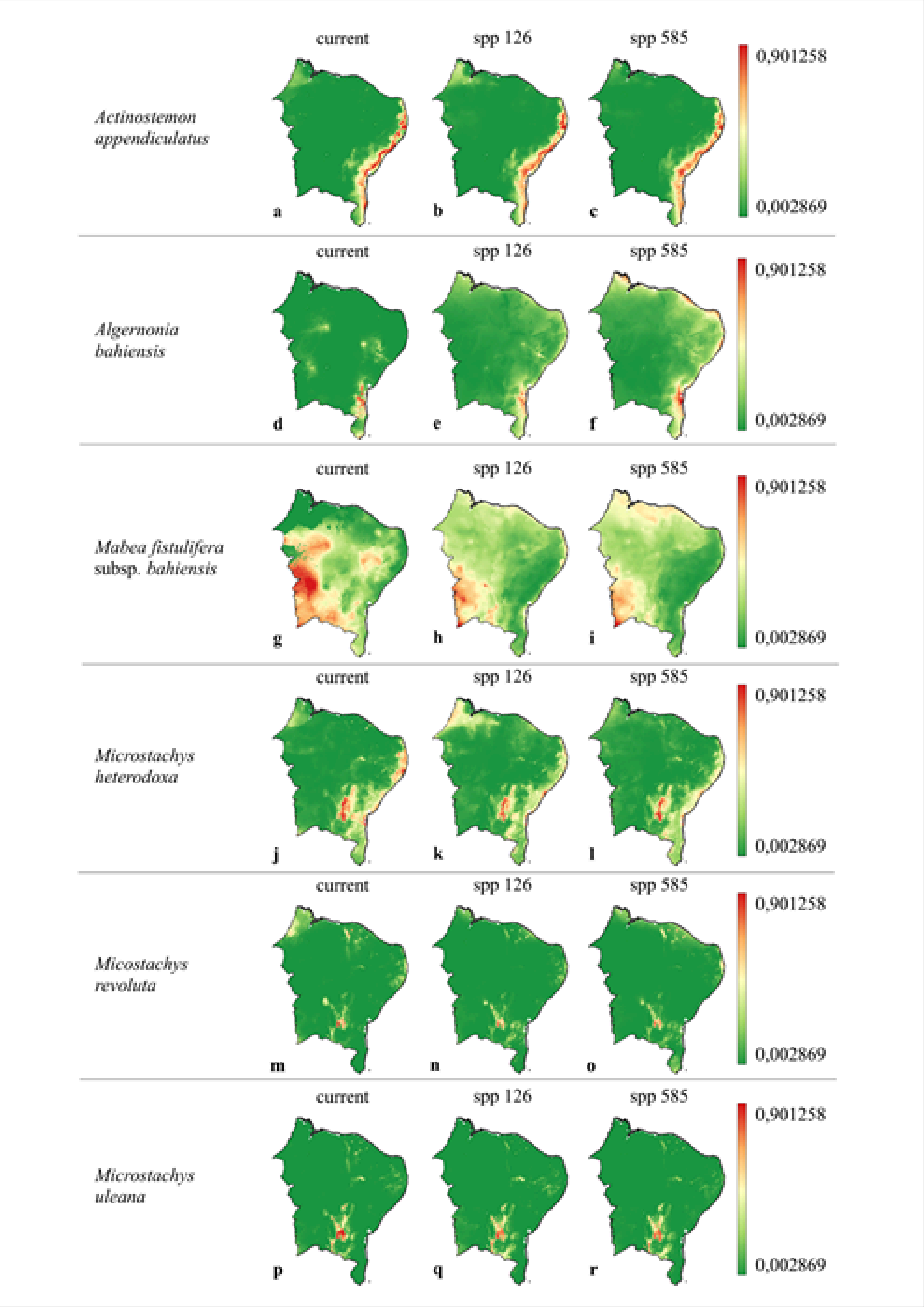

Figure 1

Consensus models of potential distribution for *Actinostemon appendiculatus, Algernonia bahiensis, Mabea fistulifera* subsp.*bahiensis, Microstachys heterodoxa, Microstachys revoluta* and *Microstachys uleana* projected for Northeastern Brazil under three climate scenarios: current (Current), optimistic (SSP126), and pessimistic (SSP585). The color scale represents the climate suitability per pixel, ranging from 0 (light green) to ≥ 0.9 (dark red)

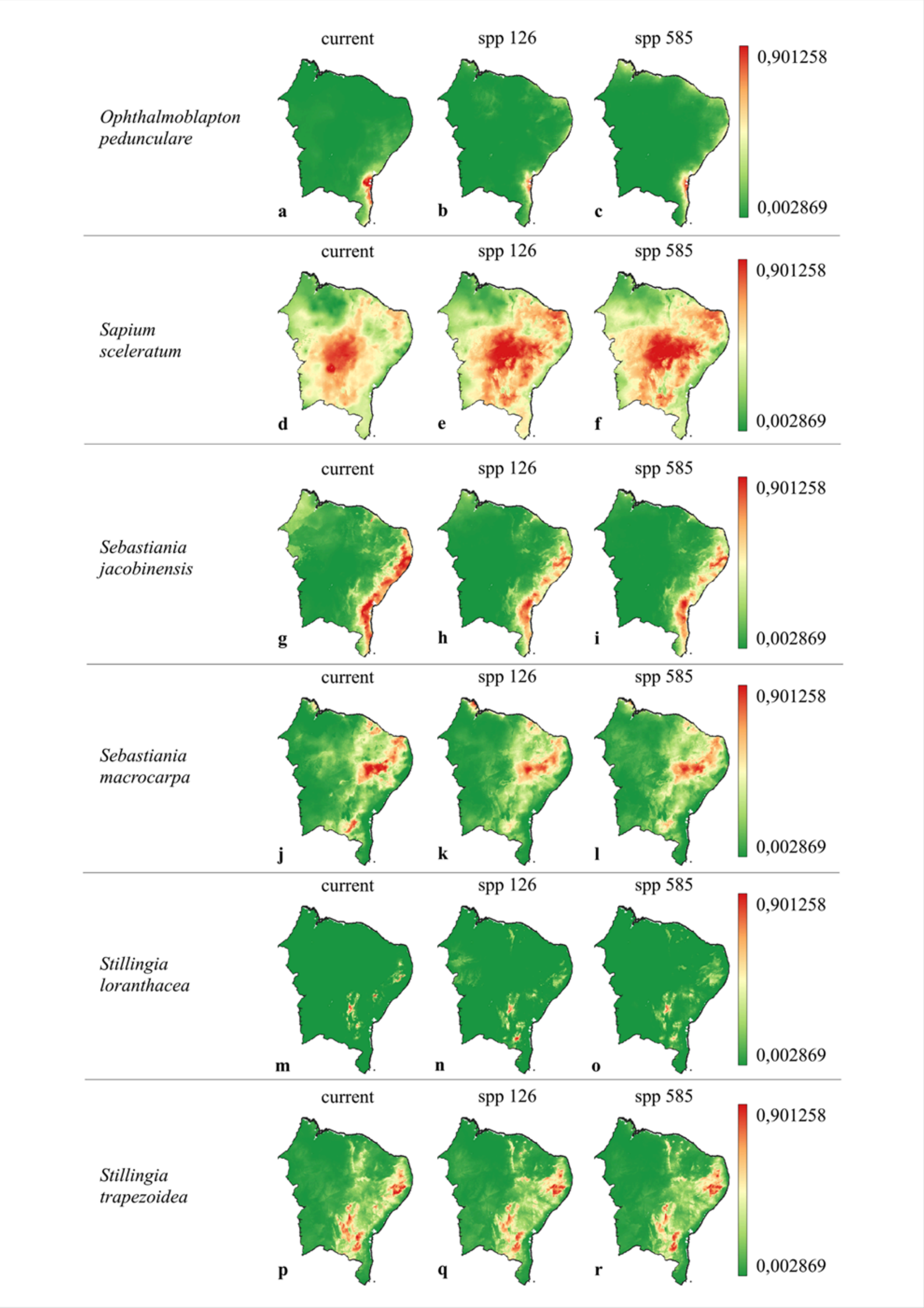

Figure 2

Consensus models of potential distribution of *Ophthalmoblapton pedunculare, Sapium sceleratum, Sebastiania jacobinensis, Sebastiania macrocarpa, Stillingia loranthacea* and *Stillingia trapezoidea* projected for Northeastern Brazil under three climate scenarios: current (Current), optimistic (SSP126), and pessimistic (SSP585). The color scale represents the climate suitability per pixel, ranging from 0 (light green) to ≥ 0.9 (dark red)

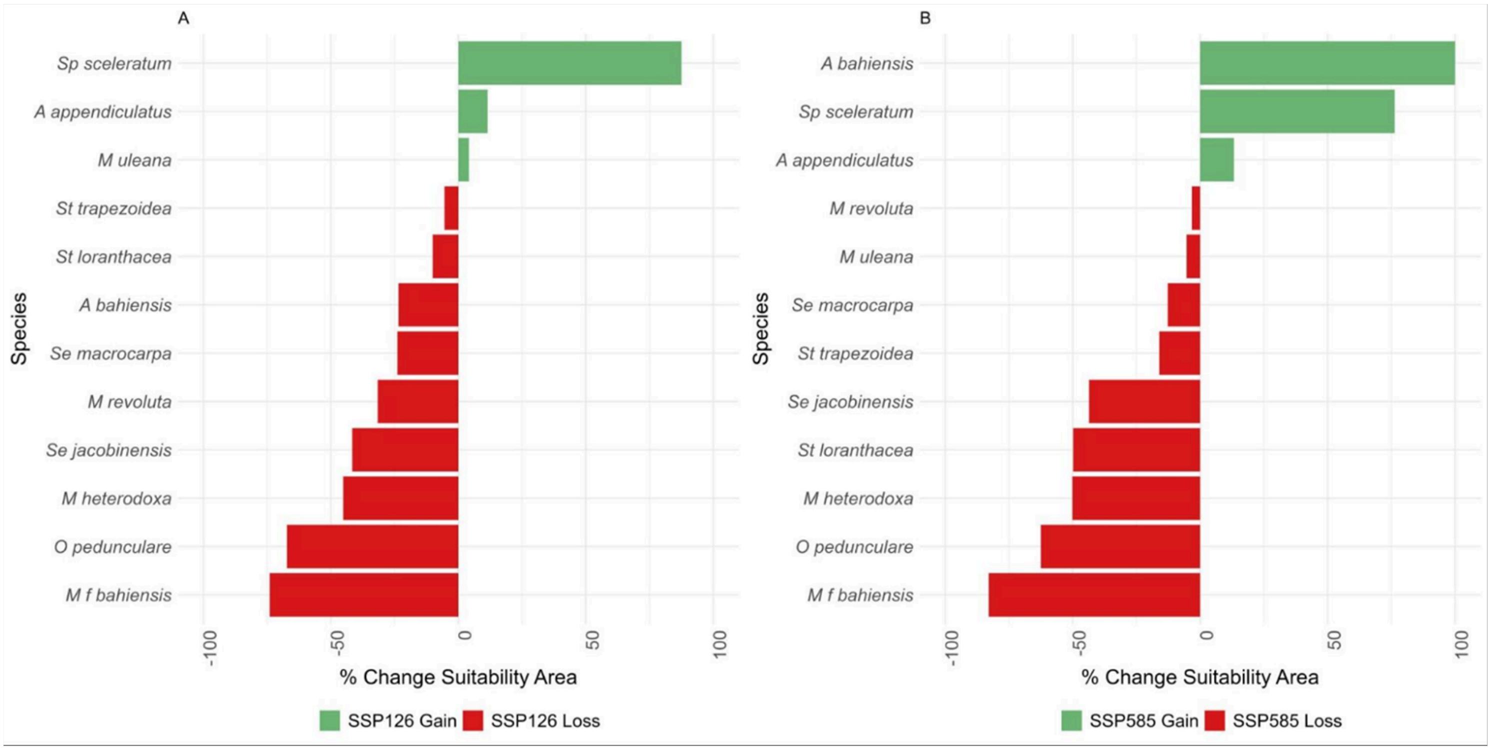

Figure 3

Percentage of loss and gain of environmental suitability area for endemic species under different climate scenarios: A = optimistic (SSP126); B = pessimistic (SSP585)

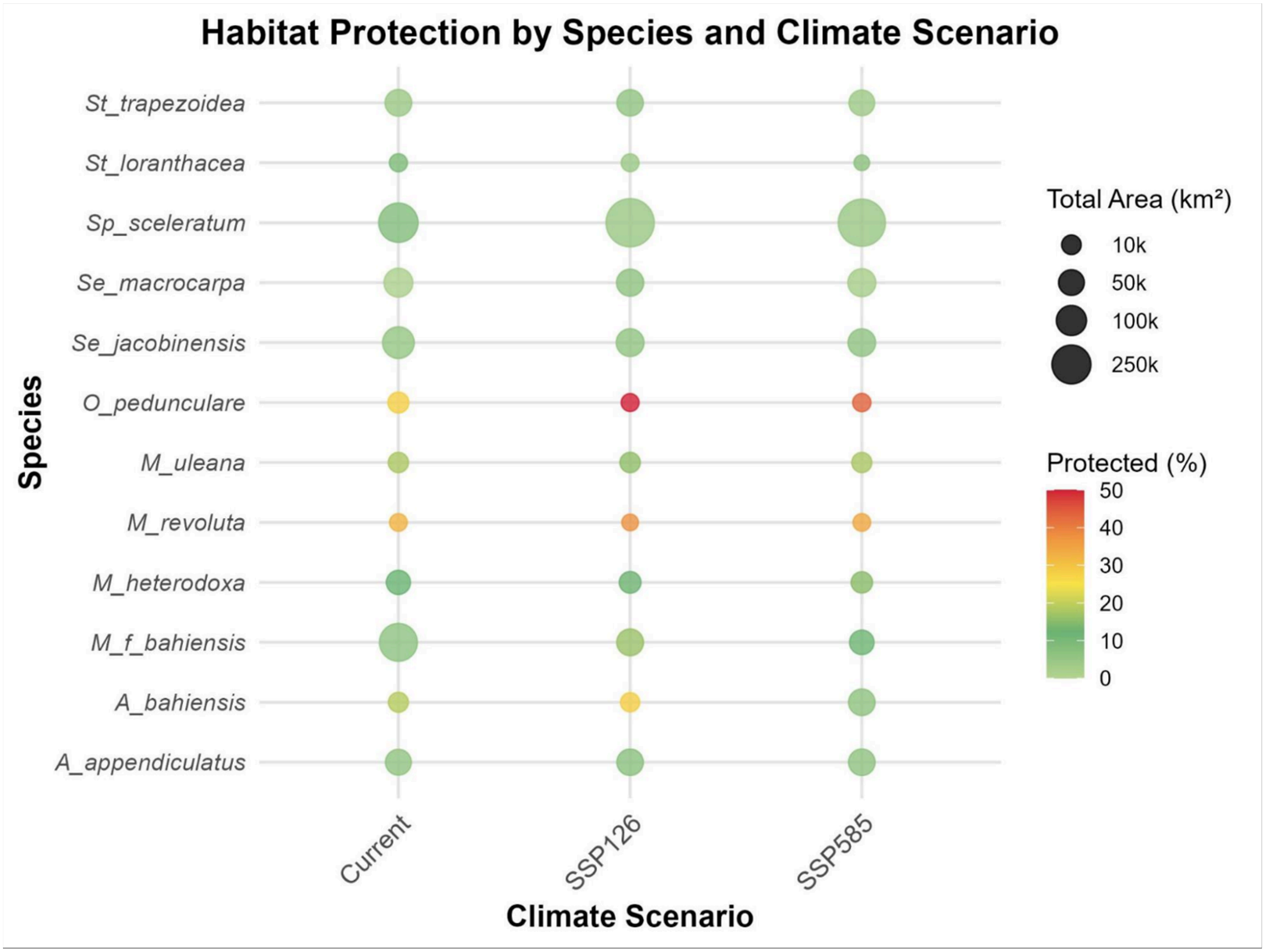

Figure 4

Total area of environmental suitability (represented by the size of the circles) and percentage of overlap with protected areas (color scale) for 12 species under three climate scenarios: current, SSP126 (optimistic), and SSP585 (pessimistic). Red and orange circles indicate a high proportion of protected habitat (above 30%), while green shades represent low protection (less than 20%)

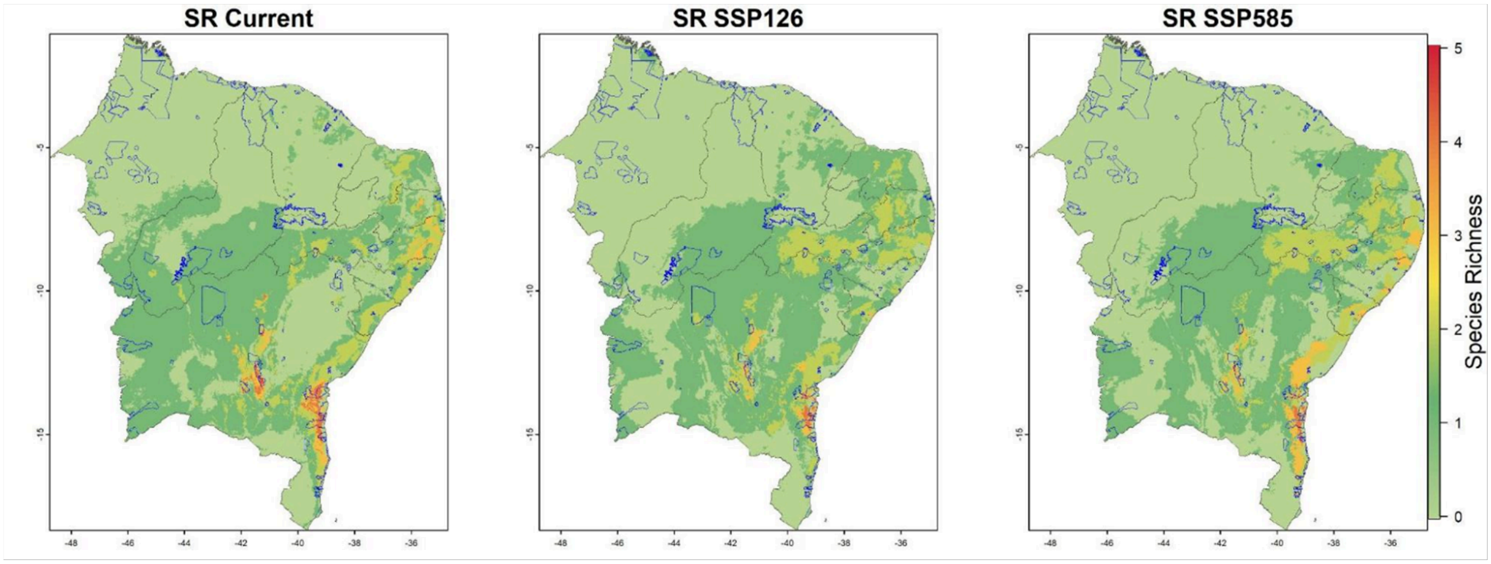

Figure 5

Projected species richness distribution for Northeastern Brazil under three climate scenarios: current (Current), optimistic (SSP126), and pessimistic (SSP585). The color scale represents the number of species (SR) with climatic suitability per pixel, ranging from 0 (light green) to ≥5 (dark red). Blue contours indicate protected areas

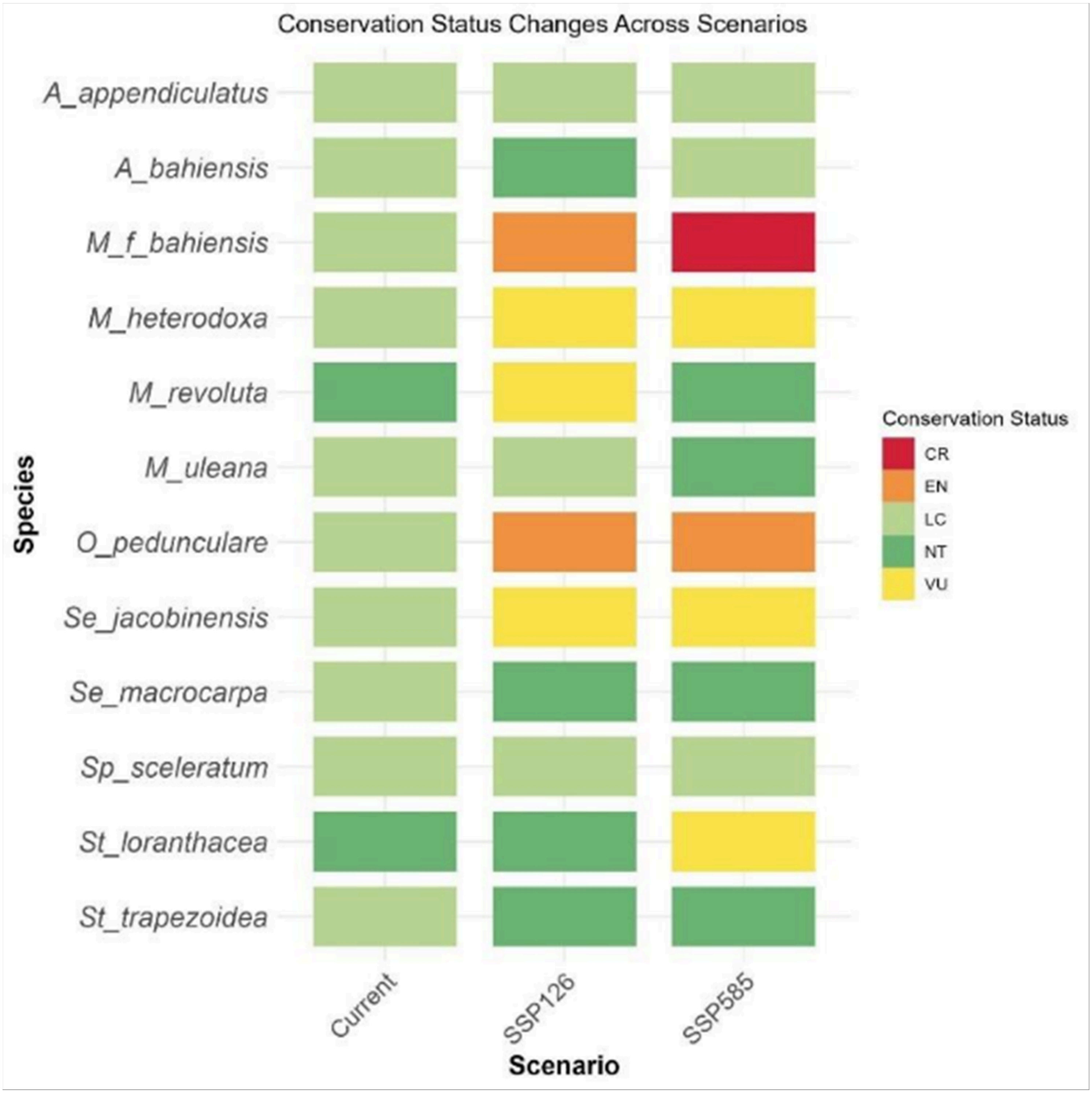

Figure 6

Conservation status projections of 12 endemic species of Northeastern Brazil under the current, optimistic (SSP126) and pessimistic (SSP585) climate scenarios

Supplementary Files

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- Supplementarydata.docx