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CLIMATE CHANGE IS EXPECTED TO REDUCE THE POTENTIAL DISTRIBUTION OF *Ceiba glaziovii* IN CAATINGA, THE LARGEST AREA OF DRY TROPICAL FOREST IN SOUTH AMERICA

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Abstract
Ecological niche modeling is a widely used tool to predict species distribution considering current, past, or future climate change scenarios across different geographic areas. Modeling scenarios allow researchers to assess the impacts of climate change on species distribution and identify priority areas for conservation. This study aimed to model the current and future potential distribution of *Ceiba glaziovii* under different climate change scenarios in Brazil. The MaxEnt algorithm was used to correlate species occurrence points with bioclimatic variables in current and future climate scenarios. Four General Circulation Models (GCMs) from CMIP6 were employed: BCC-CSM2-MR, CNRM-CM6-1, IPSL-CM6A-LR, and MIROC6, considering optimistic and pessimistic projections. The contribution of variables and model accuracy were assessed using the Jackknife statistical test and the Area Under the Curve (AUC) parameter. AUC values for current and future scenarios demonstrated high accuracy. The bioclimatic variables of precipitation and temperature were the main contributors to determining areas with higher habitat suitability. In the future climate scenario, there was a reduction in areas with good climatic suitability for all four GCMs, considering optimistic and pessimistic projections. Among the areas with high habitat suitability, the IPSL-CM6A-1 model in the optimistic projection showed the smallest reduction, while in the pessimistic scenario, all areas with high suitability disappeared. The species' climatic niche is expected to decrease under all tested climate change scenarios. The central areas of the Caatinga and its transition zones exhibit the highest climatic suitability in current and future scenarios and should be prioritized for the species' conservation.

Keywords: Bioclimatic variables. Brazilian semiarid. Caatinga. Ecological niche modeling. Global warming.

1. Introduction

The Caatinga is the main biogeographic dominion in the Northeast region of Brazil and encompasses the largest continuous area of Seasonally Dry Tropical Forests (SDTF) in South America (Moro et al. 2016). Among the SDTF nuclei, the Caatinga stands out for having high species richness, with over 3,300 native species and a high incidence of endemic species, summing over 500 endemics (Queiroz et al. 2017; Fernandes et al. 2020). Due to inappropriate use and predatory exploitation of natural resources, the Caatinga is one of the domains most altered by human activity in Brazil. The native vegetation cover has been reduced to only 11%, with only 4% corresponding to forest cover (Araujo et al. 2023).

Among the factors that have influenced the alteration and reduction of this vegetation are the relatively high population density (~25 inhabitants per km²), indiscriminate deforestation for the establishment of crops, illegal timber trade for firewood and charcoal production, recurring wildfires, overgrazing, and inadequate land use (Pereira Júnior et al. 2014; Althoff et al. 2018).

These practices are responsible for a significant degradation of Caatinga, compromising ecological balance and biodiversity conservation, resulting in the loss of vegetation cover, and interfering with essential ecological processes for ecosystem maintenance. Despite this scenario, only 7.96% of the domain's occurrence area is legally protected, mostly by reserves in the category Environmental Protection Areas (Área de Proteção Ambiental - APA), the category with the smallest legal level of protection. Only 1.3% of Caatinga is protected by reserves under fully protected categories, the ones with larger legal safeguard (Teixeira et al. 2021). Currently, conservation units are considered the cornerstone for biodiversity conservation and maintenance (Gonçalves et al. 2023). Therefore, due to the limited number of conservation units, particularly those with full protection, the vegetation of the Caatinga dominion is exposed to various threats and human pressures.

Human pressures, combined with ongoing climate change, are considered the greatest threat to biodiversity in the 21st century (Anjos and Toledo 2018). Future projections indicate that in future global warming scenarios climate change will cause environmental, social, and economic impacts (Burke et al. 2015). In Brazil, the Caatinga is among the most vulnerable domains (Gonçalves et al. 2023). Predictions indicate increased temperature, reduced precipitation, and aridification (Santos et al. 2014; Cavalcante and Sampaio 2022).

Endemic plant species in the Caatinga are highly vulnerable to climate change and may lose a significant portion of their climatic envelopes because they are deeply adapted to specific environmental conditions (Silva et al. 2019; Simões et al. 2020; Rabelo-Costa et al. 2022). This is because climate strongly influences species occurrence and distribution (Santos et al. 2014; Capo et al. 2022). However, responses to temperature and precipitation changes are not uniform and can vary considerably from one species to another (Leão et al. 2021). The predicted climate changes can alter suitable locations for species development and establishment, leading to a reduction in geographic distribution, significant loss of biodiversity, and disruption of ecological processes responsible for ecosystem functioning (Nabout et al. 2016). Therefore, it is necessary to understand the potential distribution of species in the face of climate change.

Ecological niche modeling has been widely used to predict species distribution in geographic space and time through the development of probability occurrence maps (Lima et al. 2022). These are low-complexity correlational models based on the statistical relationship between species occurrence and local climate, with various applications in ecology and conservation (Phillips and Dudík 2008; Giamminola 2020).

In the current context of climate change, projected scenarios for understanding the ecological niche of species that are well adapted to specific environmental conditions can be used to assess the impacts of climate change on species' potential distribution (Silva et al. 2019), as a basis for identifying priority conservation areas or for targeted species. Given the above, this study aimed to model the current and future potential distribution of the endemic large tree *Ceiba glaziovii* in the scenario of climate change in Brazil.

2. Material and Methods

Target species

Ceiba glaziovii (Kuntze) K. Schum, commonly known as "barriguda" or "paineira-branca," is a forest tree species belonging to the Malvaceae family. The species is endemic to Brazil, being found in the Caatinga dominion in the states of Bahia, Ceará, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe (Figueiredo et al. 2020), occurring in very low densities (Domingos-Melo et al. 2021).

It can be easily recognized by its distinctive trunk with a bulge at mid-height, measuring an average of 1 meter in diameter, giving the idea that the tree has a big 'belly', thus the name 'barriguda' ('big bellied tree') in Portuguese. The light gray bark is covered with a large number of conical prickles, up to 5 centimeters in length. The branches are also provided with rigid spines (Du Bocage and Sales 2002; Nascimento 2012).

The different species of *Ceiba* have economic and ecological importance in different regions of Brazil (Ribeiro et al. 2019). Landscaping and reforestation of degraded areas are recommended due to its fast growth (Nascimento 2012; Araújo et al. 2019). The fibrous structure (wool) that covers the seeds is used as stuffing in the upholstery industry (Nascimento 2012). Additionally, the species is widely used in folk medicine (Pereira Júnior et al. 2014).

Data acquisition

Species occurrence records were obtained from the freely accessible databases SpeciesLink (https://specieslink.net/) and the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/). Initially, duplicate geographic coordinates were removed using ENMTools version 1.4.3 (http://enmtools.blogspot.com/). Subsequently, each record was carefully reviewed individually. This review involved analyzing the data through virtual herbariums and satellite images to identify and exclude records with missing coordinates, discrepant locations, and descriptions of cultivars. After these validation and filtering steps, a total of 138 natural occurrence points for the species were obtained (Figure 1).

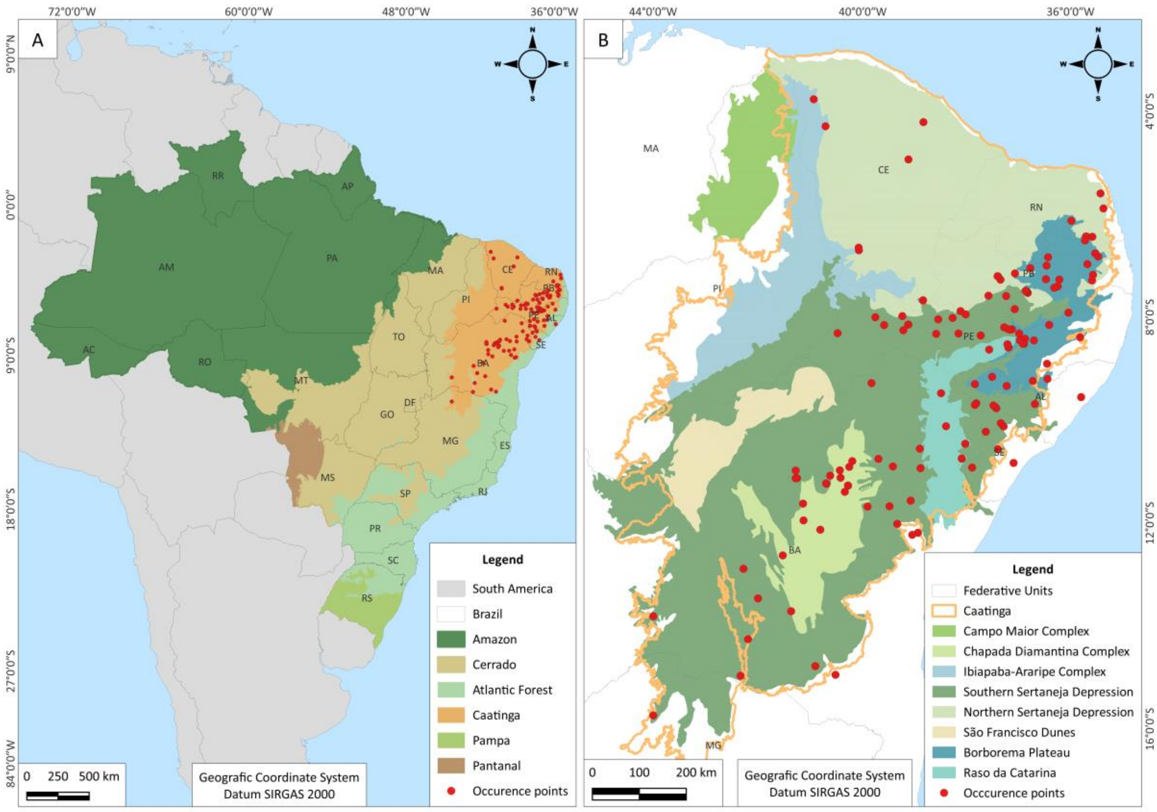

Figure 1. Occurrence points and geographical distribution of *Ceiba glaziovii* in Brazilian states.

The bioclimatic variables for the current scenario (average for the period 1970-2000) and future scenario (average for the periods 2081-2100) were obtained from the WorldClim database version 2.1 (https://www.worldclim.org/), with a spatial resolution of 30 arc-seconds (~1 km). The bioclimatic variables used include: Bio 01 (Annual average temperature), Bio 02 (Average daytime temperature variation), Bio 03 (Isothermality), Bio 04 (Temperature seasonality), Bio 05 (Maximum temperature of the hottest month), Bio 06 (Minimum temperature of the coldest month), Bio 07 (Current thermal amplitude), Bio 08 (Average temperature of the wettest trimester), Bio 09 (Average temperature of the driest trimester), Bio 10 (Average temperature of the hottest trimester), Bio 11 (Average temperature of the coldest trimester), Bio 12 (Annual rainfall), Bio 13 (Rainiest month precipitation), Bio 14 (Precipitation of the driest month), Bio 15 (Precipitation seasonality), Bio 16 (Rainiest quarter rainfall), Bio 17 (Precipitation of the driest trimester), Bio 18 (Precipitation in the hottest trimester), and Bio 19 (Precipitation of the coldest trimester). For the future scenario, four General Circulation Models (GCMs) from CMIP6 were obtained: BCC-CSM2-MR, CNRM-CM6-1, IPSL-CM6A-LR, and MIROC6.

The prediction for the future climate scenario was conducted using two Shared Socioeconomic Pathways (SSPs): SSP1-2.6 and SSP5-8.5. The SSPs are projections of future climate scenarios based on different socioeconomic assumptions, including population growth, technological advancements, and economic development (Lima et al. 2022). The SSP1-2.6 represents an optimistic scenario where global temperature increase ranges from 1.3 to 2.4°C, with an average of 1.8°C. On the other hand, the SSP5-8.5 (2081-2100) represents a high-emission scenario. This scenario assumes that global temperatures continue to rise throughout the 21st century due to the absence of significant climate change mitigation actions. The estimated temperature increases in this scenario ranges from 3.8 to 7.4°C, with an average of 4.4°C (IPCC 2021).

Data processing

The bioclimatic variables were subjected to a Pearson correlation analysis. This procedure is performed to reduce model overfitting (Chagas et al. 2020). The analysis was conducted using the 'ENMTools' and 'raster' packages in R software version 4.2.1. Highly correlated variables ($r \geq 0.70$ or $r \leq -0.70$) were eliminated. This procedure is employed to reduce multicollinearity among the bioclimatic variables and improve the transferability of species distribution models (Cavalcante and Sampaio 2022).

Data analysis

The modeling of the current and future potential distribution of the species was based on the maximum entropy principle (MaxEnt) (Phillips et al. 2006a). MaxEnt software version 3.4.4 was used to model the species distribution (Phillips et al. 2022). MaxEnt estimates species potential distribution using presence-only data and a set of predictor variables (Phillips et al. 2008). It predicts the environmental suitability of the species based on environmental variables (Phillips et al. 2006b). The method is widely used due to its high performance compared to other available algorithms (Lima et al. 2022).

The parameters used in the model construction were a convergence threshold of 1.0E-5 with 500 iterations. The dataset was also subjected to 10 repetitions, and cross-validation was performed for each repetition.

The contribution of each bioclimatic variable was analyzed using the Jackknife statistical test. The accuracy of the models was evaluated by calculating the parameter Area Under the Curve (AUC). This parameter represents the probability that a randomly chosen presence location will be ranked higher than a randomly chosen absence location (Phillips and Dudík 2008). Models with an AUC value below 0.5 are considered worse than random estimation. Random models have an average AUC of 0.5. Perfectly predicted models have an AUC of 1 (Phillips and Dudík 2008). The Jackknife statistical test and AUC were calculated using the post-analysis tools available in the MaxEnt software.

To create the maps of the specie potential distribution, the information obtained from the models generated in MaxEnt was inputted into QGIS software version 3.22. The suitability of the species is visualized using a color gradient. The value of each pixel ranges from 0 to 1. Values that indicate greater environmental suitability are represented by reddish tones, while green tones represent lesser environmental suitability. Subsequently, to assess the impact of the future climate scenario on the species distribution, areas with good and high suitability were quantified for all analyzed climate scenarios.

3. Results

The species had occurrence records in seven states in the Northeastern region and one state in the southeast region (Figure 1). The occurrence records were predominantly found in the states of Pernambuco (40 records, 28.99%), Bahia (38 records, 27.54%), and Paraíba (25 records 18.12%), followed by Sergipe (11 records, 7.97%), Alagoas (10 records, 7.25%), Ceará (8 records, 5.80%), Rio Grande do Norte (5 records, 3.62%), and Minas Gerais (1 record, 0.72%). The states of Pernambuco, Bahia, and Paraíba accounted for 74.65% of the total recorded occurrences for the species.

Of the 19 initial bioclimatic variables, 6 bioclimatic variables were selected to model the distribution of *Ceiba glaziovii*. These were selected because they had correlation smaller than 0.7 (Figure 2). Selected variables were mean annual temperature (Bio 01), mean diurnal temperature range (Bio 02), isothermality (Bio 03), annual precipitation (Bio 12), precipitation of the driest month (Bio 14), and precipitation of the warmest quarter (Bio 18).

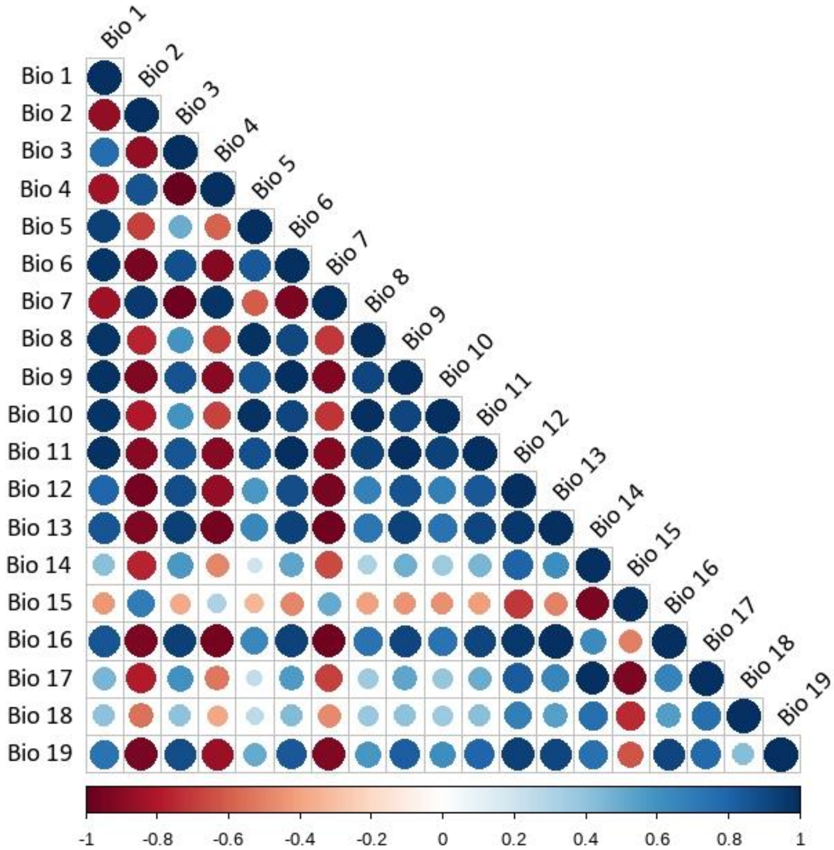

Figure 2. Pearson correlation between bioclimatic variables. The red and blue colors indicate negative and positive correlations, respectively, with the intensity of the colors reflecting the magnitude of the correlation. Significant at the 5% probability level.

In the current scenario (1970-2000), the AUC parameter was 0.973, with a standard deviation of 0.015. The bioclimatic variables with the highest contribution percentage were annual precipitation (Bio 12), mean diurnal temperature range (Bio 02), and precipitation of the warmest quarter (Bio 18). Regarding permutation importance, the most significant variables were annual precipitation (bio12), mean diurnal temperature range (Bio 02), and mean annual temperature (Bio 01) (Table 1).

Table 1. Contribution and permutation importance values of bioclimatic variables for modeling the distribution of *Ceiba glaziovii* species in the current scenario (1970-2000).

Bioclimatic variables	Contribution (%)	Importance for permutation (%)
Bio 01	13.2	8.8
Bio 02	22.3	34
Bio 03	13.6	12.7
Bio 12	34.6	36.4
Bio 14	0.8	0.8
Bio 18	15.5	7.2
AUC	0.973 ± 0.015	

For the future scenario (2081-2100), considering the optimistic projection (SSP-1.2.6), the AUC parameter for the four GCMs used ranged from 0.969 to 0.972, with a standard deviation ranging from 0.013 to 0.022 (Table 2). The lowest value was obtained for the MIROC6 model, while the highest value was obtained for the IPSL-CM6A-LR model. In the BCC-CSM2-MR, CNRM-CM6-1, and IPSL-CM6A-LR models, the bioclimatic variable with the highest percentage of contribution was annual precipitation (Bio 12). However, in the MIROC6 model, the bioclimatic variable with the highest percentage of contribution was the annual mean temperature (Bio 01). Regarding permutation importance, for BCC-CSM2-MR and MIROC6, annual mean temperature (Bio 01) was the most influential bioclimatic variable. In the CNRM-CM6-1 model, annual precipitation (Bio 12) had the highest permutation importance, and in the IPSL-CM6A-LR model, it was the mean diurnal temperature range (Bio 02).

Table 2. Contribution (C), permutation importance (PI), and AUC values of bioclimatic variables for modeling the distribution of *Ceiba glaziovii* species in the future scenario (2081-2100), under the SSP-1.2.6 (optimistic) and SSP-5.8.5 (pessimistic) projection, considering four GCMs.

Scenario	SSP-1.2.6 Optimistic (2081-2100)							
	BCC-CSM2-MR		CNRM-CM6-1		IPSL-CM6A-LR		MIROC6	
Variables	C (%)	PI (%)	C (%)	PI (%)	C (%)	PI (%)	C (%)	PI (%)
Bio 01	21.3	34.9	14.6	14.7	16.4	15.7	32.1	43
Bio 02	5.5	6.6	22.3	26.7	21.4	33.3	14.8	21.4
Bio 03	25.3	18	9.8	15.7	9.7	6.1	7.9	9.3
Bio 12	35.4	11	40.6	29.1	34	21.3	23.3	6.9
Bio 14	1.3	16.5	0.1	1.4	2.7	17	5	17.1
Bio 18	11.3	13	12.7	12.4	15.9	6.7	17	2.2
AUC	0.971 ± 0.018		0.970 ± 0.017		0.972 ± 0.017		0.969 ± 0.022	
Scenario	SSP-5.8.5 Pessimistic (2081-2100)							
	BCC-CSM2-MR		CNRM-CM6-1		IPSL-CM6A-LR		MIROC6	
Variables	C (%)	PI (%)	C (%)	PI (%)	C (%)	PI (%)	C (%)	PI (%)
Bio 01	24.6	54.2	31	42	32.1	40.8	32.1	40.8
Bio 02	2.5	1.9	11.9	15.9	14.8	22.1	14.8	22.1
Bio 03	24.7	19.5	7.3	11.2	7.9	9.5	7.9	9.5
Bio 12	42.4	5.8	26.2	7.3	23.2	8.3	23.2	8.3
Bio 14	1.7	7.5	1.3	9.1	5	15.2	5	15.2
Bio 18	4.2	11.2	22.3	14.6	17	4.1	17	4.1
AUC	0.973 ± 0.013		0.970 ± 0.020		0.969 ± 0.022		0.969 ± 0.022	

For the future scenario (2081-2100), considering the pessimistic projection (SSP-5.8.5), the AUC parameter for the four GCMs used ranged from 0.969 to 0.973, with a standard deviation ranging from 0.013 to 0.022 (Table 2). The lowest values corresponded to the IPSL-CM6A-LR and MIROC6 models. The highest AUC value was obtained for the IPSL-CM6A-LR model in the CNRM-CM6-1, IPSL-CM6A-LR, and MIROC6 models, the bioclimatic variable with the highest contribution and permutation importance was the Annual Mean Temperature (Bio 01). The Annual Precipitation (Bio 12) was the second variable with the highest contribution, and the Diurnal Temperature Range (Bio 02) was the second most important in terms of permutation importance. In the BCC-CSM2-MR model, the Annual Precipitation (Bio 12) had the highest contribution, and the Annual Mean Temperature (Bio 01) had the highest permutation importance, similar to the other models.

Overall, for the current (1970-2000) and future (2081-2100) scenarios, as well as for the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections, the bioclimatic variables related to precipitation and temperature were the ones that contributed the most to determine the areas with higher habitat suitability.

Considering the current scenario, the areas with the highest climatic suitability for the *Ceiba glaziovii* species were found in the states of Rio Grande do Norte (RN), Paraíba (PB), and Pernambuco (PE)

(Figure 2A). In RN, the area of highest climatic suitability predominantly covered the Agreste mesoregion. In PB, it extended across the Agreste and Borborema mesoregions. In PE, it predominated in the Zona da Mata and Agreste regions.

In the future scenario (2081-2100), considering the optimistic projection (SSP-1.2.6), the BCC-CSM2-MR model (Figure 2B), CNRM-CM6-1 model (Figure 2C), IPSL-CM6A-LR model (Figure 2D), and MIROC6 model (Figure 2E) indicate a reduction in areas of higher climatic suitability, which can be observed mainly in RN, PB, and PE. In the IPSL-CM6A-LR model, there is also the emergence of new areas with higher climatic suitability in Sergipe (SE) and Bahia (BA). In SE, they prevail in the Sertão mesoregion, and in BA, in the Centro-Norte and Centro-Sul Baiano mesoregions. In the MIROC6 model, new areas of higher climatic suitability are observed in Alagoas (AL) (Agreste mesoregion) and SE (Sertão mesoregion).

In the pessimistic projection (SSP-5.8.5) of the future scenario (2081-2100), a reduction in areas with high climatic suitability is observed for the four GCMs used (Figure 2F, G, H, and I). In general, this reduction occurs throughout the central area of the Caatinga dominion. In these models, it can be observed that the areas of higher climatic suitability are located in the transition areas between the Caatinga and Atlantic Forest domains, predominantly within the Borborema Plateau ecoregion.

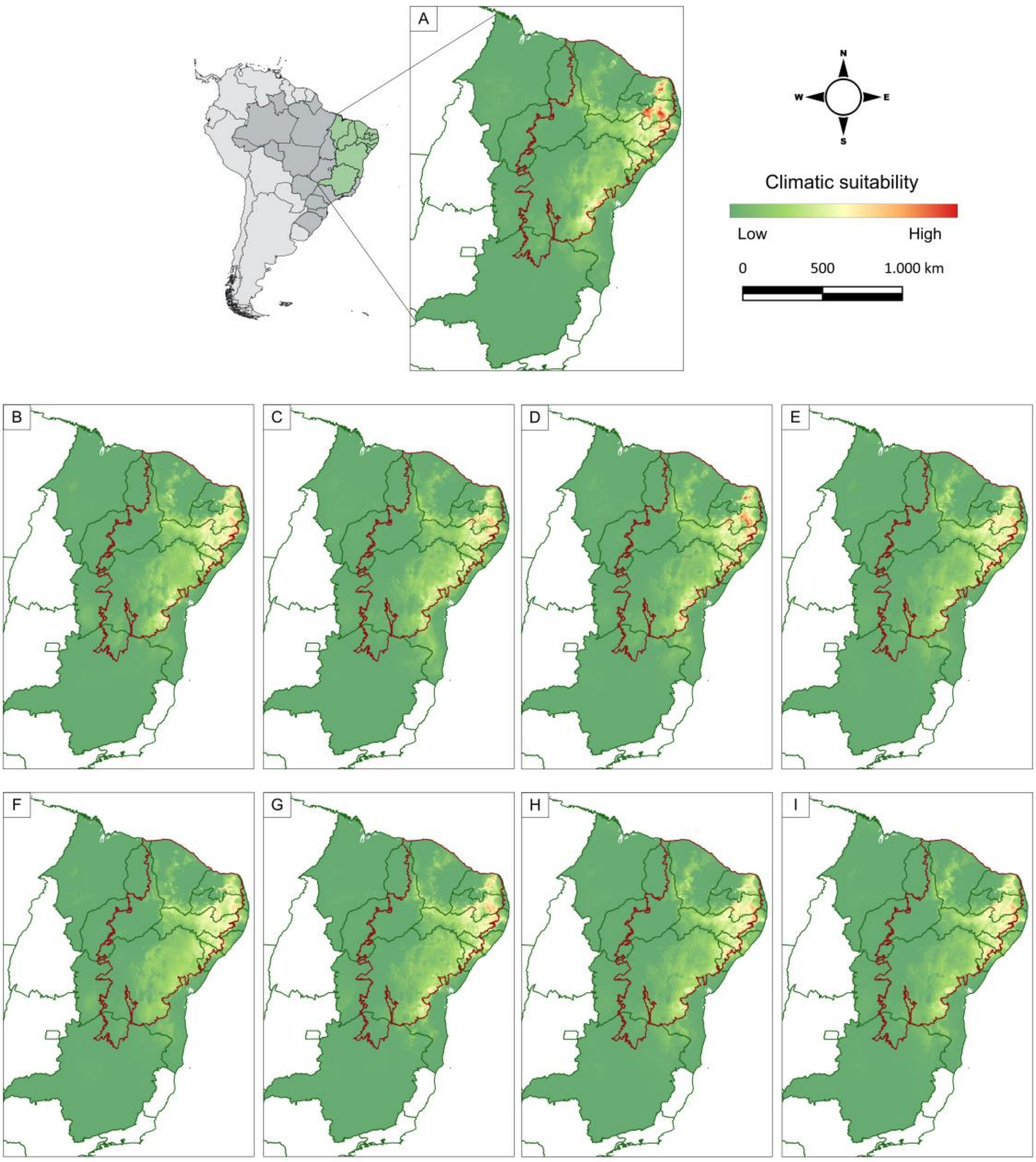

Figure 2. Potential distribution and climate suitability of *Ceiba glaziovii* in current (1970-2000) and future (2081-2100) climate scenarios. Current scenario (A); optimistic future scenario (SSP-1.2.6): BCC-CSM2-MR (B), CNRM-CM6-1 (C), IPSL-CM6A-LR (D) and MIROC6 (E); pessimistic future scenario (SSP-5.8.5): BCC-CSM2-MR (F), CNRM-CM6-1 (G), IPSL-CM6A-LR (H) and MIROC6 (I).

In terms of territorial extent, the current scenario presented total suitable area of 648,412 km^2, of which 14,173 km^2 represents areas with good suitability and 1,087 km^2 represents areas with high climatic suitability for the species. In the future climate scenario (2081-2100), there was a reduction in areas with good climatic suitability for all four GCMs used, considering both the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections (Table 3). The smallest habitat reduction was observed for the IPSL-CM6A-1 model in the optimistic projection (SSP-1.2.6). Meanwhile, the largest reduction was seen for the BCC-CSM2-MR model in the pessimistic projection (SSP-5.8.5). For the other GCMs used, regardless of the future projection, the average reduction in habitat with good suitability was around 60%.

Table 3. Absolute and relative values of areas with good (0.5 - 0.75) and high (> 0.75) suitability in relation to the current climate scenario.

Good suitability			
GMCs	Interval	Future projection	
		SSP-1.2.6	SSP-5.8.5
BCC-CSM2-MR	Area (km^2)	5220	993
	Variation (%)	-63.17	-92.99
CNRM-CM6-1	Area (km^2)	5883	5849
	Variation (%)	-58.49	-58.73
IPSL-CM6A-LR	Area (km^2)	13430	5705
	Variation (%)	-5.24	-59.75
MIROC6	Area (km^2)	5772	5705
	Variation (%)	-59.27	-59.75
High suitability			
GMCs	Interval	Future projection	
		SSP-1.2.6	SSP-5.8.5
BCC-CSM2-MR	Area (km^2)	2	0
	Variation (%)	-99.82	-100
CNRM-CM6-1	Area (km^2)	3	0
	Variation (%)	-99.72	-100
IPSL-CM6A-LR	Area (km^2)	398	0
	Variation (%)	-63.39	-100
MIROC6	Area (km^2)	0	0
	Variation (%)	-100	-100

For the four GCMs used, there was a reduction in areas with high habitat suitability, considering the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections. The smallest reduction in habitat was observed for the IPSL-CM6A-1 model in the optimistic projection (SSP-1.2.6). For the other GCMs used, regardless of the future projection, the average reduction in habitat with high suitability was 100% (Table 3).

Therefore, for the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections of the future scenario (2081-2100), all the GCMs used indicate a reduction in areas with high and good climatic habitat suitability for the species *Ceiba glaziovii*. For the pessimistic projection (SSP-5.8.5) of the future scenario (2081-2100), all areas with high habitat suitability have disappeared.

4. Discussion

Occurrences of the species *Ceiba glaziovii* were predominantly found within the Caatinga dominion. However, records were also found in the Atlantic Forest dominion and transition areas between Caatinga and Atlantic Forest. The states of Maranhão and Piauí, located in the northeastern region of Brazil, were the only ones without records of the species. This absence may be related to the strong influence of the Cerrado and Amazon domains in Maranhão, as well as the intense influence of the Cerrado in Piauí. Additionally, the lack of data in Piauí may be attributed to the scarcity of collections, given the vast areas of Caatinga in the state. As a result, these states are characterized by phytophysiognomies where the species does not naturally occur.

Ceiba glaziovii is an endemic species of Brazil, predominantly found in the northeastern region, with records in the states of Bahia, Ceará, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe (Figueiredo et al. 2020). It is considered a typical species of Seasonally Dry Tropical Forests (FTSS) (Fernandes et al. 2020), occurring naturally in the Hypoxerophytic Caatinga (Agreste) in hilly areas and the Arboreal Caatinga of the Middle São Francisco Valley (Araújo et al. 2019). The species can also occur in transition areas between Caatinga and Mata Atlântica (Nascimento 2012) and the Mata Atlântica dominion (Figueiredo et al. 2020).

In the dry forests of the Caatinga, where the species predominantly occurs, the Malvaceae family is among the families with the highest diversity of flowering species (Fernandes et al. 2020). Species within this family exhibit a high morphological diversity of secretory structures, which have significant ecological and taxonomic importance. Notable examples include mucilage-producing structures, such as glandular trichomes, idioblasts, canals, and cavities, found in reproductive and/or vegetative organs (Pimentel et al. 2011).

Ceiba glaziovii is among the species in this family that has developed adaptations to tolerate dry periods. In addition to displaying typical characteristics of Caatinga species to survive the dry season, such as deciduousness, photosynthetic efficiency, maintenance of leaf metabolism under low water availability through photoprotective mechanisms, and high water use efficiency, the species can store water in the cortical cells of the trunk and utilize it during long periods of drought (Coe and Souza 2014; Santos et al. 2014; Costa et al. 2023). As a result, it has a swollen stem with a protuberance in the middle region, measuring approximately 1 m in diameter (Du Bocage and Sales 2002; Figueiredo et al. 2020).

The most suitable areas for the occurrence of the species are concentrated in the northeast region of Brazil. Ecological niche modeling showed satisfactory adjustments for the four GCMs used, considering the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections. The parameter AUC close to 1 indicates high accuracy in the species distribution modeling. Perfectly predicted models have an AUC of 1 (Phillips and Dudík 2008). Therefore, the generated models showed a high capacity to identify suitable and unsuitable habitats.

In general, the areas of high environmental suitability are in the states north of the São Francisco River (Ceará, Rio Grande do Norte, Paraíba, and Pernambuco), which constitute the so-called "Nordeste Setentrional", with particular emphasis on the Borborema Plateau. According to Araújo et al. (2005), these states exhibit the most characteristic semi-arid climate and likely represent the flora of the Caatinga in the strict sense. The authors emphasize that in addition to having higher aridity, these areas mainly comprise low-altitude crystalline complex terrains. Therefore, the flora of this region occurs predominantly on shallow and rocky soils, with annual rainfall below 800 mm.

The generated models showed that the bioclimatic variables of precipitation and temperature have the greatest influence on the distribution of *Ceiba glaziovii*. This result may indicate a higher sensitivity of the species to variations in precipitation and temperature, particularly because it typically occurs in drier areas.

In the dry forest of the Caatinga, the natural habitat of the species, ecological processes above and below the ground, vegetation structure, as well as the presence or absence of species in specific locations, are influenced by water availability (Allen et al. 2017; Chagas et al. 2020). Temperature also directly affects the maintenance of the structure and function of these ecosystems (Anjos and Toledo 2018).

The reduction and/or disappearance of areas with good or high environmental suitability in future climate scenarios, particularly in the pessimistic projection (SSP-5.8.5), are associated with predictions of increased temperature and altered rainfall patterns, which can lead to severe and prolonged dry season. This climate modification can increase aridity and contribute to the desertification of the Caatinga (Rodrigues et al. 2015).

Allen et al. (2017) emphasize that changes and variability in rainfall patterns can alter vegetative growth patterns, physiology, and phenology. Furthermore, in the long term, droughts can alter community dynamics and species distribution. Therefore, changes in the volume, intensity, and frequency of monthly, quarterly, or annual rainfall can impact the flora of the Caatinga (Cavalcante and Sampaio 2022). Meanwhile, variations in bioclimatic temperature can directly and negatively affect forest resilience (Anjos and Toledo 2018).

As a result, increased aridity is among the main threats to the Caatinga (Santos et al. 2014). Species do not possess adaptations to tolerate this climatic condition. Although the Caatinga has a large number of unique species that are adapted to high temperatures and drought, this strongly xerophytic character demonstrates that the semi-aridness of the region did not originate centuries ago, but probably millions of years ago (Coe and Sousa 2014, Queiroz et al. 2017). This indicates that species have been developing mechanisms and adaptations to tolerate semi-arid conditions over time, with only the most resistant species remaining.

Therefore, increased aridity can cause structural changes in vegetation complexity (Moura et al. 2022). Small-sized species are particularly vulnerable to habitat loss, while widespread species are more resistant and can often benefit from predicted climate changes (Leão et al., 2021). However, both widely distributed species and species with restricted ranges can be affected by climate change (Cavalcante and Sampaio 2022; Lima et al. 2022).

Moura et al. (2022) report that climate change will drastically alter the plant biodiversity of the Caatinga. The authors highlight that approximately 90% of species may lose areas with high habitat suitability by 2060, particularly species with restricted distribution.

Studies have been conducted on the tree species *Aspidosperma pyrifolium* Mart. & Zucc. (pereiro) (Rodrigues et al. 2015), *Anadenanthera colubrina* (Vell.) Brenan (angico) (Giamminola 2020), *Mimosa tenuiflora* (Willd) Poiret (jurema-preta) (Chaves et al. 2020), *Sarcomphalus joazeiro* (Mart.) Hauenschild (Juazeiro) (Lucas et al. 2021), and *Myracrodruon urundeuva* FR. ALL (aroeira) (Capo et al. 2022), which are typical of the Caatinga, to assess their potential distribution in the face of climate change. In general, the authors identified that, for the future climate scenario, considering the pessimistic projection, the areas with high habitat suitability in the Caatinga for these species may reduce or disappear in the future.

The predictions from CMIP6 models suggest extreme climate changes. These changes can lead to a significant reduction in areas with high habitat suitability (Leão et al. 2021). In the pessimistic projection (SSP-5.8.5) of the future scenario (2081-2100) for the four Global Climate Models (GCMs) used, the areas with high habitat suitability for *Ceiba glaziovii* disappeared. For the optimistic projection (SSP-1.2.6), the BCC-CSM2-MR, CNRM-CM6-1, IPSL-CM6A-LR, and MIROC6 models projected a reduction in areas with high habitat suitability. Therefore, avoiding the pessimistic projection (SSP-5.8.5) of the future climate scenario (2081-2100) can be highly beneficial for the conservation of the species.

Modeling the distribution of *Ceiba glaziovii* in the future climate scenario (2081-2100), considering the optimistic (SSP-1.2.6) and pessimistic (SSP-5.8.5) projections, also demonstrates the emergence of new areas with higher habitat suitability. Generally, these are regions that are currently more humid and are expected to become drier in the future climate scenario.

Agostini et al. (2019) emphasize that ecological niche models, due to climate change, show a trend of species migration to regions with milder temperatures. However, according to the authors, these regions may be unsuitable for the establishment and development of these species. This migration can alter community composition and species interactions (Collevatti et al. 2013). Additionally, changes in distribution ranges can lead to population size reduction, threatening the persistence of the species in the environment (Centeno-Alvarado et al. 2022).

Rodrigues et al. (2015) report that areas currently occupied by moist forests and savannas may become more suitable for the occurrence of specialist trees from FTSS (Seasonally Dry Tropical Forests). In contrast, in regions typically occupied by the Caatinga, these specialist trees would likely not tolerate the future level of unsuitability, such as increased aridity.

A similar pattern was observed by Anjos and Toledo (2018), who reported that forests are more vulnerable to climate change than savannas and grasslands. The authors emphasize that the consolidation of non-analogous climate conditions can reduce the resilience of forest ecosystems, significantly increasing the probability of transitioning to a stable state with lower vegetation cover density.

In the optimistic projection (SSP-1.2.6) of the future climate scenario (2081-2100), the IPSL-CM6A-LR and MIROC6 models indicate a reduction in areas with high habitat suitability. However, there is the emergence of new areas with higher habitat suitability for *Ceiba glaziovii*, particularly in transition areas between the Caatinga and the Atlantic Forest.

This result may indicate that despite the species having adaptations to tolerate periods of water stress, the increase in temperature associated with reduced precipitation can modify its ecological niche. Climate change alters geographic ranges, phenology, and biological interactions, which are key components for maintaining the ecological niche (Centeno-Alvarado et al. 2022).

Ceiba glaziovii is a key species in the northeast region of Brazil. Vulnerability to climate change can reduce the areas with good and high habitat suitability for the species. Ecological niche modeling provides a basis for species conservation planning and the expansion and/or designation of priority areas for conservation, as well as ecological corridors. These areas should be defined considering the current and future distribution potential. The results obtained reinforce the need to implement policies for the maintenance of *Ceiba glaziovii* populations, given that the Caatinga is highly susceptible to climate change.

5. Conclusions

The obtained models demonstrated high accuracy in modeling the current and future potential distribution of the species *Ceiba glaziovii*. The bioclimatic variables of precipitation and temperature were the most relevant for these models. In the future climate scenario, it is expected that areas with good and high habitat suitability for the species will reduce or disappear.

The increase in temperature and changes in rainfall patterns in the Caatinga region can modify the ecological niche of the species. Therefore, it is important to consider these factors when planning for its conservation.

The central region of the Caatinga and the transition zones between it and the Atlantic Forest were identified as the areas with the highest climatic suitability in current and future climate scenarios. These areas should be prioritized for the preservation of the species.

The information provided by the potential distribution models highlights the importance of implementing conservation measures and preservation policies to ensure the maintenance of *Ceiba glaziovii* populations, especially in the face of climate change that may affect the Caatinga region.

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