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Research Article

Prediction of geographic distribution and ecological niche modeling of açaí palm trees in the Amazon[1]

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ABSTRACT

Euterpe precatoria Mart. (açaí-do-amazonas) and *Euterpe oleracea* Mart. (açaí-do-pará) are palm trees of socioeconomic importance to Brazil, and fruit demand has increased due to its nutritional characteristics. This study aimed to evaluate the effect of global climate change on the current geographic distribution of *E. precatoria* and *E. oleracea* and in future climate scenarios using the ecological niche modeling in the scope of Brazilian territories. The modelings used 28 environmental variables, including climatic and edaphic data. The current distribution was verified for the reference period (2009-2019) and future projections were evaluated in two scenarios (Shared Socioeconomic Pathways - SSP): SSP 245 (less pessimistic) and SSP 585 (more pessimistic), in the time interval of 2061-2080. All algorithms presented satisfactory evaluation indexes. *Euterpe precatoria* has a predominant geographic distribution in the Amazon domain, while *E. oleracea* has potential occurrence in three Brazilian phytogeographic domains: Amazon, Cerrado and Atlantic Forest. *Euterpe oleracea* showed to be more sensitive to climate change in both scenarios, while *E. precatoria* was more resilient up to a certain level of temperature increase (SSP 245).

KEYWORDS: *Euterpe* ssp., climate change, species distribution modeling.

RESUMO

Predição de distribuição geográfica e modelagem de nicho ecológico de açaizeiros na Amazônia

Euterpe precatoria Mart. (açaí-do-amazonas) e *Euterpe oleracea* Mart. (açaí-do-pará) são palmeiras de importância socioeconômica para o Brasil, e a demanda por frutos vem aumentando devido às suas características nutricionais. Objetivou-se avaliar o efeito das mudanças climáticas globais na distribuição geográfica atual de *E. precatoria* e *E. oleracea* e em cenários climáticos futuros, por meio de modelagem de nicho ecológico, nos âmbitos dos territórios brasileiros. As modelagens foram realizadas utilizando-se 28 variáveis ambientais, incluindo dados climáticos e edáficos. A distribuição atual foi verificada para o período de referência (2009-2019) e as projeções futuras em dois cenários (Shared Socioeconomic Pathways - SSP): SSP 245 (menos pessimista) e SSP 585 (mais pessimista), no intervalo de tempo 2061-2080. Todos os algoritmos apresentaram índices de avaliação satisfatórios. *Euterpe precatoria* possui distribuição geográfica predominante no domínio Amazônia, enquanto *E. oleracea* possui ocorrência potencial em três domínios fitogeográficos brasileiros: Amazônia, Cerrado e Mata Atlântica. *Euterpe oleracea* se mostrou mais sensível às alterações climáticas nos dois cenários, enquanto *E. precatoria* foi mais resiliente até certo nível de aumento de temperatura (SSP 245).

PALAVRAS-CHAVE: *Euterpe* spp., mudanças climáticas, modelagem de distribuição de espécies.

INTRODUCTION

Global climate change has received greater attention and prominence due to the negative impacts it causes on the environment and human life (Almeida et al. 2020). The data presented by the Sixth Climate Change Assessment Report (AR6), prepared by the Intergovernmental Panel on Climate Change - IPCC, show impacts on all continents and oceans (Almeida et al. 2020, IPCC 2021), with increasing frequency of

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extreme events (Silva & Behr 2021). The greenhouse effect due to the emission of gases such as carbon dioxide, methane and nitrous oxide, resulting from natural and mainly anthropogenic activities, has been considered one of the main causes of climate change (Félix et al. 2020).

Anthropogenic activities, especially those related to the burning of fossil fuels and Agriculture, Forestry and Other Land Uses (AFOLU), have caused increases in greenhouse gases in the atmosphere, leading to severe climate change on the planet (Félix et al. 2020). Among the consequences of climate change, it is possible to highlight biodiversity losses, impacts on ecosystems, water resources, and even human mortality, because forest resource-dependent peoples are severely threatened by climate change (Tomaz et al. 2022, Xavier et al. 2022, Cordeiro et al. 2023).

The reduction of forest areas may affect society, especially the people who depend on their resources for subsistence (Tomaz et al. 2022). In addition to forest reduction, the natural distribution of some species may be impaired due to significant increases in temperatures and other extreme weather events. The genetic variability of these species may also be altered, with the reduction of forest areas and the eventual reduction of their populations (Gomes et al. 2022, Tomaz et al. 2022).

Euterpe oleracea Mart. and *Euterpe precatoria* Mart. belong to the Arecaceae family and are popularly known as "açaí-do-pará" and "açaí-do-amazonas", respectively. They are native and preferred species of the Amazon phytogeographic domain and have recognized social, commercial and environmental importance (Silva et al. 2023).

In agroclimatic zoning studies, crops of these species also occur in different areas of the Amazon domain and in other states of the country, such as Espírito Santo, for example (Laurindo et al. 2023), generating a relevant national annual revenue equivalent to 9 billion dollars (Laurindo et al. 2023, Silva et al. 2023).

Studies that point to the need for conservation of species such as *E. oleracea* and *E. precatoria* focus on the development of strategies to mitigate the loss of genetic variability and conservation in future climate scenarios and the species resources (Pan et al. 2022). In this sense, the ecological niche modeling is one of the main tools used to delimit and analyze the adaptation and conservation of plant species (Tomaz et al. 2022). Thus, this study aimed to present models for the natural distribution of *E. oleracea* and *E. precatoria* in the present and future scenarios of climate change using bioclimatic and edaphic variables through ecological niche modeling.

MATERIAL AND METHODS

The geographic coordinates of the occurrence points of *E. precatoria* and *E. oleracea* were compiled at the Universidade Federal do Amazonas, in 2023, from open-access databases as the Reference Center for Environmental Information (CRIA 2020) and Global Biodiversity Information Facility (GBIF 2023), physical and virtual herbaria as the Reflora (2023), as well as scientific articles available in the literature. All occurrences were restricted to the Brazilian territory. This procedure was carried out using the geographic information system (GIS) in the ArcMap software (Esri 2011).

A total of 712 points of occurrence of *E. precatoria* and 872 points of occurrence of *E. oleracea* were obtained, using the tidyverse package (Wickham 2017, RStudio Team 2023), which helped in the removal of possible errors and inconsistencies in relation to the current distribution area as points in duplicate, incorrect and/or absent coordinates. After the point consistency analysis process through the collinearity analysis, there was a reduction of 87.5 % of the points of presence, leaving 89 and 109 points qualified for use in the modeling process for *E. precatoria* and *E. oleracea*, respectively (Figure 1).

Reducing the autocorrelation in species occurrence data can eliminate possible sampling bias. Furthermore, points of occurrences that were closer than a 5 km radius were excluded. Regarding the area of occurrence, *E. precatoria* presented a predominance of points in the Amazonian phytogeographic domain (Figure 1), with higher occurrence in the Amazonas, Acre, Rondônia and Mato Grosso states.

The analyses were performed with the use of 28 environmental variables provided by the WorldClim project version 2.1, with spatial resolution of 1 km² for the period 1970-2000 (Fick & Hijmans 2017), of which 19 were bioclimatic variables: Bio1: average annual temperature (ºC); Bio2: monthly average of daily temperature variation (maximum - minimum temperature) (ºC); Bio3: isothermality [(Bio2/Bio7) * 100]; Bio4: temperature

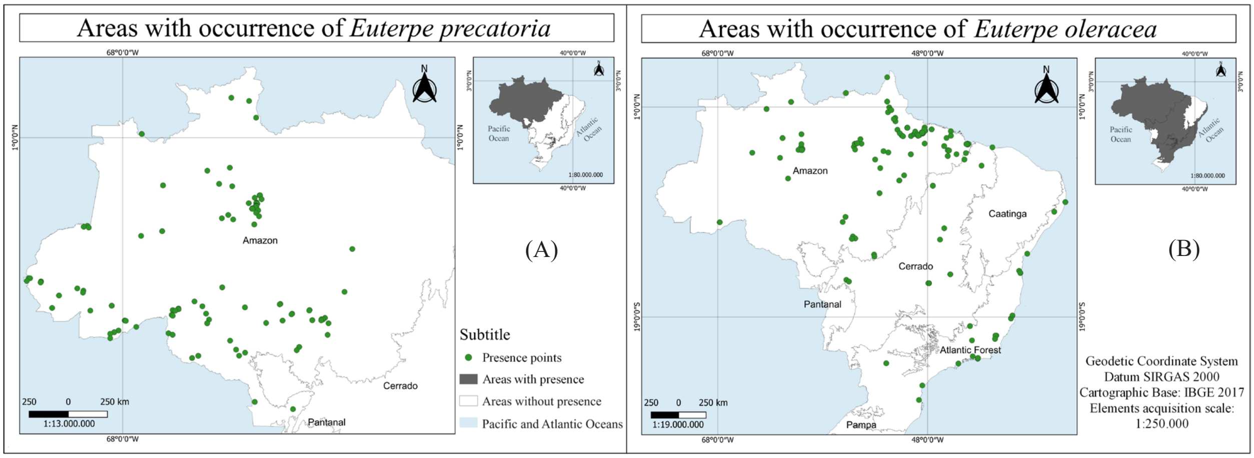

Figure 1. Areas of occurrence after collinearity analysis and current distance (2022) for *Euterpe precatoria* (A) and *E. oleracea* (B).

seasonality (standard deviation * 100); Bio5: maximum temperature in the hottest month (ºC); Bio6: minimum temperature in the coldest month (ºC); Bio7: annual temperature variation (Bio5 - Bio6) (ºC); Bio8: average temperature in the wettest quarter (ºC); Bio9: average temperature in the driest quarter (ºC); Bio 10: average temperature in the hottest quarter (ºC); Bio 11: average temperature in the coldest quarter (ºC); Bio 12: rainfall accumulated in the year (mm); Bio 13: rainfall accumulated in the wettest month (mm); Bio 14: rainfall accumulated in the driest month (mm); Bio 15: rainfall seasonality (coefficient of variation); Bio 16: rainfall accumulated in the wettest quarter (mm); Bio 17: rainfall accumulated in the driest quarter (mm); Bio 18: rainfall accumulated in the hottest quarter (mm); and Bio 19: rainfall accumulated in the coldest quarter (mm).

Nine of them were soil variables: bulk density (g cm^{-3}), clay content (%), coarse fragments (%), sand content (%), silt content (%), organic carbon content (g kg^{-1}), pH in H_2O, cationic exchange capacity ($cmol_c$ kg^{-1}) and expected probability of occurrence of the horizon, which were represented for two soil depths (0-20 and 20-40 cm) (FAO 2023). This data is available in the Harmonized World Soil Database with a spatial resolution of 1 km² (30 seconds) (version 2.0; FAO 2023). The soil variables were used to improve the ecological niche modeling, since soil attributes interfere with the development of plant species (Alvarez et al. 2022). The spatial resolution of these variables was the same as that used for the climate data.

For the collinearity analysis and identification of the contribution of each variable, the Principal Component Analysis (PCA) was performed by the R Environment (R Development Core Team 2023) and its complement, RStudio Team (2023). Among the principal components (PC) generated in the PCA, the first six were used in the species modeling process, which together represented about 97 % of the total data variability. The axes that best explained the variation were observed in the first and second PC, representing 56 and 19 % of the total variability of the database, respectively. Among the most expressive values for PC are those related to rainfall and temperature.

For the modeling process, the ENMTML package (Andrade et al. 2020) was used, in the R Environment (R Development Core Team 2023), for the periods 2009-2019 and 2061-2080, in scenarios (Shared Socioeconomic Pathways - SSP) SSP 245 (less pessimistic) and SSP 585 (more pessimistic). The distribution of the species was modeled to the Brazilian territory based on the Terra Brasilis platform of the National Institute of Space Research (Brasil 2022).

The following algorithms were tested: Bioclim - BIO (Xu & Hutchinson 2013), Domain - DOM (Carpenter et al. 1993), Maximum Entropy - MXS (Anderson & Gonzalez Júnior 2011), Random Forests - RDF (Prasad et al. 2006) and Support Vector Machine - SVF (Prasad et al. 2006), in order to find the one with the best predictive quality. As there is no consensus on the ideal evaluation index for the algorithms, five indexes were selected: Area Under the Curve (AUC) (Fielding & Bell 1997), Kappa, True Skill Statistics (TSS), Sorensen (Leroy et al. 2018) and Jaccard (Leroy et al. 2018). The value 1.0 indicates a perfect discrimination and values lower than 0.5 denote a poor modeling performance. Models with values greater than 0.7 in all metrics are considered satisfactory (Leroy et al. 2018).

For the modeling of the projections in the future scenarios (2061-2080) of *E. precatoria* and *E. oleracea*, the projections of the Sixth Evaluation Report of the Intergovernmental Panel on Climate Change (AR6/IPCC) (IPCC 2021) were considered. Three atmospheric circulation models were selected: HadGEM-GC31-LL, IPSL-CM6Ä-LR (Firpo et al. 2022) and MIROC6 (Monteverde et al. 2022), two of which were obtained together to increase the accuracy of the model (Dormann et al. 2018, Borges et al. 2023). The consensus models are formed by binary maps with pixel values of 0 and 1, where 0 (blue areas) corresponds to locations considered environmentally inappropriate and 1 (red areas) to regions with appropriate environmental conditions for the species (Figure 2).

The decades between 2061 and 2080 were considered for two scenarios: SSP 245, in which it is assumed that actions will be taken to mitigate greenhouse gas emissions in the atmosphere, and SSP 585, in which it is considered that no measures will be adopted to mitigate these effects (IPCC 2021).

RESULTS AND DISCUSSION

The three most important climatic variables (with higher eigenvector values) were present in the PC1 and were related to air temperature: minimum temperature in the coldest month: Bio6 (PC1: -0.2940); average temperature in the coldest quarter: Bio11 (PC1: -0.2858); and average temperature in the driest quarter: Bio9 (PC1: 0.2765). In the PC2, the most representative variables were related to rainfall: rainfall accumulated in the driest month: Bio14 (PC2: 0.3955); rainfall accumulated in the driest quarter: Bio17 (PC2: 0.3949). In the PC3, the most representative variable was rainfall seasonality: Bio15 (PC3: -0.4061) (Table 1).

The five tested algorithms showed satisfactory values (higher than 0.7) in all evaluation indexes for both species of açaí (Table 2). The RDF algorithm presented the best metrics considering all evaluation

Table 1. Eigenvector values of the six main components used in the modeling process.

Variables	Principal component (PC)					
	PC1	PC2	PC3	PC4	PC5	PC6
Bio1	-0.2707	-0.2257	0.1302	-0.0462	0.0612	0.0022
Bio2	0.1767	-0.2413	0.1159	0.4889	-0.1291	0.5284
Bio3	-0.2378	-0.0120	-0.3183	0.1014	0.2300	0.5198
Bio4	0.2489	0.0078	0.3866	-0.0643	-0.2282	-0.0908
Bio5	-0.1927	-0.3193	0.3409	-0.0384	-0.1331	0.0694
Bio6	-0.2940	-0.1193	-0.0036	-0.1567	0.0890	-0.0169
Bio7	0.2492	-0.1248	0.3247	0.1931	-0.2547	0.0897
Bio8	-0.2334	-0.2547	0.2325	0.0629	0.1127	-0.0032
Bio9	-0.2765	-0.1545	-0.0162	-0.1722	0.0048	0.0252
Bio10	-0.2304	-0.2633	0.3052	-0,1006	-0.0318	-0.0260
Bio11	-0.2858	-0.1827	0.0033	-0.0302	0.1026	0.0274
Bio12	-0.2630	0.2206	0.0386	0.1832	-0.1994	-0.0609
Bio13	-0.2692	0.0792	-0.1161	0.2335	-0.3329	-0.2086
Bio14	-0.1442	0.3955	0.2416	0.0341	0.1130	0.3041
Bio15	0.0331	-0.3381	-0.4061	0.3321	-0.1420	0.0019
Bio16	-0.2698	0.0876	-0.1038	0.2389	-0.3300	-0.2091
Bio17	-0.1551	0.3949	0.2323	0.0355	0.0830	0.2766
Bio18	-0.1602	0.1883	0.2022	0.5774	0.3222	-0.3318
Bio19	-0.1991	0.2068	-0.0761	-0.2126	-0.5974	0.2389

Bio1: average annual temperature (ºC); Bio2: average monthly daily temperature variation (ºC); Bio3: isothermality; Bio4: seasonality of temperature; Bio5: maximum temperature in the hottest month (ºC); Bio6: minimum temperature in the coldest month (ºC); Bio7: annual temperature change (ºC); Bio8: average temperature in the wettest quarter (ºC); Bio9: average temperature in the driest quarter (ºC); Bio10: average temperature in the hottest quarter (ºC); Bio11: average temperature in the coldest quarter (ºC); Bio12: rainfall accumulated in the year (mm); Bio13: rainfall accumulated in the wettest month (mm); Bio14: rainfall accumulated in the driest month (mm); Bio15: rainfall seasonality; Bio16: rainfall accumulated in the wettest quarter (mm); Bio17: rainfall accumulated in the driest quarter (mm); Bio18: rainfall accumulated in the hottest quarter (mm); Bio19: rainfall accumulated in the coldest quarter (mm).

Table 2. Indicator variables and standard deviation for validation of five models for the prediction of the potential area of occurrence of *Euterpe precatoria* and *E. oleracea.*

Algorithms	*Euterpe precatoria*					*Euterpe oleracea*				
	BIO	DOM	MXS	RDF	SVM	BIO	DOM	MXS	RDF	SVM
AUC	0.93 ± 0.06	0.94 ± 0.02	0.97 ± 0.02	0.98 ± 0.01	0.98 ± 0.01	0.93 ± 0.05	0.98 ± 0.01	0.96 ± 0.02	0.99 ± 0.01	0.99 ± 0.01
Kappa	0.86 ± 0.13	0.75 ± 0.05	0.89 ± 0.04	0.91 ± 0.07	0.90 ± 0.02	0.86 ± 0.10	0.92 ± 0.05	0.81 ± 0.06	0.95 ± 0.06	0.94 ± 0.03
TSS	0.86 ± 0.13	0.75 ± 0.05	0.89 ± 0.04	0.91 ± 0.07	0.90 ± 0.02	0.86 ± 0.10	0.92 ± 0.05	0.81 ± 0.06	0.95 ± 0.06	0.94 ± 0.03
Jaccard	0.86 ± 0.13	0.80 ± 0.03	0.89 ± 0.03	0.92 ± 0.06	0.90 ± 0.02	0.86 ± 0.10	0.92 ± 0.05	0.83 ± 0.05	0.96 ± 0.05	0.94 ± 0.02
Sorensen	0.92 ± 0.08	0.89 ± 0.02	0.94 ± 0.02	0.96 ± 0.03	0.95 ± 0.01	0.92 ± 0.06	0.96 ± 0.03	0.91 ± 0.03	0.98 ± 0.01	0.97 ± 0.03

BIO: Bioclim; DOM: domain; MXS: maximum entropy simple; RDF: random forest; SVM: support vector machine; AUC: area under the curve; TSS: true skill statistics.

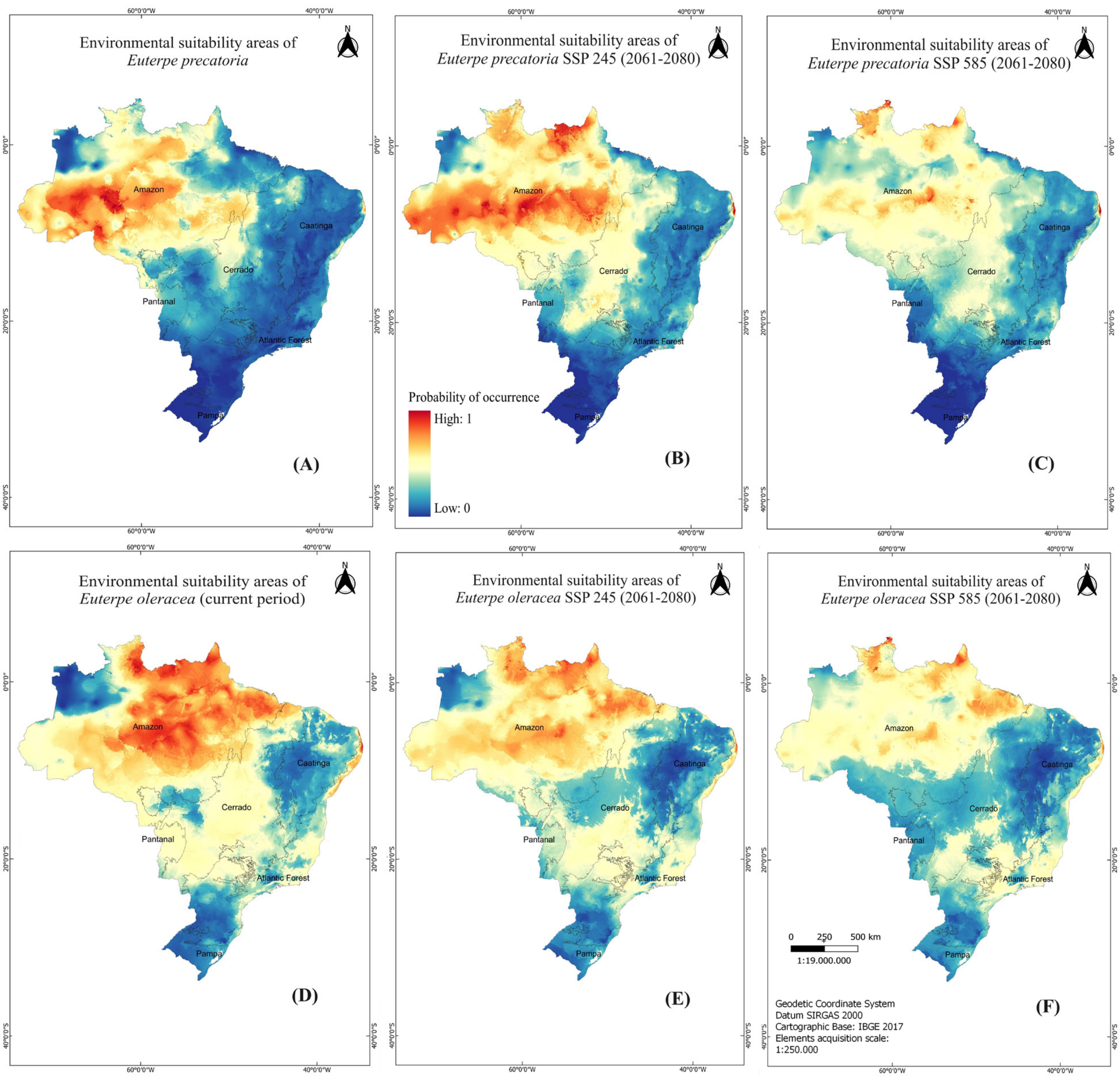

Figure 2. Maps of environmental suitability: present period (A and D); more optimistic future scenario (SSP 245; B and E); and more pessimistic future scenario (SSP 585; C and F) for the *Euterpe precatoria* and *E. oleracea* species.

indexes for both species. For *E. precatoria*, the DOM algorithm, except for the AUC evaluation, presented the lowest values, but was still considered higher. For *E. oleracea*, the MXS algorithm presented the lowest values, but within the acceptable value of 0.7, corroborated by the low values of the standard deviation (Table 2).

In the current scenario, the Amazon has a higher probability of occurrence of *E. precatoria* (Figure 2A), corroborating the map of points of occurrence (Figure 1A). This area has an extension of 3,309,481.70 km². For the less pessimistic future scenario SSP 245, it is possible to observe an increase in areas of climate adaptation in the Amazon and Cerrado (Figure 2B). It was also observed that the species had a higher probability of occurrence in a wide range of the central region of Brazil, indicating that, in the most positive scenario, the species could expand.

The most pessimistic scenario (SSP 585; Figure 2C) shows a reduction in the area with the highest probability of occurrence of *E. precatoria*. This scenario indicates that there is an increase in its occurrence; however, the probability of occurrence is low. It also considers that if there are no public policies to mitigate climate effects, higher temperatures may cause a reduction in the *E. precatoria* populations. It can also be observed that there was no significant expansion of *E. precatoria* to other domains, increasing the threat of extinction and reducing the genetic variability of the remaining populations.

The distribution maps of current occurrences show that *E. oleracea* presents a more comprehensive distribution regarding the Brazilian phytogeographic domains, when compared to *E. precatoria* (Figure 2D). Thus, it currently occupies 88 % of the phytogeographic domain of the Amazon, with an area of 3,705,476.75 km², approximately 12 % larger than the area with the highest probability of occurrence of *E. precatoria* in this same phytogeographic domain. In addition, the climate adequacy region is also in this phytogeographic domain (Figure 2D).

The areas with the highest probability of occurrence of *E. oleracea* occupy the entire length of the Pará and Amapá states, in addition to the central region of the Amazonas and a part further east of the Amapá. In the future more optimistic scenario SSP 245, there was an evident reduction in the probability of occurrence of *E. oleracea* in all domains (Figure 2E). In this scenario, part of the Cerrado region was pointed out as not favorable for the distribution of the species. The reduction of the area with fitness is even more pronounced in the SSP 585 scenario (Figure 2F). Considering the evident increase in temperature and the failure to adopt actions to reduce the emission of greenhouse gases, the greatest probability of occurrence of *E. oleracea* may be in small regions of the Amazon domain, and a greater reduction in the suitable environmental area for the species may occur in the Cerrado domain.

In the SSP 245 scenario in the Pantanal domain, there was a notable loss of areas (99.07 %) with climatic adequacy and probability of occurrence of *E. precatoria* (Table 3). Conversely, the Cerrado, Caatinga, Atlantic Forest and Amazon domains presented the highest values of area expansion, corresponding to 162.95, 149.46, 146.77 and

Table 3. Area values in the current period (2022), SSP 245 (less pessimistic) and SSP 585 (more pessimistic) (2061-2080) scenarios, with their respective percentages of area gain and loss (-) for *Euterpe precatoria* and *E. oleracea*.

Species	Phytogeographic domain	Current period (km²)	SSP 245 (km²)	Area (%)	SSP 585 (km²)	Area (%)
Euterpe precatoria	Amazon	3,309,481.70	3,787,889.97	14.46	2,701,197.58	-18.38
	Caatinga	2,645.28	6,598.89	149.46	1,081.16	-59.13
	Cerrado	401,085.95	1,054,647.43	162,95	419,967.57	4.71
	Atlantic Forest	19,831.29	48,937.76	146.77	16,245.24	-18.08
	Pampa	0	0	0	0	0
	Pantanal	9,073.37	83.95	-99.07	143.96	-98.41
Euterpe oleracea	Amazônia	3,705,476.75	3,646,971.11	-1.58	3,010,012.91	-18.77
	Caatinga	86,975.52	28,476.61	-67.26	9,098.33	-89.54
	Cerrado	1,558,739.37	1,039,383.80	-33.32	356,964.10	-77.10
	Atlantic Forest	479,323.27	502,059.34	4.74	337,755.01	-29.54
	Pampa	0	0	0	0	0
	Pantanal	145,735.04	78,559.34	-46.09	0	-100.00

14.46 %, respectively. In the SSP 585 scenario (more pessimistic), only the Cerrado domain presented a gain in area, with an increase of 4.71 %, in relation to the current period. The largest area reduction is observed in the Pantanal (-98.41 %) and Caatinga (-59.13 %) domains. The Amazon and Atlantic Forest domains presented similar percentages of area loss to the current model, with values of 18.38 and 18.08 %, respectively (Table 2). It is important to note that the points of occurrence identified outside the center of origin of the species, in this case, are in the phytogeographic domain of the Amazon. It is possible then infer the occurrence of populations or individuals of *E. precatoria* that can be cultivated or naturally occur. Thus, there is a current agronomic suitability for species outside their domain of origin; however, most of them do not refer to the natural occurrence of the species.

For *E. oleracea* in the SSP 245 scenario only the Atlantic Forest domain showed an increase in climate adequacy (4.74 %), if compared to the current period. In the Amazon domain, despite showing a remarkable reduction in the probability of occurrence in absolute values, this retraction was only 1.58 % in area extension. Comparing the Caatinga domain to the current period, the greatest area reduction (-67.26 %) was observed. The Pampa domain did not present values of area and climatic adequacy in any of the scenarios for the two species. In the SSP 585 scenario, all domains presented a reduction in area, reaching 100 % in the Pantanal domain. The Caatinga, Cerrado and Atlantic Forest domains showed reductions of -89.54, -77.10 and -29.54 %, respectively. In the Amazon domain, a decrease of -18.77 % was anticipated, which is comparable to that observed for *E. precatoria* (18.38 %) in the same scenario. The values of area reduction for the *E. oleracea* species were higher when compared to *E. precatoria*, indicating that this species can be more sensitive to changes in climate.

Climate change may directly affect the distribution of the species under study, leading to the retraction of the areas of occurrence in the Brazilian phytogeographic domains (Lima et al. 2022). Studies on climate change considering native species (Gomes et al. 2022, Tomaz et al. 2022, Cordeiro et al. 2023) show a significant decline in the SSP 585 scenario between 2061 and 2080. The results of this study reinforce this hypothesis, given that significant reductions were foreseen in the SSP 585 scenario in areas with environmental suitability that were present for both species, reaching 100 % for *E. oleracea* in the Pantanal.

Temperature may increase by up to 5.7 ºC in the SSP 585 scenario, when compared to the base period of 1850-1900 (IPCC 2021). These temperature changes may alter the pattern of rainfall distribution, as well as generate heat waves and droughts that may become more frequent and severe in the Amazon rainforest (Amaral et al. 2023). The *E. oleracea* species is highly dependent on moisture and conditions in its natural distribution to regions of soils with higher water availability (Souza et al. 2018), such as those found in floodplain areas in the Amazon domain. These factors may explain the high percentage of reduction in *E. oleracea* areas verified in the Caatinga, Cerrado and Atlantic Forest domains, and, consequently, the lower percentage in the Amazon biome in the SSP 585 scenario.

In the SSP 585 scenario, the projection of *E. oleracea* distribution was significantly affected. The successful response of a species to climate change depends on the frequency and magnitude of exposure, sensitivity (survival, resilience and performance) and ability to cope with change (Dawson et al. 2011).

In the Amazon, restrictions are foreseen in the potential areas of the central and northern portions of the Amazon domain, restricting the two species of study in forest fragments. The processes of habitat fragmentation and anthropogenic activities affect geographic distribution, restricting gene flow, and consequently reducing the rate of climate adaptation to levels below those required by climate change (Woodward et al. 2010).

Some isolation barriers prevent hybridization, among them the ecological reproductive isolation (Cordeiro et al. 2023). According to Yuyama et al. (2011), *E. oleracea* populations are predominantly distributed in lowland and *E. precatoria* areas. This habitat preference may reduce the frequency of hybridization zones between these species, a factor reinforced by the maps of environmental suitability in the present period (Figures 2A and 2D), in which it is possible to observe the highest occurrence of *E. precatoria* in the eastern Amazon and *E. oleracea* further north.

Changes in the landscape and environment may favor the contact among species that occupy contrasting environments (Santana et al. 2022).

With the possibility of species tracking areas of greater environmental suitability, this increases the probability of interspecific hybridization among closely correlated taxa (Cordeiro et al. 2023). Thus, the ability of forest species to adapt to habitat changes is essential for long-term permanence. Gene flow, through hybridization between two distinct gene pools, can generate genetic variations necessary to adapt to the selective pressures of the environment (Janes & Hamilton 2017).

Another aggravating factor is the strong burning that affects the edges of the Amazon in the southern, southeastern and eastern portions. According to the Annual Report on Deforestation in Brazil (Santana et al. 2022), in 2021 the Amazon and the Cerrado together corresponded to 89.2 % of the total deforested area, with the Amazon facing a total of 977,733 ha (59 %) and the Cerrado 500,537 ha (30.2 %) of deforestation. This strip of land is known as the "Arc of Deforestation" and has a great anthropic intervention action, due to the expansion of agricultural areas in the Amazon. The current models point to an almost total absence of potential areas for *E. precatoria* and *E. oleracea* in portions that encompass the Arch, which currently extends in the Pará, Tocantins, Mato Grosso and Rondônia states.

The Pantanal presented the highest percentage of area loss for both species in the two scenarios (SSP 245 and SSP 585). By analyzing this information, it is possible to conclude that advances in deforestation rates may reflect in a future scenario even more worrying than that observed in the current modeling. This fact is due to the intense expansion of agricultural areas and the conversion of areas into pastures in the domain (Abdo et al. 2024).

Vaz & Nabout (2016) found areas of climatic adequacy associated with regions with high yield of *E. oleracea* by examining climate niche models and suggested that such regions be considered when delimiting said conservation areas. Consequently, additional Arecaceae species may also be impacted by climate change, such as palm trees of the *Astrocaryum* genus, such as *A. aculeatum* Mart. and *A. acaule* Mart. (Cordeiro et al. 2023). Although it was observed that the areas of occurrence between them were very similar, *A. aculeatum* was more sensitive to climatic variations. *Astrocaryum acaule* demonstrated a greater resilience to changes in climate, when compared to the models generated, and would be able to recolonize the southern portion of the Amazon in future scenarios by the year 2070.

Due to the socioeconomic importance that palm species have for Brazil, and knowing the behavior of these species in face of global climate change, based on studies developed over the years, the future prediction of palm trees has become a relevant management strategy to ensure the conservation and maintenance of native populations in the Brazilian phytogeographic domains. Thus, the natural populations of açaí located in the domains most sensitive to climate change should be prioritized for their conservation *in situ* and *ex-situ*, thus ensuring the maintenance of the genetic variability of species in the long term.

CONCLUSIONS

1. According to the projected distribution models, *Euterpe oleracea* maintains most of the eastern Amazon occupation area, while *E. precatoria* would occupy the western Amazon and present coincidence of occurrence mainly in the central Amazon, which should be regarded as a region of naturally occurring interspecific hybridization and generation of genetic variability for the evolution and conservation of the Amazon açaí palm trees;
2. The Amazon açaí palm trees present risks of loss of adaptation area in future scenarios, with *E. precatoria* showing a greater rusticity in resistance to future scenarios and adaptability, when compared to *E. oleracea*;
3. The loss of areas with environmental suitability for the occurrence of *E. oleracea* and *E. precatoria* in the SSP 585 (more pessimistic) scenario were intense in all Brazilian phytogeographic domains.

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