Research Article
doi: 10.1590/01047760202531013465
vol(31), 2025

CERNE

Fruit exploitation and climate suitability for *Spondias tuberosa*: implications for management and conservation

Raiane Pereira de Sales[1], Abidã Gênesis da Silva Neves[1], Luciana Gomes Pinheiro[1], Cristiane Gouvêa Fajardo[1], Tatiane Kelly Barbosa de Azevedo[1], Fábio de Almeida Vieira[1]✤

[1]Federal University of Rio Grande do Norte, Forestry Engineering, Macaíba, Rio Grande do Norte, Brazil

FOREST MANAGEMENT

ABSTRACT

Background: *Spondias tuberosa* Arruda (Anacardiaceae) is a tree species of growing conservation concern due to population decline driven by current land-use practices in the Caatinga, a highly vulnerable ecosystem. The decline of *S. tuberosa* populations is particularly concerning given its ecological importance and value to local communities. This study aims to quantify the impact of fruit extraction on *S. tuberosa* populations and to predict current and future climatically suitable habitats for the species, thereby providing critical insights for developing effective management and conservation strategies. Production data (tons) and commercial value (U.S. dollars) were collected from 1994 to 2021. Using the Maxent algorithm, we correlated species occurrence records with key climatic variables under two climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC): an optimistic scenario (RCP2.6) and a pessimistic scenario (RCP8.5).

Results: Bahia was the leading producer and trader of *S. tuberosa* fruits between 1994 and 2021, despite the species' broader distribution across the Northeast Brazil. The Maxent models demonstrated high predictive accuracy (AUC > 0.94) for both current conditions and future climate change scenarios. Annual precipitation was identified as the most influential climatic variable shaping the distribution of *S. tuberosa*.

Conclusion: Future climate scenarios project a significant expansion of suitable habitats for *S. tuberosa* in Pernambuco and Bahia. The findings support the development of sustainable resource management strategies, such as establishing commercial plantations and the creation of *ex-situ* conservation banks alongside environmental protection areas.

Keywords: Caatinga; climate change; fruit extraction; habitat prediction; population decline.

HIGHLIGHTS

S. tuberosa faces population decline due to Caatinga land-use practices.
Fruit extraction impacts *S. tuberosa* populations and future distributions.
Maxent models predict expanded suitable habitats in Pernambuco and Bahia.
Annual precipitation is the key factor in *S. tuberosa* distribution.

SALES, R. P.; NEVES, A. G. S.; PINHEIRO, L. G.; FAJARDO, C. G.; AZEVEDO, T. K. B. A.; VIEIRA, F. A. Fruit exploitation and climate suitability for *Spondias tuberosa*: implications for management and conservation. CERNE, v.31, e-103465, 2025. doi: 10.1590/01047760202531013465

✤Corresponding author: fabio.almeida@ufrn.br
Scientific Editor: Samuel José Silva Soares da Rocha

Received: August 9/2024
Accepted: April 7/2025

CERNE
ISSN 0104-7760
UNIVERSIDADE FEDERAL DE LAVRAS

INTRODUCTION

The Northeast region of Brazil is predominantly covered by xerophytic vegetation known as Caatinga, classified as Seasonally Dry Tropical Forest and Woodland (SDTFW) (Queiroz et al., 2017). The Caatinga's unique climate, characterized by irregular rainfall, has driven the evolution of vegetation with remarkable adaptations to prolonged drought. However, this ecosystem faces significant threats, including anthropization and deforestation, primarily due to the intensive illegal exploitation of native plant species (Oliveira & Bernard, 2017). These pressures raise critical concerns about the conservation and sustainable management of the Caatinga.

Overexploitation can lead to environmental degradation, especially in biomes already experiencing deforestation (Santos et al., 2021). However, for traditional populations, sustainable plant extraction provides employment opportunities and income while supporting environmental conservation through the protection of exploited species (Soares et al., 2018). *Spondias tuberosa* Arruda (Anacardiaceae) is among the most economically important trees in the Caatinga biome. Official government data (IBGE, 2021) report an annual production value exceeding $3.6 million from fruit extraction. The fruits are rich in bioactive compounds, exhibiting significant antioxidant potential, high levels of vitamin C, and abundant phenolic compounds (Rodrigues et al., 2024). They also contain considerable amounts of total and soluble pectin, underscoring their potential for both fresh consumption and industrial processing (Santos et al., 2021).

Climate change and its associated shifts in temperature and precipitation can dramatically alter suitable habitat distributions, potentially causing biome transitions in tropical forests (Donoghue & Edwards, 2014). Trees are particularly vulnerable due to their slower response times, experiencing phenological and distributional disruptions (Margrove et al., 2015; Wang et al., 2022). Their limited capacity for rapid adaptation increases susceptibility to climate-triggered catastrophic events in forest ecosystems, including heat and water stress (Butt et al., 2015).

Therefore, studying the ecological factors influencing species distribution across different geographic areas is crucial. Ecological niche models (ENMs) have become a valuable and widely used tool in scientific research, contributing significantly to various scientific fields (Nabout et al., 2016). ENMs can predict spatial abundance relationships, genetic variability, species distribution, habitat suitability, and even extinction risks (Soares et al., 2015; Lucas et al., 2021). Research indicates that *S. tuberosa* is experiencing reduced regeneration capacity, leading to population decline (Mertens et al., 2017). When combined with various natural and anthropogenic threats, this decline raises concerns about potential species extinction (Mertens et al., 2017).

Previous studies have employed modelling approaches to evaluate climate change impacts on *Spondias tuberosa* and other wild food plants in the Brazilian semiarid region (da Silva et al., 2024). These studies underscore the vulnerability of *S. tuberosa* to habitat reduction and overharvesting, highlighting the urgent need for research on combined climate change and anthropogenic pressures (Caetano et al., 2023). Based on these findings, our study aims to analyze historical fruit extraction patterns and assess the habitat suitability for *Spondias tuberosa* under current and future climate change scenarios. These analyses aim to provide insights for developing management and conservation strategies to safeguard the species, addressing concerns about population decline, ecological importance, and potential socio-economic benefits for local communities. We tested the following hypotheses: i) regions with greater fruit extraction show higher production values, indicating regional commercialization; ii) regions with higher extraction have greater suitability; iii) annual precipitation, a limiting factor in semiarid environments, is the key suitability variable; iv) climate warming may create new suitable areas for *S. tuberosa*.

MATERIAL AND METHODS

Target species

Spondias tuberosa is a tree naturally occurring in the semiarid region of Northeast Brazil (Balbino et al., 2018). Despite its economic and ecological importance, studies on its physiology and interactions with the ecosystem remains limited (Mertens et al., 2015). The species survives during the dry season through deciduousness, which reduces the transpirational surface and effectively controls water loss (Veras et al., 2018). The flowers are male and hermaphroditic, characterizing an andromonoecious sexual system (Nadia et al., 2007). During dry seasons, *S. tuberosa* provides nectar and pollen, attracting various insects, including bees (*Apis mellifera* and *Trigona* sp.), wasps (*Polistes canadensis*, *Zethus mexicanus*), and flies (Sarcophagidae) (Nadia et al., 2007; Mertens et al., 2015). The fruits are glabrous or slightly pilose, rounded, measuring 2-4 cm in diameter and weighing 10-20 g (Figure 1). The fruits have barochoric and zoochoric dispersal, but the absence of dispersers due to hunting pressure contributes to a severe reduction in the population of *S. tuberosa* in the Caatinga (Mertens et al., 2017). Fruit extraction represents an important income source in Northeast Brazil, highlighting its potential as a crop with economic and social benefits (Lins Neto et al., 2010). The fruits are commercialized fresh or processed into pulps, drinks, jellies, and sweets (Lins Neto et al., 2010).

Data on fruit extraction, geographical distribution, and climatic variables

Production data (fruit extraction) and commercial values were obtained from the Brazilian Institute of Geography and Statistics (IBGE) database using the Automatic Retrieval System (SIDRA) (IBGE, 2021). We analysed the most recent 24 years of available data (1994 to 2021), covering all Brazilian states with records of *S. tuberosa* fruit production. Descriptive statistical analyses were then performed.

S. tuberosa occurrence data were obtained from SpeciesLink (http://splink.cria.org.br). After filtering available records, only data with geographic coordinates spaced ≥ 5 km apart were retained to eliminate duplicates and overlapping data (Oliveira et al., 2018). For current and future distribution modelling, we considered nineteen bioclimatic variables (bio1-bio19) representing temperature, precipitation, and seasonality parameters, obtained from WorldClim 1.4 at 30 arc-second (~1 km) resolution. BIOCLIM variables (Booth et al., 2014) were selected by: (1) excluding variables with Area Under the Receiver Operating Characteristic Curve (AUC-ROC) values < 0.7; (2) removing predictors showing low training/test gain values (Table S1), as these demonstrate poor predictive performance (Pearce & Ferrier, 2000); and (3) eliminating highly correlated variables (|r| ≥ 0.85, Table S2) to avoid multicollinearity (Wei et al., 2017). Multicollinearity analysis was performed using ENMTools 1.4.3 (http://purl.oclc.org/enmtools), resulting in eight final predictor variables (Table S3).

Ecological niche modelling

We used Maxent software version 3.3.3k to build models for potential geographic distribution areas (Elith et al., 2006; Phillips et al., 2006). We assessed variable importance with the Jackknife test and ensured model convergence through 5,000 iterations and 10-fold cross-validation. Maxent computes the Area Under the Curve (AUC) index, ranging from 0.5 to 1, with 1 indicating the best model fit (Phillips et al., 2006).

The analyses were performed for two periods: the current baseline, using the average of the years 1960 - 1990, and the future period, using the average of the years 2061 to 2080 (2070s). Future predictions considered optimistic (RCP2.6) and pessimistic (RCP8.5) climate scenarios using four Atmospheric General Circulation Models (AGCM): HadGEM2-ES, GISS-E2-R, MIROC-ESM, and CCSM4 (Watanabe et al., 2011; Goberville et al., 2015) (Table 1). Species distribution maps were created using QGIS software v. 3.0.0 (https://www.qgis.org/pt_BR/site/). Habitat suitability is represented by a colour gradient, with red indicating high suitability and blue indicating low suitability.

RESULTS

Geographic Distribution and Extractivism

We obtained 253 occurrence records of *S. tuberosa*, with most concentrated in the Northeast Brazil (Figure 2).

Fruit extraction of *S. tuberosa* (tons) varied among states from 1994 to 2021 (Figure 3). Bahia led in production

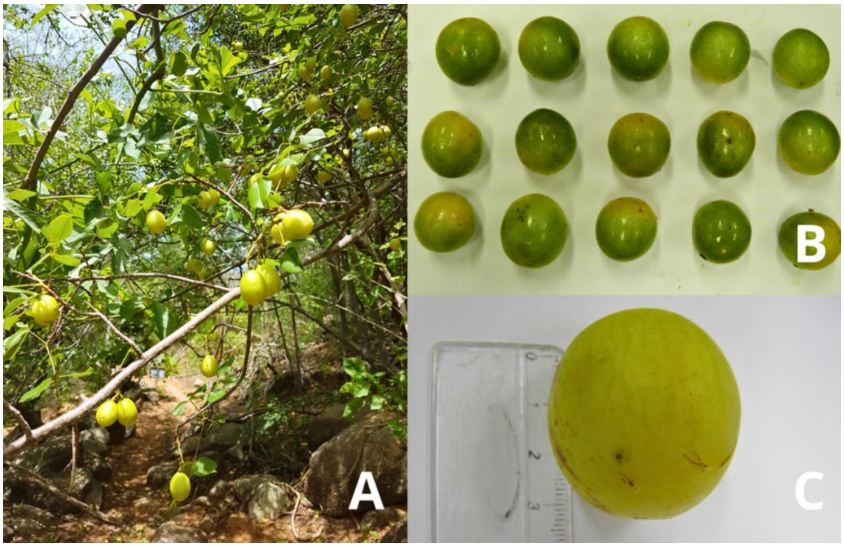

Figure 1: (A) *Spondias tuberosa* Arruda (Anacardiaceae) specimen in its natural habitat, bearing mature fruits. (B) Close-up of *S. tuberosa* fruits, showing their characteristic shape and colour variation. (C) Collected fruit, with a size reference in centimetres for scale.

Table 1: AGCM models used for modelling the future scenario.

Model Code	Model Name	Source
HADGEM2-ES	Hadley Centre Global Environment Model	Jones et al. 2011
GISS-E2-R	Goddard Institute for Space Studies	Schmidt et al. 2014
MIROC-ESM	Model for Interdisciplinary Research on Climate	Watanabe et al. 2011
CCSM4	The Community Climate System Model	Gent et al. 2011

throughout this period, peaking at 10,078 tons in 1997. However, Bahia's production declined to 8,624 tons in 2010 and continuing decreasing in subsequent years. Pernambuco maintained the second-highest production, equivalent to the levels observed in 1995, totalling 874 tons. Minas Gerais showed significant increases starting in 2016, reaching 1,198 tons. Notably, Minas Gerais experienced substantial production growth between 2016 and 2021, reaching 5,077 tons in 2021.

Bahia dominated fruit production value (U.S. dollars) throughout 1994-2021 (Figure 4), maintaining its position as the top producer. In 2021, Bahia's production of *S. tuberosa* fruits amounted to 1,460 thousand dollars. Minas Gerais followed closely with 981 thousand dollars in 2021. Additionally, Pernambuco and Alagoas achieved significant values for the fruit in 2020 ($109 thousand; $125 thousand) and 2021 ($125 thousand; $179 thousand), respectively, despite lower extraction volumes (tons).

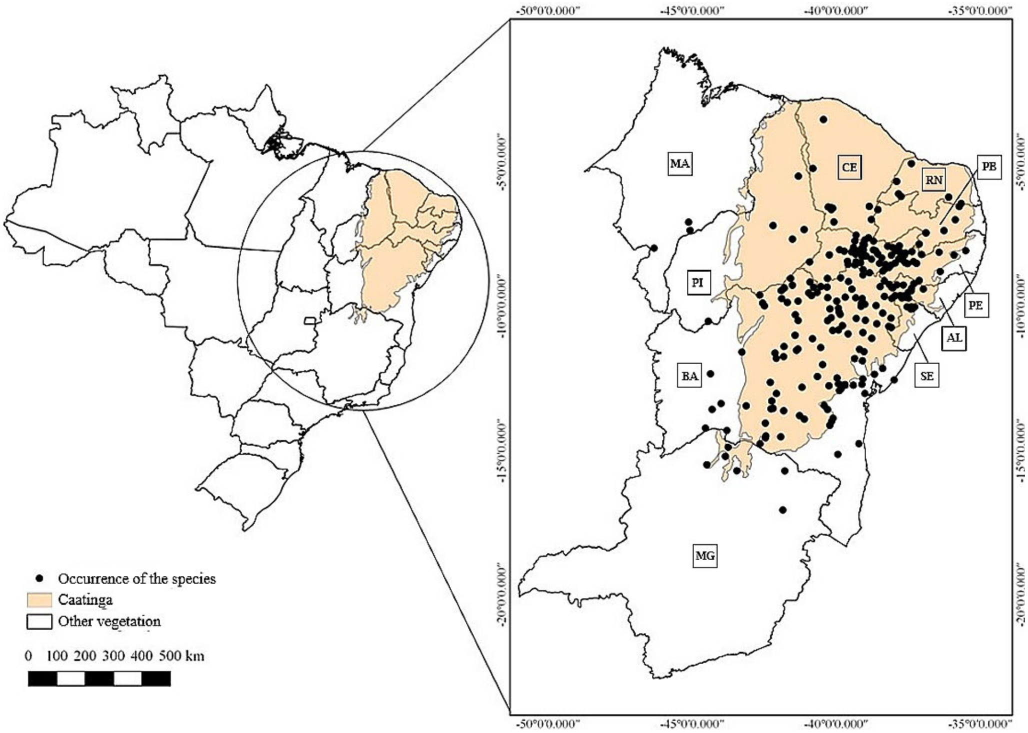

Figure 2: Geographic distribution of *Spondias tuberosa* across Brazilian states, including Maranhão (MA), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Piauí (PI), Alagoas (AL), Sergipe (SE), Bahia (BA), and Minas Gerais (MG). Projection system: WGS 84 datum.

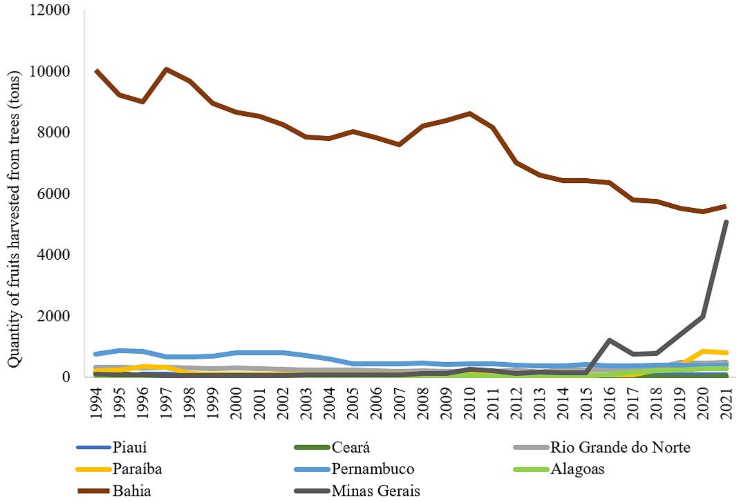

Figure 3: Annual extraction of *Spondias tuberosa* fruits in Brazil, measured in tons, from 1994 to 2021. Data source: IBGE, 2021.

Ecological Niche Modelling

Multicollinearity analysis (Table 2) selected eight bioclimatic variables for modelling *S. tuberosa* distribution: bio 1, bio 4, bio 7, bio 12, bio 13, bio 15, bio 18, and bio 19 (Table S3). After variable selection, the current period model showed high predictive accuracy (AUC = 0.94 ± 0.01). Based on the Jackknife test for the current period, annual precipitation (bio 12) was the variable with the most significant impact when used alone. This variable also exhibited the highest values for information contribution and permutation importance. Pre-selection AUC values ranged from 0.63 to 0.93 (Table 2), while post-selection values improved between 0.70 and 0.93.

For RCP2.6 scenario projections, annual precipitation showed the highest contribution percentage and permutation importance across all four AGCMs (Table 3), with consistent AUC values (0.97 for all four models). Similarly, under RCP8.5 scenario, annual precipitation also exhibited the highest contribution percentage and permutation importance values, with minimal variation in AUC (0.97-0.98).

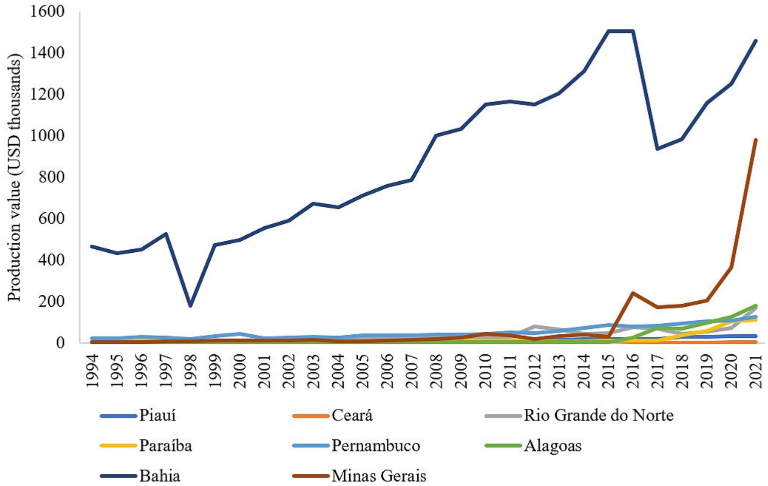

Figure 4: Economic value of *Spondias tuberosa* fruit extraction in Brazil, expressed in thousand U.S. dollars (USD), from 1994 to 2021. Data source: IBGE, 2021.

Table 2: Predictive modelling values before and after variable selection, showing the contribution and permutation importance of environmental variables for modelling the ecological niche of *Spondias tuberosa* for the current period.

		Pre-selection			Post-selection		
Variables	**Description**	**Contribution (%)**	**Perm. Import. (%)**	**AUC**	**Contribution (%)**	**Perm. Import. (%)**	**AUC**
bio 1	Annual Mean Temperature	0.1	0.1	0.72	1.9	0.1	0.73
bio 2	Mean Diurnal Range	5	1.7	0.67			
bio 3	Isothermality	1.1	1	0.63			
bio 4	Temperature Seasonality	5.6	4.9	0.83	8	20.5	0.84
bio 5	Max Temperature of Warmest Month	0.6	0.7	0.68			
bio 6	Min Temperature of Coldest Month	1.1	3.2	0.78			
bio 7	Temperature Annual Range	1.6	2.3	0.81	7.4	4.8	0.82
bio 8	Mean Temperature of Wettest Quarter	0.8	0.5	0.64			
bio 9	Mean Temperature of Driest Quarter	0.2	0.2	0.75			
bio 10	Mean Temperature of Warmest Quarter	1.2	0.3	0.64			
bio 11	Mean Temperature of Coldest Quarter	0.6	0.3	0.78			
bio 12	Annual Precipitation	75.3	77.5	0.93	78	69.6	0.93
bio 13	Precipitation of Wettest Month	1.8	0.0	0.89	1.7	0.6	0.93
bio 14	Precipitation of Driest Month	0.4	2.5	0.70			
bio 15	Precipitation Seasonality	0.2	1.1	0.74	0.2	0.1	0.73
bio 16	Precipitation of Wettest Quarter	2.2	0.7	0.90			
bio 17	Precipitation of Driest Quarter	0.2	0.2	0.72			
bio 18	Precipitation of Warmest Quarter	1.3	0.9	0.80	1.9	4	0.80
bio 19	Precipitation of Coldest Quarter	0.6	1.8	0.71	0.7	0.3	0.70

Post-selection excluded variables meeting any of these criteria: (1) AUC-ROC values < 0.7; (2) low training/test gain values (Table S1); and (3) multicollinearity (|r| ≥ 0.85, Table S2). The final model incorporated eight bioclimatic variables.

Table 3: Percentage of contribution (%C), permutation importance (%IP), and area under the curve (AUC) of bioclimatic variables used in four atmospheric general circulation models (AGCM) for *Spondias tuberosa*.

RCP2.6 optimistic (2070)		**HadGEM2-ES**		**GISS-ES-R**		**MIROC-ESM**		**CCSM4**	
Variables	**Description**	**%C**	**%IP**	**%C**	**%IP**	**%C**	**% P**	**%C**	**%IP**
bio 1	Annual Mean Temperature	4.6	2.5	3.7	3.1	5.9	2	1	0.8
bio 4	Temperature Seasonality	2.2	3.6	14.5	15.1	7.4	5.2	13.2	6.5
bio 7	Temperature Annual Range	27.8	15.3	20.7	6.6	21.6	26.7	22.1	12.1
bio 12	Annual Precipitation	54.1	74.4	57.5	69.2	43.7	40.3	55.6	73.3
bio 13	Precipitation of Wettest Month	0.5	1	1	0.3	0.9	0.8	0.8	0.7
bio 15	Precipitation Seasonality	0.3	0.3	0.2	0.3	0.4	0.7	0.2	0.3
bio 18	Precipitation of Warmest Quarter	0.6	0.6	2	3.4	10.9	20.8	6.4	5.5
bio 19	Precipitation of Coldest Quarter	9.9	2.5	0.5	1.9	9.3	3.4	0.8	0.9
AUC		0.97 ± 0.01		0.97 ± 0.02		0.97 ±	± 0.02	0.97 ± 0,01	
RCP8.5 pessimistic (2070)		**HadGEM2-ES**		**GISS-ES-R**		**MIROC-ESM**		**CCSM4**	
Variables	**Description**	**%C**	**%IP**	**%C**	**%IP**	**%C**	**%IP**	**%C**	**%IP**
bio 1	Annual Mean Temperature	2.9	2.2	6.8	2.2	5	4.9	1.9	3.1
bio 4	Temperature Seasonality	1.9	6.2	13.9	4.2	9.7	7.6	4.5	4.2
bio 7	Temperature Annual Range	25.7	7.2	10.1	8.8	19.7	17.8	23.2	7.7
bio 12	Annual Precipitation	55	77.3	61.4	80	37.4	42.8	65.7	80.8
bio 13	Precipitation of Wettest Month	1.1	1.6	2.8	1.8	0.9	7.6	0.9	0.6
bio 15	Precipitation Seasonality	0.7	0.7	0.4	0.4	0.4	4	0.8	0.4
bio 18	Precipitation of Warmest Quarter	1.2	0.6	3.8	1.1	10.2	13.7	2.2	2.3
bio 19	Precipitation of Coldest Quarter	11.4	4.1	0.7	1.4	16.7	0.6	0.9	0.9
AUC		0.97 ± 0.01		0.98 ± 0.01		0.97± 0.02		0.98 ± 0.02	

The suitability analysis shows *S. tuberosa* widely distributed across Northeast Brazil, with Pernambuco showing the highest suitability intensity, followed by Bahia (Figure 5 A). Other states also present suitable environmental conditions for *S. tuberosa*, though in progressively smaller proportions moving northward through Maranhão, Piauí, Ceará, and Rio Grande do Norte.

Future projections (2070s) across all models (Figure 5 B-I) indicate an increase in suitable areas under both optimistic and pessimistic scenarios. This expansion occurs primarily within the Caatinga biome, notably in Rio Grande do Norte, northern/southeastern Bahia, and minimally in the northern Minas Gerais (Figure 5).

DISCUSSION

The state of Bahia plays a central role in *S. tuberosa* fruit extraction and commercialization, both in quantity (tons) and commercial value. Numerous collective interest associations, known as "Family Cooperatives", have been established in Bahia, uniting rural producers engaged in fruit extraction and processing (Lins Neto et al., 2010). These cooperatives have achieved national and international markets recognition (Batista et al., 2015), transforming semiarid Bahia's development by demonstrating its economic potential. This progress has fostered fruit cultivation expansion in the region, diversifying product use through derivatives like jellies and sweets (Batista et al., 2015; De Araujo et al., 2016). Consequently, these initiatives have created opportunities and enhanced living conditions for many farming families involved in fruit exploitation (Batista et al., 2015).

Despite conservation efforts (e.g., Sustainable Use Conservation Units protecting approximately 7.5% of Bahia territory [Hauff, 2008]), *S. tuberosa* fruit extraction declined from 1994 to 2021. This reduction may result from: (1) fewer mature *S. tuberosa* plants; (2) increased land fencing; (3) deforestation; and (4) declining reproductive adult populations. Land-use changes favouring cotton, soybean, and pasture expansion further threaten natural *S. tuberosa* populations in the semiarid region (De Araujo et al., 2016). Studies in Brazil's semiarid areas emphasize risks from overexploitation and human disturbances, particularly for maintaining natural populations and genetic diversity (Santos et al., 2021; Chagas et al., 2023).

The appreciation of *S. tuberosa* fruit prices over the years indicates its increasing scarcity and reduced supply in the market, which has stimulated economic activity around this fruit. Periodic fluctuations in its commercial value are linked to annual variations in fruit production, demonstrating the relationship between supply and demand. As supply decreases, prices rise, explaining the 25-year upward trend. On the other hand, the significant increase in *S. tuberosa* fruit extraction and commercial value in the northern Minas Gerais likely results from efforts by EPAMIG (Agricultural Research Company of Minas Gerais) and researchers to identify and propagate high-yield regional genotypes (Abreu et al., 2007). This highlights the economic potential of this fruit for Brazil's agriculture and as an alternative income source for the semiarid region. However, intense competition from producers in states like Bahia and Minas Gerais has caused some local traders to abandon the fruit due to unfavourable costs- earnings ratios (Lins Neto et al., 2010).

Future studies should prioritize selecting high-yield mother trees and establishing commercial orchards. Combined *in situ*/*ex situ* conservation of genotypes could enhance availability of quality propagules (seeds/grafts) to meet market demand, supporting extractive production in climatically suitable regions. *S. tuberosa* cultivation could focus strategically on Northeast Brazil, particularly Pernambuco, as indicated by model performance (AUC = 0.94). While AUC remains widely used for model evaluation, its limitations (Lobo et al., 2008) and tendency for higher values in restricted-distribution species (Yang et al., 2013) warrant consideration. Despite ongoing AUC accuracy debates, it persists as a standard metric in distribution modelling (Ayan et al., 2022).

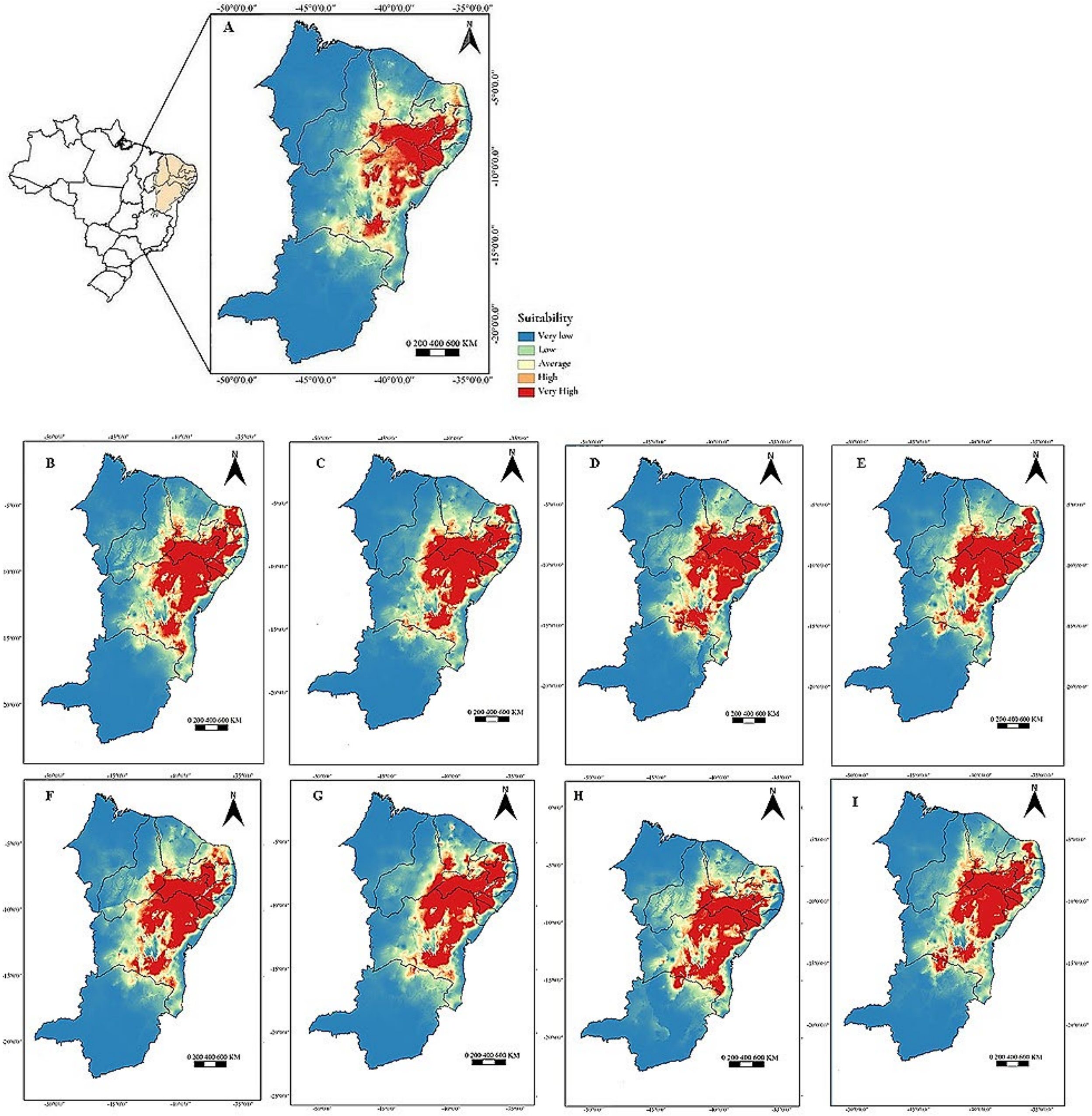

Figure 5: Current and projected future distribution of *Spondias tuberosa* in Brazil under different climate scenarios for 2070. (A) Present distribution. (B-I) Projected suitability for 2070 under the RCP2.6 optimistic scenario: (B) HadGEM2-ES, (C) GISS-E2-R, (D) MIROC-ESM, (E) CCSM4. Under the RCP8.5 pessimistic scenario: (F) HadGEM2-ES, (G) GISS-E2-R, (H) MIROC-ESM, and (I) CCSM4.

As expected, annual precipitation was the most influential variable in our models, given its critical role in fruit production. Within the Caatinga biome, precipitation influences species distribution (Rodrigues et al., 2015; Chagas et al., 2020) and is linked to the reproductive cycle of many plants (Rocha et al., 2015). For *S. tuberosa*, reproduction begins during dry periods (Lins Neto et al., 2013) characterized by high temperatures and low humidity. This triggers flowering followed by the emergence of the first leaves – an adaptation for survival and reproduction (Lima Filho, 2011). Leaf emergence after a drought reduces water consumption, and the absence of leaves during the dry seasons minimizes transpiration until the rains return (Lima Filho, 2011).

Both climate scenarios (optimistic and pessimistic) reveal similar suitability patterns for *S. tuberosa*, with high-suitability areas consistently predicted across all models. Notably, all models project suitability expansion within the Caatinga biome, particularly in Rio Grande do Norte, northern Bahia, and new areas in northern Minas Gerais. These results suggest climate change may maintain or even increase suitable habitats for the species. Future studies should quantify these areas using additional methodologies (Chiu-Valderrama et al., 2022) and incorporate soil/topographic data to better understand environmental responses. Spatial analyses should also measure habitat expansion, contraction, and persistence patterns.

The projected suitability of *Spondias tuberosa* in future scenarios holds particular importance for food security under climate change. Our models predict substantial habitat expansions in Pernambuco and Bahia, suggesting this species may maintain climatic resilience. This contrasts with most wild food plants in semiarid regions, which face projected reductions in suitable areas – potentially decreasing species richness and altering community composition (da Silva et al., 2024). Such changes could significantly impact regional nutrition security, subsistence, and economic development. Our findings position *S. tuberosa* as a potential climate adaptation resource, supporting conservation and food security strategies.

As demonstrated here, integrating plant extraction data with species distribution modelling provides valuable insights for managing commercially important native species (Vaz & Nabout, 2016). Our suitability maps can guide *S. tuberosa* conservation areas and commercial plantations (Nabout et al., 2016). While future studies should incorporate production data, physiological responses to climate change, and additional variables, our models highlight optimal cultivation regions: Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, and Bahia.

Sustainable management of *S. tuberosa* populations requires implementing extraction limits to ensure long-term viability. *In situ* conservation is needed to preserve genetic diversity (Sales et al., 2024), complemented by *ex situ* germplasm banks (Santos et al., 2021). These strategies are crucial for guiding *S. tuberosa* conservation in Brazil's semiarid region, ensuring sustainable resources for traditional communities. Figure 6 outlines recommended sustainable extraction practices, highlighting collaboration between extractivists, researchers, and regulatory agencies.

Experienced extractivists hold valuable traditional knowledge about the species and ecosystem, essential for implementing sustainable practices. Research findings can enhance these methods by recommending: a) rotational harvesting to enable population recovery, b) selective harvesting of mature fruits to minimize damage to younger trees and promote long-term productivity, and c) habitat restoration to increase *S. tuberosa* carrying capacity. Simultaneously, environmental agencies can provide oversight, enforce sustainable practices, and ensure regulatory compliance.

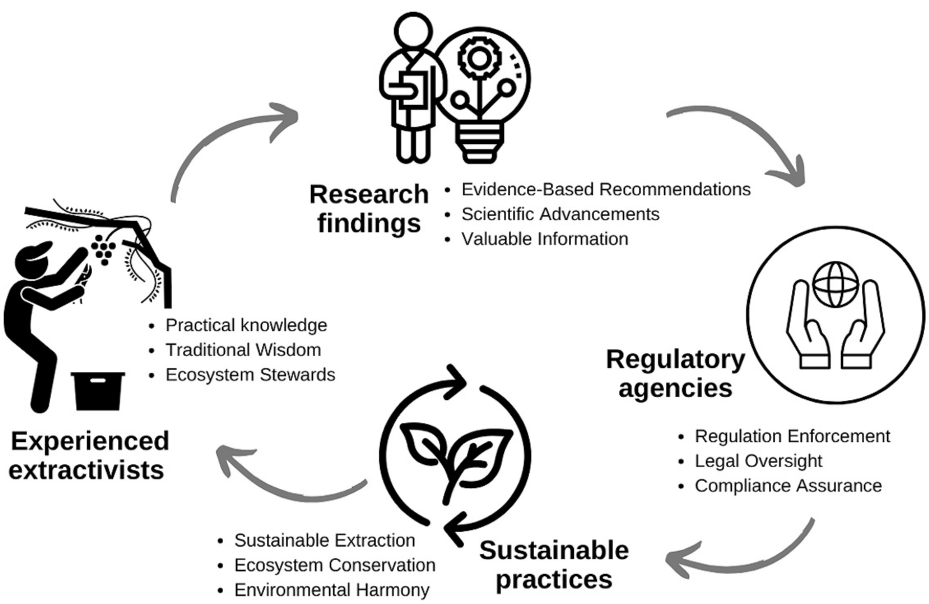

Figure 6: Collaborative approach to sustainable management of *Spondias tuberosa*. The circular diagram illustrates the interactions between experienced extractivists, scientific research, and environmental and regulatory agencies in promoting sustainable harvesting practices.

CONCLUSIONS

Brazilian states with highest *S. tuberosa* fruit production show correspondingly high commercial values, with Bahia leading in both extraction and suitable areas. Annual precipitation is the key climatic variable influencing the species' distribution, and predictive modelling identified favourable regions for its production in Piauí, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Bahia, and northern Minas Gerais. Climate projections indicate expanding suitability for *S. tuberosa*.

Sustainable extraction requires integrating traditional extractivist knowledge with scientific research and agency coordination. Key recommendations include: (1) collecting fruits only from trees bases, (2) leaving damaged fruits on the ground, and (3) rotating harvest areas to maintain seed dispersal and population viability. These practices offer essential guidance for policymakers and conservationists in similar ecosystems.

ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - finance Code 001. The authors acknowledge the Conselho Nacional de Desenvolvimento Científco e Tecnológico (CNPq) for their financial support (Grant no. 407700/2023-4).

AUTHORSHIP CONTRIBUTION

Project Idea: CGF; FAV

Funding: FAV

Database: RPS; RAGSN; CGF; FAV

Processing: RPS; RAGSN; LGP; CGF; FAV

Analysis: RPS; RAGSN; LGP; CGF; FAV

Writing: RPS; RAGSN; CGF; FAV

Review: RAGSN; TKBA; FAV

REFERENCES

ABREU, P. M.; PIMENTA, M. A. S.; SATURNINO, H. M.; et al. Variabilidade genética de umbuzeiro na região norte do estado de Minas Gerais. Revista Brasileira de Biociências, v. 5, n. S1, 279-281, 2007.

AYAN, S.; BUGDAY, E.; VAROL, T.; et al. Effect of climate change on potential distribution of oriental beech (*Fagus orientalis* Lipsky.) in the twenty-first century in Turkey. Theoretical and Applied Climatology, v. 148, n. 1, p. 165-177, 2022. https://doi.org/10.1007/s00704-022-03940-w

BALBINO, E.; CAETANO B.; ALMEIDA, C. Phylogeographic structure of *Spondias tuberosa* Arruda Câmara (Anacardiaceae): seasonally dry tropical forest as a large and continuous refuge. Tree Genetics & Genomes, v. 14, n. 5, p. 67, 2018. https://doi.org/10.1007/s11295-018-1279-4. https://doi.org/10.1007/s11295-018-1279-4

BATISTA, F. R. da C.; SILVA, M. M. de A; ARAÚJO, V. S. Uso sustentável do umbuzeiro: estratégia de convivência com o semiárido. Campina Grande: INSA, 15p., 2015.

BOOTH, T.H.; NIX H.A.; BUSBY, J.R.; et. al. BIOCLIM: the first species distribution model ling package, its early applications and relevance to most current MAXENT studies. Diversity and Distributions, v. 20, n. 1, p1–9, 2014. https://doi.org/10.1111/ddi.12144

BUTT, N.; SEABROOK, L.; MARON, M.; et al. Cascading effects of climate extremes on vertebrate fauna through changes to low-latitude tree flowering and fruiting phenology. Global change biology, v. 21, n. 9, p. 3267-3277, 2015. https://doi.org/10.1111/gcb.12869

CAETANO, R.; SANTOS, E. M. da C.; POIAN, R. Z. et al. Wild food plants with the potential to improve food and nutrition security may be threatened by timber extraction: A systematic review of the Brazilian context. Ethnobiology and Conservation, v. 12, 2023. https://doi.org/10.15451/ec2023-07-12.15-1-35

CHAGAS, K. P. T.; LUCAS, F. M. F.; VIEIRA, F. A. Predictive modeling of *Mimosa tenuiflora* (Willd) Poiret: how can climate change affect its potential distribution range? Floresta, v. 50, n. 2, p. 1315-1324, 2020. http://dx.doi.org/10.5380/rf.v50i2.62980

CHAGAS, K.P.T.; PINHEIRO, L.G.; LUCAS, F.M.F.; et al. Genetic diversity of *Mimosa tenuiflora* (Willd.) Poir.: an intensively exploited wood tree in the Brazilian tropical semi-arid vegetation. Genetic Resources and Crop Evolution, v. 70, p. 1531–1544, 2023. https://doi.org/10.1007/s10722-022-01520-5

CHIU-VALDERRAMA, J. I.; SIUROB-ESPÍNDOLA, B.E.; ZÚÑIGA-VEGA J.J.; et al. Nowhere to go: Potential distribution shifts of a widespread lizard under two climate change scenarios. Ecological Informatics, v. 70, p. 101735, 2022. https://doi.org/10.1016/j.ecoinf.2022.101735

DA SILVA, A. S. S.; ARNAN, X.; DE MEDEIROS, P. M. Climate change may alter the availability of wild food plants in the Brazilian semiarid. Regional Environmental Change, v. 24, n. 2, p. 86, 2024. https://doi.org/10.1007/s10113-024-02250-3

DE ARAUJO, F. P.; AIDAR, S. de T.; MATTA, V. M. da; et al. Extrativismo do umbu e alternativas para a manutenção de áreas preservadas por agricultores familiares em Uauá, BA. Embrapa Semiárido-Documentos (INFOTECA-E), 2016, 21p. Available at: https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/1051576/extrativismo-do-umbu-e-alternativas-para-a-manutencao-de-areas-preservadas-por-agricultores-familiares-em-uaua-ba. Accessed on 28 March, 2025.

DONOGHUE, M. J.; EDWARDS, E. J. Biome shifts and niche evolution in plants. Annual Review of Ecology, Evolution, and Systematics, v. 45, p. 547-572, 2014. https://doi.org/10.1146/annurev-ecolsys-120213-091905. https://doi.org/10.1146/annurev-ecolsys-120213-091905

ELITH, J.; GRAHAM, C. H.; ANDERSON, R. P.; et al. Novel methods improve prediction of species' distributions from occurrence data. Ecography, v. 29, n. 2, p. 129-151, 2006. https://doi.org/10.1111/j.2006.0906-7590.04596.x

GENT, P. R.; DANABASOGLU, G.; DONNER, L. J.; et al. The community climate system model version 4. Journal of climate, v. 24, n. 19, p. 4973-4991, 2011. https://doi.org/10.1175/2011JCLI4083.1

GOBERVILLE, E.; BEAUGRAND, G.; HAUTEKÈETE, N.-C.; et al. Uncertainties in the projection of species distributions related to general circulation models. Ecology and evolution, v. 5, n. 5, p. 1100-1116, 2015. https://doi.org/10.1002/ece3.1411

HAUFF, S. Unidades de conservação e terras indígenas do bioma caatinga. The Nature Conservancy e Ministério do Meio Ambiente, 2008, 2p. Available at: https://antigo.mma.gov.br/estruturas/203/_arquivos/mapa_das_ucs.pdf Accessed on: 28 March, 2025.

IBGE. Produção da extração vegetal e da silvicultura. v. 36, p. 1-8, 2021. Ministério do planejamento desenvolvimento e gestão. Instituto Brasileiro de geografia e estatística - IBGE. Rio de Janeiro. Available at: https://biblioteca.ibge.gov.br/visualizacao/periodicos/74/pevs_2021_v36_informativo.pdf. Accessed on: 28 March, 2025.

JONES, C. D.; HUGHES, J. K.; BELLOUIN, N.; et al. The HadGEM2-ES implementation of CMIP5 centennial simulations. Geoscientific Model Development, v. 4, n.3, p.543-570, 2011. https://doi.org/10.5194/gmd-4-543-2011.

LIMA FILHO, J. M. P. Ecofisiologia do umbuzeiro (*Spondias tuberosa*, Arr. Cam.). Embrapa Semiárido-Documentos (INFOTECA-E), 2011. 24p. https://www.infoteca.cnptia.embrapa.br/bitstream/doc/911418/4/SDC240.pdf

LINS NETO, E. M. F. ; PERONI, E.M.; de ALBUQUERQUE, U. P. Traditional knowledge and management of umbu (*Spondias tuberosa*, Anacardiaceae): An endemic species from the semi-arid region of Northeastern Brazil. Economic Botany, v. 64, p. 11-21, 2010. https://doi.org/10.1007/s12231-009-9106-3

LINS NETO, E. M. L.; ALMEIDA, A. L.; PERONI, N.; et al. Phenology of *Spondias tuberosa* Arruda (Anacardiaceae) under different landscape management regimes and a proposal for a rapid phenological diagnosis using local knowledge. Journal of Ethnobiology and Ethnomedicine, v. 9, 1-13, 2013. https://doi.org/10.1186/1746-4269-9-10

LOBO, J. M.; JIMÉNEZ-VALVERDE, A.; REAL, R. AUC: a misleading measure of the performance of predictive distribution models. Global ecology and Biogeography, v. 17, n. 2, p. 145-151, 2008. https://doi.org/10.1111/j.1466-8238.2007.00358.x

LUCAS, F.M.F.; DAS CHAGAS, K. P. T.; VIEIRA, F. A. Modeling the spatial distribution of a tropical dry forest tree facing climate change. Revista Brasileira de Ciências Agrarias, v. 16, n.1, p. 1-7, 2021. https://doi.org/10.5039/agraria.v16i1a8856

MARGROVE, J. A.; BURSLEM, D. F. R. P.; GHAZOUL, J.; et al. Impacts of an extreme precipitation event on dipterocarp mortality and habitat filtering in a Bornean tropical rain forest. Biotropica, v. 47, n. 1, p. 66-76, 2015. https://doi.org/10.1111/btp.12189

MERTENS, J. et al. Umbuzeiro (*Spondias Tuberosa*): a systematic review. Brazilian Journal of Environmental Sciences (Online), n. 36, p. 179-197, 2015. https://doi.org/10.5327/Z2176-947820151006

MERTENS, J.; ALMEIDA-CORTEZ, J. S.; GERMER, J.; et al. *Spondias tuberosa* Arruda (Anacardiaceae), a threatened tree of the Brazilian Caatinga? Brazilian Journal of Biology, v. 77, n. 3, p. 542-552, 2017. https://doi.org/10.1590/1519-6984.18715

NABOUT, J. C.; MAGALHÃES, M. R.; GOMES, M. A. A.; et al. The impact of global climate change on the geographic distribution and sustainable harvest of *Hancornia speciosa* Gomes (Apocynaceae) in Brazil. Environmental management, v. 57, n. 4, p. 814-821, 2016. https://doi.org/10.1007/s00267-016-0659-5

NADIA, T. L.; MACHADO, I. C.; LOPES, A. V. Pollination of *Spondias tuberosa* Arruda (Anacardiaceae) and analysis of pollinators share with *Ziziphus joazeiro* Mart. (Rhamnaceae), fruit species endemic to the "Caatinga". Brazilian Journal of Botany, v. 30, n. 1, p. 89-100, 2007. http://dx.doi.org/10.1590/S0100-84042007000100009

OLIVEIRA, A. P. C.; BERNARD, E. The financial needs vs. the realities of *in situ* conservation: an analysis of federal funding for protected areas in Brazil's Caatinga. Biotropica, v. 49, n. 5, p. 745-752, 2017. https://doi.org/10.1111/btp.12456

OLIVEIRA, B. F.; COSTA, G. C.; FONSECA, C. R. Niche dynamics of two cryptic *Prosopis* invading South American drylands. Biological invasions, v. 20, n. 1, p. 181-194, 2018. https://doi.org/10.1007/s10530-017-1525-y

PEARCE, J.; FERRIER, S. Evaluating the predictive performance of habitat models developed using logistic regression. Ecological modelling, v. 133, n. 3, p. 225-245, 2000. https://doi.org/10.1016/S0304-3800(00)00322-7

PHILLIPS, S. J.; ANDERSON, R. P.; SCHAPIRE, R. E. Maximum entropy modeling of species geographic distributions. Ecological Modelling, v. 190, n.3-4, p. 231-259, 2006. https://doi.org/10.1016/j.ecolmodel.2005.03.026

QUEIROZ, L. P.; CARDOSO, D.; FERNANDES, M. F.; et al. Diversity and evolution of flowering plants of the Caatinga Domain. In: Silva, J.M.C., Leal, I.R., Tabarelli, M. (eds) Caatinga. Springer, Cham, p. 23-63, 2017. https://doi.org/10.1007/978-3-319-68339-3_2

ROCHA, T. G. F.; SILVA, R. A. R.; DANTAS, E. X.; et al. Fenologia da *Copernicia prunifera* (Arecaceae) em uma área de caatinga do Rio Grande do Norte. Cerne, v. 21, n.4, 673-681, 2015. https://doi.org/10.1590/01047760201521041758

RODRIGUES, P. M. S.; SILVA, J. O.; EISENLOHR, P. V.; et. al. Climate change effects on the geographic distribution of specialist tree species of the Brazilian tropical dry forests. Brazilian Journal of Biology, v. 75, n. 3, p. 679-684, 2015. https://doi.org/10.1590/1519-6984.20913

RODRIGUES, N. L.; SOUZA, A. L. C.; OLIVEIRA, C. C.; et al. Nutritional and biological attributes of *Spondias tuberosa* (Umbu) fruit: An integrative review with a systematic approach. Journal of Food Composition and Analysis, v. 130, n. June 2024, p. 106196, 2024. https://doi.org/10.1016/j.jfca.2024.106196

SALES, R. P.; SILVA, L. C.; NEVES, A. G. S.; et al. Addressing conservation needs: genetic diversity and population ecology of the endemic tree *Spondias tuberosa* Arruda. Scientifica, v. 2024, n. 1, p. 5023974, 2024. https://doi.org/10.1155/2024/5023974

SANTOS, J. R. M.; VIEIRA, F. A.; FAJARDO, C. G. et al. Overexploitation and anthropogenic disturbances threaten the genetic diversity of an economically important neotropical palm. Biodiversity and Conservation, v. 30, p. 2395-2413, 2021. https://doi.org/10.1007/s10531-021-02200-z

SCHMIDT, G. A.; KELLEY, M.; NAZARENKO, L.; et al. Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. Journal of Advances in Modeling Earth Systems, v. 6, n. 1, p. 141-184, 2014. https://doi.org/10.1002/2013MS000265

SOARES, T. N. DINIZ-FILHO, J. A. F.; NABOUT, J. C.; et al. Patterns of genetic variability in central and peripheral populations of *Dipteryx alata* (Fabaceae) in the Brazilian Cerrado. Plant systematics and evolution, v. 301, p. 1315-1324, 2015. https://doi.org/10.1007/s00606-014-1155-0

SOARES, K. R.; FERREIRA, E. E. S.; SEABRA JUNIOR, S.; et al. Extrativismo e Produção de Alimentos como Estratégia de Reprodução de Agricultores Familiares do Assentamento Seringal, Amazônia Meridional. Revista de Economia e Sociologia Rural, v. 56, n. 4, p. 645-662, 2018. https://doi.org/10.1590/1234-56781806-94790560406

VAZ, Ú. L.; NABOUT, J. C. Using ecological niche models to predict the impact of global climate change on the geographical distribution and productivity of *Euterpe oleracea* Mart. (Arecaceae) in the Amazon. Acta Botanica Brasilica, v. 30, n. 2, p. 290-295, 2016. http://doi.org/10.1590/0102-33062016abb0036

VERAS, M. L. M.; MENDONÇA, R. M. N.; SILVA, S. M. et al. Propagation of Umbuzeiro (*Spondias tuberosa* Arr. Cam.), a native plant to Brazilian semi-arid regions, using ethephon and indolebutyric acid (IBA). Australian Journal of Crop Science, v. 12, n. 4, p. 602, 2018. https://doi.org/10.21475/ajcs.18.12.04.pne888

WANG, H.; LIN, S.; DAI, J.; GE, Q. Modeling the effect of adaptation to future climate change on spring phenological trend of European beech (*Fagus sylvatica* L.). Science of The Total Environment, v. 846, p. 157540, 2022. https://doi.org/10.1016/j.scitotenv.2022.157540

WATANABE, S.; HAJIMA, T.; SUDO, K.; et al. MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. Geoscientific Model Development, v. 4, p. 845-872, 2011. https://doi.org/10.5194/gmd-4-845-2011

WEI, J.; ZHANG, H.; ZHAO, W.; et al. Niche shifts and the potential distribution of *Phenacoccus solenopsis* (Hemiptera: Pseudococcidae) under climate change. PLoS One, v. 12, n. 7, p. e0180913, 2017. https://doi.org/10.1371/journal.pone.0180913

YANG, X.; KUSHWAHA, S. P. S.; SARAN, S.; et al. Maxent modeling for predicting the potential distribution of medicinal plant, *Justicia adhatoda* L. in Lesser Himalayan foothills. Ecological Engineering, v. 51, p. 83-87, 2013. https://doi.org/10.1016/j.ecoleng.2012.12.004