PREDICTION OF THE GEOGRAPHIC DISTRIBUTION AND CONSERVATION OF AMAZONIAN PALM TREES *Astrocaryum acaule* MART. AND *Astrocaryum aculeatum* MART.

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[1] Received on 13.09.2022 accepted for publication on 25.07.2023.
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ABSTRACT – *Astrocaryum aculeatum* Mart. Moreover, *Astrocaryum acaule* Mart. are palm trees with ecological and extractive importance in the Amazon. These are hearty species that have been associated with archaeological sites and thrive in the presence of humans in certain areas. This work aimed to verify the effect of global climate change on the potential geographic distribution of *A. acaule* and *A. aculeatum* in the current period and future climate scenarios using ecological niche modeling in Brazilian phytogeographic domains. The modeling was based on 19 bioclimatic variables obtained from the *Worldclim* website and four algorithms (Climate space model, Envelope Score, Niche Mosaic, and *Environmental Distance*). Additionally, the *Environmental Distance* algorithm showed greater similarity regarding species distribution with potential occurrence in the five Brazilian domains (Amazon, Pantanal, Caatinga, Cerrado, and Atlantic Forest). The dispersion patterns were very similar between the two *Astrocaryum* palms though *A. aculeatum* was more sensitive to climatic variations. *A. acaule* may be more resilient to changes, as demonstrated by being able to recolonize in the southern portion of the Amazon in future scenarios in the year 2070. The modeling helped to delimit potential areas for *A. aculeatum* and *A. acaule*, indicating the need for the conservation of the species in more sensitive regions.

Keywords: Climate niche modeling; Climate change; Vulnerability of plant species.

PREDIÇÃO DA DISTRIBUIÇÃO GEOGRÁFICA E CONSERVAÇÃO DAS PALMEIRAS AMAZÔNICAS Astrocaryum acaule *MART. E* Astrocaryum aculeatum *MART.*

RESUMO – ***Astrocaryum aculeatum*** *Mart. e* ***Astrocaryum acaule*** *Mart. são palmeiras que apresentam importância ecológica e para o extrativismo na Amazônia. São espécies rústicas e que foram associadas a sítios arqueológicos e à presença de humanos em determinadas áreas. O objetivo deste trabalho foi verificar o efeito das mudanças climáticas globais na distribuição geográfica potencial de* ***A. acaule*** *e* ***A. aculeatum****, no período atual e em cenários climáticos futuros, utilizando a modelagem de nicho ecológico nos domínios fitogeográficos brasileiros. As modelagens foram baseadas em 19 variáveis bioclimáticas, obtidas no site do* ***Worldclim****, e quatro algoritmos (Climate space model, Envelope Score, Niche Mosaic e Enviromental Distance), dos quais o algoritmo* ***Environmental Distance*** *apresentou maior similaridade quanto à distribuição das espécies com* *ocorrência potencial nos cinco domínios brasileiros (Amazônia, Pantanal, Caatinga, Cerrado e Mata Atlântica). Os padrões de dispersão foram muito similares entre as duas palmeiras de* ***Astrocaryum****, porém A. aculeatum é mais sensível às variações climáticas.* ***A. acaule*** *tem potencial para ser mais resiliente às mudanças, podendo recolonizar a porção sul da Amazônia em cenários futuros, no ano de 2070. A modelagem auxiliou a delimitar as áreas potenciais de* ***A. aculeatum*** *e* ***A. acaule****, indicando a necessidade de conservação das espécies em regiões mais sensíveis.*

Palavras-Chave: Modelagem de nicho ecológico; Mudanças climáticas; Vulnerabilidade de espécies vegetais.

1. INTRODUCTION

The repercussions of global temperature fluctuations pose significant economic risks, due in large part to the limited resilience of species to withstand extreme abiotic conditions. These conditions notably include increases in local temperature, shifts in precipitation frequency, and elevated CO_2 levels that affect photosynthesis. In tropical forests, these climatic variables can have a profound impact on the distribution, life cycles, biological interactions, and human extractive practices (Menezes-Silva et al., 2019; Freitas et al., 2021; Forzieri et al., 2022).

Archaeological sites that exhibit evidence of human presence frequently feature palm trees as indicator species (Junqueira et al., 2010). Species that have been domesticated and utilized by both contemporary and ancient communities often belong to the genus *Astrocaryum* (Junqueira et al., 2010). *Astrocaryum* is a genus known for its role in facilitating the recolonization and natural succession of areas influenced by anthropization (Gomes et al., 2011; Ramos et al., 2016; Patrício et al., 2020). Species within this genus are both wild and resilient, making them ideal subjects for studies on the effects of climate change in the Amazon rainforest ecosystem. *Astrocaryum acaule* Mart. and *Astrocaryum aculeatum* Mart. are commonly observed in both natural and spontaneously occurring populations, with the latter species showing particular associations with areas affected by human influence (Schroth et al., 2004).

Astrocaryum aculeatum, commonly known as "tucumã-do-Amazonas," is a valued fruit tree species in the northern region of Brazil. The pulp of its fruits is widely used in culinary applications, making it a primary target for extractive practices, especially in secondary forests. Conversely, *Astrocaryum acaule*, or "tucumã-i," produces small fruits that, while edible, have seeds that are predominantly utilized in the crafting of bio-jewelry, such as rings. Additionally, the leaves of *A. acaule* serve as a source of fibers for producing natural textiles in the Amazon region (Gomes et al., 2011).

Phylogenetic evidence suggests a close relationship between *A. aculeatum* and *A. acaule*, both of which belong to the same subgroup within the *Astrocaryum* genus (Roncal et al., 2015). Considering the sexual reproduction and gene flow processes of these species (Ramos et al., 2016), as well as their sympatric occurrences, it is plausible to identify areas with a high likelihood of natural interspecific hybridization. Such hybridization contributes to generating genetic variability (Turchetto et al., 2015). Subsequent ecological niche research is expected to shed light on how climate change may impact the common areas of occurrence for these species and the genetic diversity within their natural populations.

Research on forest vulnerability and the effective adaptation of species to forest ecosystems has been identified as a priority area (Lecina-Diaz et al., 2021; Roshani et al., 2022). One key approach to studying vulnerability to climate change is through ecological niche modeling. This methodology focuses on delineating the potential distribution ranges of specific species based on climatic variables and occurrence data. It serves multiple roles within the fields of ecology and biogeography, including predicting the impacts of global warming, inferring the distribution areas of target species, and informing conservation strategies (Tomaz et al., 2022; Gomes et al., 2022). Such modeling can be particularly useful for projecting the geographic distribution of species in the Amazonian Forest, relying on climatic predictor variables for its assessments (Tomaz et al., 2022).

The primary objective of this study is to rigorously examine the potential impacts of global environmental changes on the geographic distribution of *Astrocaryum acaule* and *Astrocaryum aculeatum*, specifically under projected future climate scenarios. To provide a robust analysis, we utilized ecological niche modeling techniques, focusing on vital Brazilian phytogeographic domains. This endeavor aims to contribute valuable insights into adaptive strategies and conservation planning, thereby enhancing our understanding of species resilience in the face of ongoing climate alterations.

2. MATERIAL AND METHODS

Data for *Astrocaryum aculeatum* and *Astrocaryum acaule* were collected in 2021 from the Remote Sensing Laboratory of Embrapa Florestas (Brazilian Agricultural Research Corporation), utilizing open-access databases. Occurrence points for both species were extracted from a range of sources, including publications available at the Reference Center for Environmental Information (CRIA, 2019), accessible via the website (http://splink.cria.org.br), as well as the Herbarium Virtual Reflora (Reflora, 2021). Additional data were obtained from a review of geographical coordinates presented in scientific articles relevant to these species and published in the academic literature. An integrated analysis of this geographic information yielded 125 occurrence points for A. acaule and 144 for A. aculeatum within Brazilian territory.

The scope of this data collection is confined to Brazilian phytogeographic domains. Coordinates indicating presence in other countries, as well as outliers, inverted coordinates, and data not congruent with the established natural distribution patterns for these species, were systematically excluded from the dataset.

For the predictive modeling of species occurrence, 19 bioclimatic variables were selected, including metrics for both temperature in degrees Celsius (°C) and precipitation in millimeters (mm), as outlined by Wrege et al. (2017). These variables consist of Bio1 for annual average temperature, Bio2 for the monthly average of daily temperature variation (maximum temperature minus minimum temperature), Bio3 for isothermality calculated as (Bio2/Bio7) multiplied by 100, and Bio4 for temperature seasonality expressed as the standard deviation multiplied by 100. Further variables include Bio5 for the maximum temperature in the hottest month and Bio6 for the minimum temperature in the coldest month. Bio7 represents the annual temperature range, calculated as Bio5 minus Bio6. Bio8 is the average temperature in the wettest quarter, Bio9 in the driest quarter, Bio10 in the hottest quarter, and Bio11 in the coldest quarter. Precipitation variables include Bio12 for total annual precipitation, Bio13 for precipitation in the wettest month, Bio14 for precipitation in the driest month, and Bio15 for precipitation seasonality, measured as the coefficient of variation. Additionally, Bio16 represents precipitation in the wettest quarter, Bio17 in the driest quarter, Bio18 in the hottest quarter, and Bio19 in the coldest quarter. These variables were obtained from the *Worldclim* website (www.worldclim.org), as per studies by Hijmans et al. (2005) and Kumar and Stohlgren (2009).

Based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), three key scenarios were identified: 1) a more pessimistic scenario with no maintenance or control of greenhouse gas (GHG) emissions, referred to as RCP 8.5; 2) a scenario with lower emissions; and 3) a less pessimistic scenario, known as RCP 4.5 (Nakicenovic et al., 2000). Principal Coordinates Analysis (PCA) was carried out using the R programming language (R Development Core Team, 2021) supplemented by RStudio (RStudio Team, 2019) to ascertain the contributions of individual variables.

Upon conducting the principal component analyses on the 19 climatic variables, it was determined that six variables accounted for the majority of the variation, constituting 97.5% of the first eigenvectors in the PCA. These variables were consequently used in the modeling of the two species. The axes best explaining the observed variation were the first and second Principal Components (PC), which represented 47.3% and 20.2% of the total variability in the dataset, respectively. The climate variables exhibiting the highest eigenvector values, and therefore deemed most significant, included Bio4 (temperature seasonality, measured as the standard deviation multiplied by 100), Bio13 (cumulative rainfall in the wettest month, measured in mm), and Bio17 (cumulative rainfall in the driest quarter, also in mm). The PCA was executed using RStudio (RStudio Team, 2019).

The predictive modeling for future species occurrence was conducted using Open Modeller software (http://openmodeller.cria.org.br/). Four algorithms were evaluated for predicting geographic distribution: *Climate Space Model*, *Envelope Score*, *Niche Mosaic*, and *Environmental Distance*. The quality of the fitted models was assessed by calculating the *Area Under the Curve* (AUC). All distribution maps were generated using the ArcGIS software, with an approximate spatial resolution of 1 km^2, equivalent to 30" at the equator.

3. RESULTS

All employed models—*Climate Space Model*, *Envelope Score*, *Niche Mosaic*, and *Environmental Distance*—demonstrated significant effects in ecological niche modeling ($p < 0.001$). Specifically, the *Envelope Score* model for *A. acaule* and the *Environmental Distance model* for *A. aculeatum* were selected due to their perfect Area Under the Curve (*AUC*) scores of 1.00. The remaining models yielded *AUC* values ranging from 0.64 to 0.88 for *A. acaule* and between 0.72 and 0.85 for *A. aculeatum*.

3.1 Climate modeling for *Astrocaryum acaule*

Following the organization of data and the removal of duplicate coordinates and outliers, a matrix comprising 35 occurrence points was generated. This matrix had a utilization efficiency of 28% for A. acaule (Figure 1A). In terms of species distribution, potential habitats for *A. acaule* were identified in the Amazon, Cerrado, and Caatinga domains (Figure 1B).

Future climate scenario projections indicated a decrease in suitable areas for *Astrocaryum acaule* under both RCP 4.5 and RCP 8.5 scenarios across the assessed periods (2020-2050 and 2051-2070). Particularly, the RCP 4.5 scenario predicted more substantial losses of potential habitats in the eastern, central, northern, and southwestern parts of the Amazon (Figures 1C and 1D) compared to the baseline (Figure 1B). The modeling also revealed the existence of small forest refuges in the Xingú River basin for the 2020-2050 period, with a considerable reduction projected for the years 2051-2070.

Under the RCP 8.5 scenario, there is projected to be a severe contraction in potential habitats across all current domains of occurrence for *A. acaule*. This will be accompanied by intensified colonization in the coastal areas of the Atlantic Forest, Caatinga, and Cerrado regions (Figures 1E and 1F), relative to the present-day distribution (Figure 1B). Interestingly, a recovery in climatically suitable areas is anticipated in the southern part of the Amazon, specifically in the state of Rondônia, for the 2051-2070 period (Figure 1F).

In the more optimistic RCP 4.5 scenario, *Astrocaryum acaule* is projected to experience a decline in potential habitats in the Amazon by 37.16% and 50.41% for the future intervals of 2020-2050 and 2051-2070, respectively (Table 1). The Pantanal will be the domain most adversely impacted; despite its limited area of species occurrence (44.31 km^2), a 100% habitat loss is projected for 2020-2050. The Caatinga domain will see reductions of 32.61% and 48.70% in the 2020-2050 and 2051-2070 scenarios, respectively. In savanna areas within the Cerrado domain, the species is expected to experience habitat losses of 87.81% and 95.08% for the respective periods. Conversely, in the Atlantic Forest domain, where there is presently a smaller potential distribution area for *A. acaule*, a significant increase in species occurrence is projected, with an increase of 167.48% foreseen for the 2051-2070 period (Table 1).

In the more pessimistic scenario (RCP 8.5), there was a decline of 51.89% in the Amazon domain for the period 2020-2050 and 32.33% for 2051-2070, compared to current conditions (Table 1). The Pantanal remains the sole domain where future projections do not indicate favorable conditions for the occurrence of *A. acaule*. In contrast, for the Caatinga, Cerrado, and Atlantic Forest domains, the period of 2051-2070 is projected to see increases in suitable areas for *A. acaule* occurrence by 120.79%, 59.04%, and 3,074.80%, respectively (Table 1).

3.2 Climate Predictive Modeling for *Astrocaryum aculeatum* Distribution

For *A. aculeatum*, a matrix comprising 73 occurrence points was generated, achieving an efficiency rate of 50.7% (Figure 2A). This matrix identified potential habitats for *A. aculeatum* across five Brazilian phytogeographic domains (Figure 2B). Mirroring the distribution areas for *A. acaule*, those of *A. aculeatum* spanned five extensive Brazilian domains and displayed similar arrangements (Figure 2). In the RCP 4.5 scenario, during both evaluated periods (2020-2050 and 2051-2070), a substantial decrease in potential habitat was observed for *A. aculeatum* in the Amazon region (Figures 2C and 2D), relative to the current distribution (Figure 2B).

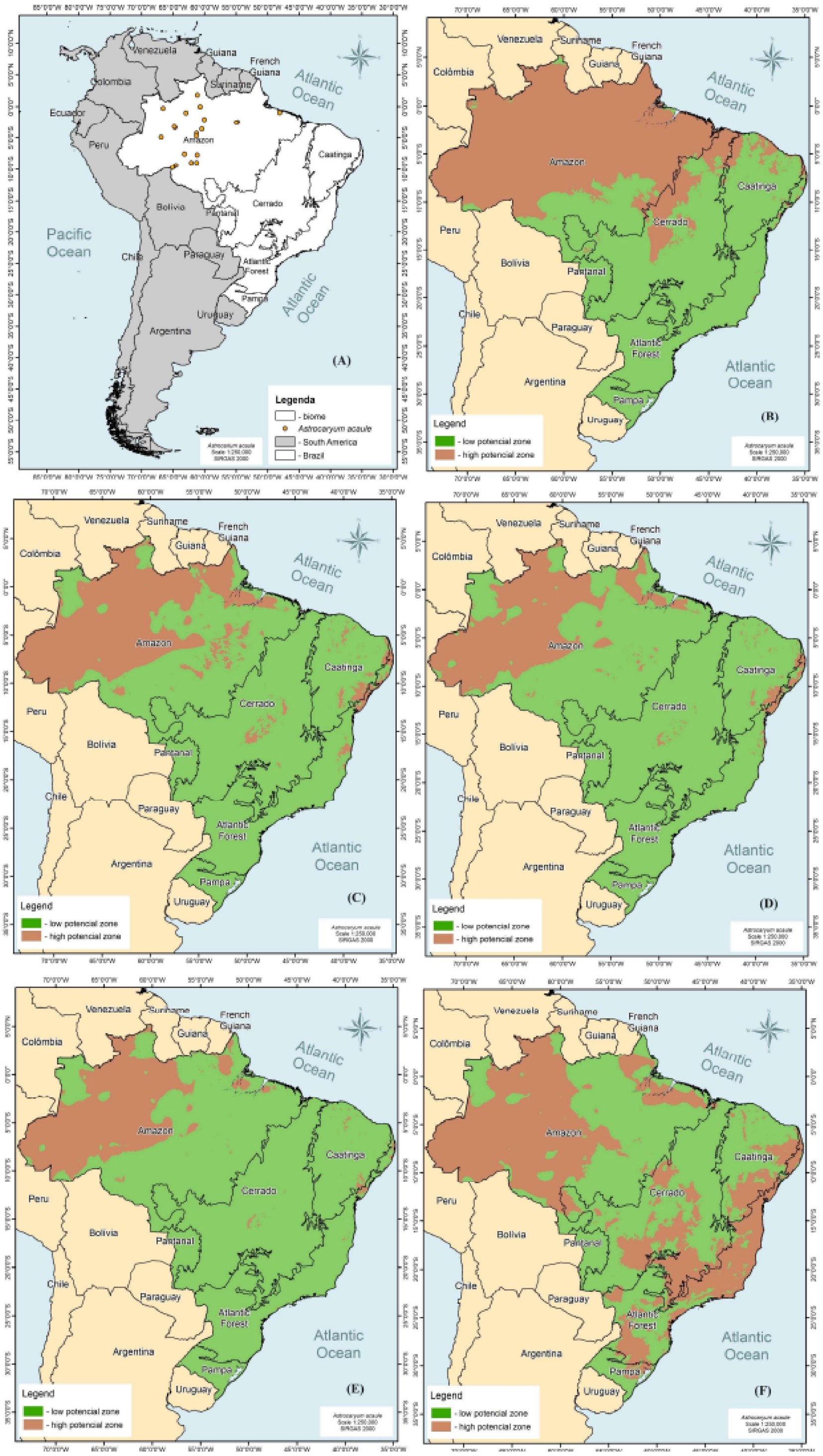

Figure 1 – Points of occurrence of *Astrocaryum acaule* (A) in the Brazilian territory and distribution of the species corresponding to the present period (2009-2019) (B) and scenarios RCP 4.5 (C and D) and RCP 8.5 (E and F). Envelope Score Model.

Figura 1 – *Pontos de ocorrência de **Astrocaryum acaule** (A) no território brasileiro e distribuição da espécie correspondente ao período presente (2009–2019) (B) e cenários RCP 4.5 (C e D) e RCP 8.5 (E e F). Modelo Envelope Score.*

Table 1– Areas (km²) of distribution of *Astrocaryum acaule* in the RCP 4.5 and 8.5 scenarios in the present period (2009-2019) and future (2020-2050 and 2051-2070). Model Envelope Score.
***Tabela 1** – Áreas (km²) de distribuição de **Astrocaryum acaule** nos cenários RCP 4.5 e 8.5 no período presente (2009-2019) e futuro (2020-2050 e 2051-2070). Modelo Envelope Score.*

Phytogeographic domains	2009-2019	2020-2050	Modified area (%)	2051-2070	Modified area (%)
			RCP 4.5		
Amazon	3,516,371.55	2,209,717.77	37.16 (-)	1,743,714.68	50.41 (-)
Pantanal	44.31	0	100 (-)	0	100 (-)
Caatinga	127,791.07	86,117.29	32.61 (-)	65,559.77	48.70 (-)
Cerrado	404,592.92	49,334.65	87.81 (-)	19,912.46	95.08 (-)
Atlantic Forest	22,213.44	69,300.27	211.97 (+)	59,416.13	167.48 (+)
Total	4,071,013.23	2,414,469.98	40.69 (-)	1,888,603.04	53.61 (-)
			RCP 8.5		
Amazônia	3,516,371.55	1,691,782.28	51.89 (-)	2,379,608.53	32.33 (-)
Pantanal	44.31	0	100 (-)	0	100 (-)
Caatinga	127,791.07	24,505.69	80.82 (-)	282,154.26	120.79 (+)
Cerrado	404,592.92	9,136.50	97.74 (-)	643,452.81	59.04 (+)
Atlantic Forest	22,213.44	23,053.58	3.78 (+)	705,233.04	3,074.80 (+)
Total	4,071,013.29	1,748,478.06	57.05 (-)	4,010,448.63	1.49 (-)

(+) or (-) mean increase or decrease, respectively, of percentage of area of future scenarios compared to the 2009-2019 scenario.
(+) ou (-) significam aumento ou diminuição, respetivamente, da percentagem de área dos cenários futuros em relação ao cenário 2009-2019.

In the more optimistic RCP 4.5 scenario, both evaluated periods forecasted the formation of isolated forest refuges predominantly to the west of the Amazon (in Acre), to the Amazon's south (in Rondônia), and in proximity to the Xingú River basin (in Pará). Consistent with observations for *A. acaule*, no climatically suitable areas are anticipated for *A. aculeatum* in the Pantanal domain within this scenario. In the Cerrado domain, the potential areas for occurrence coincided with regions facing deforestation. Conversely, in the more pessimistic RCP 8.5 scenario, the reduction in habitat area is projected to be substantial in both the 2020-2050 and 2051-2070 periods (Figures 2E and 2F).

In the current timeframe, the Amazon domain constitutes the largest distribution area for *A. aculeatum*. However, under the less pessimistic RCP 4.5 scenario, the domain faces significant reductions in suitable habitat for the species—amounting to 79.25% and 93.56% for the periods 2020-2050 and 2051-2070, respectively (Table 2). As for the Pantanal domain, it exhibits the smallest current distribution area (12,041 km²) and is projected to lack any suitable conditions for the species in future scenarios.

In the Caatinga domain, only minor reductions of 7.01% and 12.53% are anticipated in the periods 2020-2050 and 2051-2070, respectively. In contrast, the Cerrado domain will experience more substantial losses, specifically 63.55% and 78.03% in the periods 2020-2050 and 2051-2070, respectively. Conversely, the Atlantic Forest domain is expected to see an increase in suitable area of 80.53% in 2020-2050, followed by a decline of 24.96% in 2051-2070 (Table 2). All phytogeographic domains are projected to experience a decrease in potential areas, with the exception of the Atlantic Forest in the 2020-2050 period.

Under the more pessimistic RCP 8.5 scenario, a substantial contraction of suitable habitat was noted across all phytogeographic domains (Table 2). Specifically, the Amazon domain saw a dramatic decrease in the potential distribution of A. aculeatum, with reductions of 92.74% and 99.50% for the periods 2020-2050 and 2051-2070, respectively. In the Pantanal domain, the species was projected to be completely absent in future scenarios.

Regarding the Caatinga domain, significant losses of suitable areas were recorded—83.24% and 55.82% in the periods 2020-2050 and 2051-2070, respectively. The Cerrado domain also experienced substantial habitat loss for *A. aculeatum*, with contractions of 92.77% in 2020-2050 and 95.90% in 2051-2070. Similarly, the Atlantic Forest domain is projected to undergo a decline in suitable habitat of 66.12% in the 2020-2050 period and 59.80% in 2051-2070 (Table 2).

4. DISCUSSION

The findings of this study suggest a decrease in potential habitats for both *A. acaule* and *A. aculeatum*

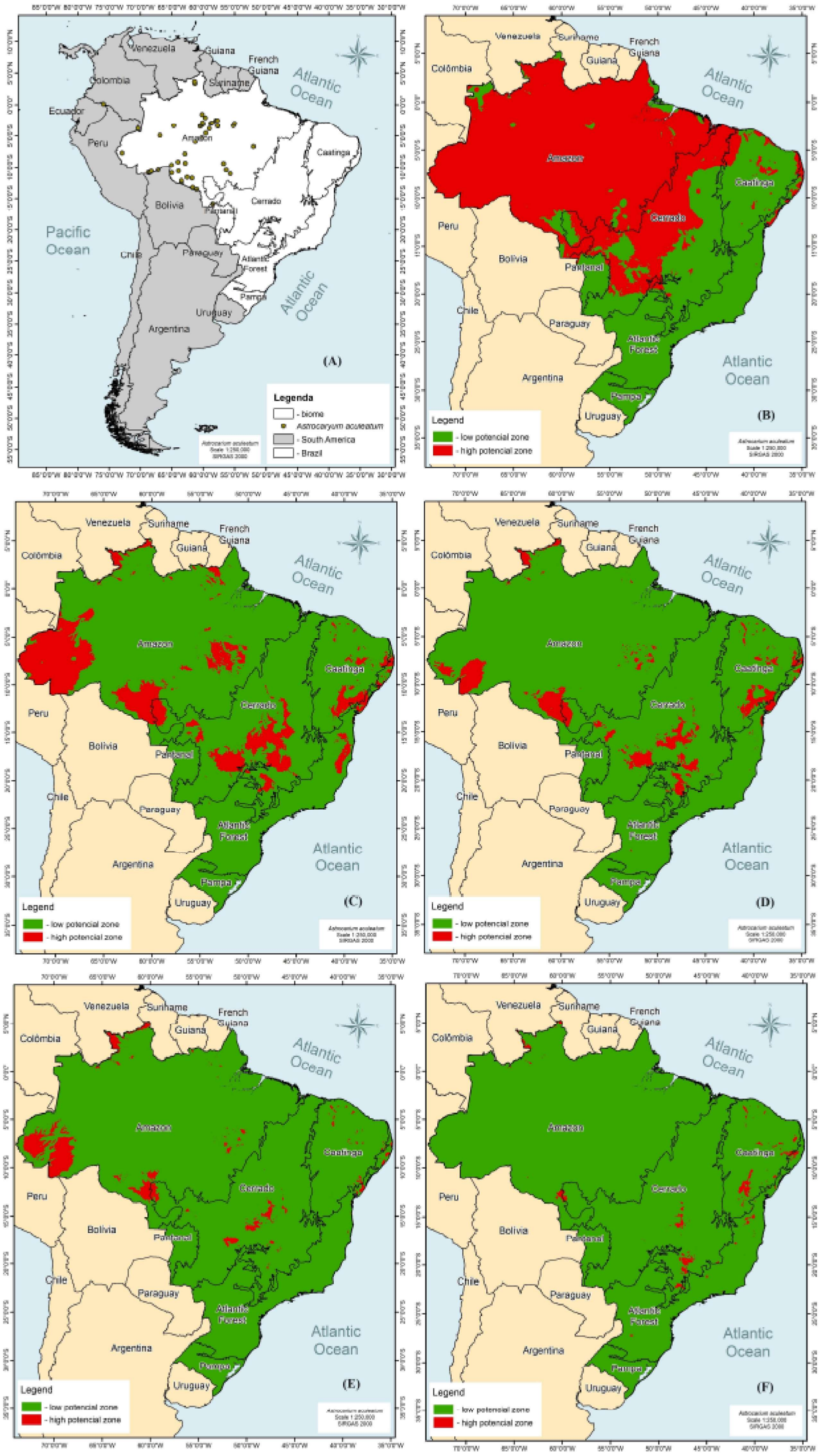

Figure 2 – Points of occurrence of *Astrocaryum aculeatum* (A) in the Brazilian territory and distribution of the species corresponding to the present period (2009-2019) (B) and scenarios RCP 4.5 (C and D) and RCP 8.5 (E and F). Environmental Distance model.
Figura 2 *– Pontos de ocorrência de* ***Astrocaryum aculeatum*** *(A) no território brasileiro e distribuição da espécie correspondente ao período presente (2009–2019) (B) e cenários RCP 4.5 (C e D) e RCP 8.5 (E e F). Modelo Environmental Distance.*

Table 2 – Areas (km^2) of distribution of *Astrocaryum aculeatum* in the RCP 4.5 and 8.5 scenarios in the present period (2009-2019) and future (2020-2050 and 2051-2070). Environmental Distance Model.
Tabela 2 *– Áreas (km^2) de distribuição de **Astrocaryum aculeatum** nos cenários RCP 4.5 e 8.5 no período presente (2009-2019) e futuro (2020-2050 e 2051-2070). Modelo Environmental Distance.*

Phytogeographic domains	2009-2019	2020-2050	Modified area (%)	2051-2070	Modified area (%)
			RCP 4.5		
Amazon	4,029,337.66	836,045.31	79.25 (-)	259,418.01	93.56 (-)
Pantanal	12,041.01	0	100 (-)	0	100 (-)
Caatinga	111,226.05	103,431.82	7.01(-)	97,292.26	12.53 (-)
Cerrado	978,225.10	356,546.36	63.55 (-)	214,879.85	78.03 (-)
Atlantic Forest	45,683.13	82,472.57	80.53 (+)	34,279.96	24.96 (-)
Total	5,176,512.95	1,378,496.05	73.37 (-)	605,870.08	88.30 (-)
			RCP 8.5		
Amazon	4,029,337.66	292,346.59	92.74 (-)	20,271.70	99.50 (-)
Pantanal	12,041.01	0	100 (-)	0	100 (-)
Caatinga	111,226.05	18,638.38	83.24 (-)	49,135.76	55.82 (-)
Cerrado	978,225.10	70,689.64	92.77 (-)	40,153.12	95.90 (-)
Atlantic Forest	45,683.13	15,475.21	66.12 (-)	18,366.28	59.80 (-)
Total	5,176,512.95	397,149.82	92.38 (-)	127,926.85	97.53 (-)

(+) or (-) mean increase or decrease, respectively, of percentage of area of future scenarios compared to the 2009-2019 scenario.
(+) ou (-) significam aumento ou diminuição, respetivamente, da percentagem de área dos cenários futuros em relação ao cenário 2009-2019.

in Brazilian territories under the future scenarios of RCP 4.5 and RCP 8.5. Similar trends have been observed for the tree species *Stryphnodendron pulcherrimum* (Willd.) Hochr. (Tomaz et al., 2022) and *Myracrodruon urundeuva* FR. (Capo et al., 2022) within the same scenarios and periods. The reduction in suitable habitats was particularly pronounced for the palm species investigated, with the exception of *A. acaule* during the 2051-2070 timeframe under the RCP 8.5 scenario; this species actually experienced an expansion in the Atlantic Forest. Over the years, a shift in species dispersal toward milder climates, such as that of the Atlantic Forest, has been documented. This pattern is exemplified by the case of *Euterpe edulis* Mart. (Arecaceae) (Colombo and Joly, 2010). However, it is hypothesized that the rapid rate of global warming, along with extensive fragmentation of the Atlantic Forest, will make the dispersal of plant species increasingly unfeasible (Zanin et al., 2017).

Despite significant altitudinal variations along the Brazilian coast, areas favorable to the growth of *A. acaule* were identified for the 2051-2070 period, spanning the Northeast and Southeast coasts in the Atlantic Forest. One of the representatives of this genus with broad distribution in this domain is “brajaúva” (*Astrocaryum aculeatissimum* (Schott) Burret). This species exhibits ecological similarities and occurs from the State of Bahia to Santa Catarina in low-altitude forests and pastures (Salomão et al., 2007).

Future climate change is expected to result in the contraction of forest niches, impacting Brazilian phytogeographic domains in various ways. In the Brazilian Amazon, the potential distribution area for the studied palm species is likely to shift further west, accompanied by a significant decline in the eastern regions. Under the RCP 8.5 scenario for the 2051-2070 period, *A. aculeatum* faces a reduction in its area, posing a risk of extinction. In contrast, *A. acaule* demonstrates greater resilience, displaying an expanded distribution and the capability to recolonize the southern Amazon. While the rise in global temperatures will directly influence Amazonian flora (Sobral-Souza et al., 2018), it should be noted that *A. aculeatum* and *A. acaule* exhibit greater resilience compared to *S. pulcherrimum*, which is predicted to go extinct in this phytogeographic domain by 2051-2070 under the RCP 8.5 scenario (Tomaz et al., 2022).

Ecological niche models reveal almost a complete absence of suitable areas for *A. acaule* and *A. aculeatum* in the region known as the "deforestation arc," which currently spans the states of Pará, Tocantins, Mato Grosso, and Rondônia. In addition to the implications of climate change, large-scale deforestation may also contribute to reductions in local precipitation rates (Nobre et al., 2016). Another significant concern is the prevalence of fires in the southern and southeastern perimeters of the Amazon. These regions are abundant in savanna vegetation, which is susceptible to water stress and faces prolonged periods of seasonal drought (Lui and Molina, 2009).

In the projections for both scenarios and timeframes assessed, there is no evidence to suggest the presence of the species *A. acaule* and *A. aculeatum* in the Pantanal domain, except for the current period. Similar projections have been made for *S. pulcherrimum* across both scenarios and periods (Tomaz et al., 2022), as well as for *M. urundeuva*, a native species to the Caatinga domain, in the 2061-2080 timeframe under the RCP 8.5 scenario (Capo et al., 2022). Given the projected global temperature increases of 1.9°C and 3.5°C under climate simulation models RCP 4.5 and RCP 8.5, respectively, by the year 2100 (Kariyawasam et al., 2019; Çoban et al., 2020), it can be concluded that the Pantanal is the domain most vulnerable to climate change. Furthermore, populations with lower genetic variability are likely to be most adversely affected (Lorenzen et al., 2011). Correspondingly, the domain currently exhibits the smallest area of palm tree occurrence, a situation that could potentially intensify endogamic mating and undermine genetic structure, rendering it insufficient for maintaining species variability (Ramos et al., 2016).

The distribution patterns for *A. acaule* and A. *aculeatum* were strikingly similar outside of the Amazon. However, *A. aculeatum* appears to have a more substantial presence in the Cerrado domain, to the extent that *A. acaule* may be confined to regions adjacent to ecotones. Forest inventories have also confirmed the presence of at least three other palm species of the genus Astrocaryum (*A. campestre* Mart., A. vulgare Mart., and *A. jauari* Mart.) in the Cerrado region of the State of Tocantins (Nascimento et al., 2009).

In the Cerrado domain, both species experienced a loss of suitable habitat. Notably, in the most pessimistic scenario (RCP 8.5) for the period 2051-2070, the occurrence of *A. acaule* increased, while *A. aculeatum* was nearly absent. A similar trend was observed for *A. acaule* in the Caatinga domain, where its habitat expanded by over 100% under the same pessimistic scenario (RCP 8.5) during 2051-2070. Comparable increases were projected for *M. urundeuva* in the Caatinga domain for the periods 2041-2060 and 2061-2080 (Capo et al., 2022). This data suggests that *A. acaule* demonstrates greater climate adaptability in the Caatinga and Cerrado domains, aligning with the hypothesis that these regions may possess greater stability and resiliency in terms of vegetation cover in future projections, as compared to other phytogeographic domains (Zanin et al., 2017).

In analyzing the total distribution area of the species across all Brazilian phytogeographic domains, diverging patterns emerge. *A. aculeatum* experienced a substantial area loss (5,176,512.95 km^2; remaining area in 2051-2070 = 127,926.85 km^2), while *A. acaule* largely retained its current range (area loss = 4,071,013.29 km^2; remaining area in 2051-2070 = 4,010,448.63 km^2). Given these projections, it appears that *A. acaule* and *A. aculeatum* may continue to coexist within certain phytogeographic domains—except in the Pantanal between 2020-2050 under scenarios RCP 4.5 and RCP 8.5, where both species are expected to go extinct. Natural interspecific hybridization may occur in the Amazon, Caatinga, Cerrado, and Atlantic Forest in future scenarios. However, it should be noted that factors such as rising temperatures and the significant reduction in future habitat for *A. aculeatum* could impede processes like interspecific hybridization and seed production (Fischer and Lindenmayer, 2007).

Based on the data presented, we recommend incorporating the western region of the Brazilian Amazon into sustainable management plans for *A. acaule* and *A. aculeatum*. Such an inclusion would facilitate population genetics studies and assist in the characterization and demarcation of conservation units. Concerns about conservation also extend to other palm species of the *Astrocaryum* genus, which are predominantly found in the Amazon domain and exhibit greater diversity (Khan et al., 2008; Alvez-Valles et al., 2018).

The importance of effective management strategies cannot be overstated. These strategies are crucial for ensuring the maintenance of a viable gene pool and native populations, serving as a baseline for future studies assessing the impact of global warming. The establishment of conservation banks or the implementation of provenance and progeny tests for these species in areas anticipated for range expansion could be highly effective actions for their conservation and survival.

5. CONCLUSIONS

In phytogeographic domains, the distribution patterns of *Astrocaryum acaule* and *Astrocaryum aculeatum* are similar. Conversely, when considering the area of future projections, *A. aculeatum* is more sensitive to climatic variations than *A. acaule*, within the Amazon domains, Caatinga, Cerrado and Atlantic Forest.

Although *A. acaule* and *A. aculeatum* may be coexist in the same phytogeographic domain within the Brazilian territory, in future scenarios the area of *A. aculeatum* area could decrease by 88.30% and 97.53% in RCP4.5 and RCP 8.5, respectively, until 2070. This would reduce the likelihood of natural interspecific hybridization.

To minimize the loss of genetic diversity related to the loss of area in the Brazilian phytogeographic domains, total genetic variability should be sampled prior to the change of the expected scenario of conservation of *A. acaule* and *A. aculeatum* in other places of greater adaptation, guided by the present study.

AUTHOR CONTRIBUTIONS

Cordeiro AL, Tomaz JS, Bezerra CS, Ramos SLF and Lopes R were responsible for data analysis and writing of manuscript. Fraxe TJP, Lopes MTG, Meneses CHSG, Aguiar AV and Wrege MS contributed with the supervision of methodology and correction. Lopes MTG, Bezerra CS and Lopes R reviewed and correct the work.

6. ACKNOWLEDGMENTS

This study was carried out with support from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq - 310307/2018-0 and 442914/2020-2) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001.

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