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ASPECTOS BIOGEOGRÁFICOS E ECOLÓGICOS DE PALMEIRAS DE BABAÇU

DIEGO PEREIRA SANTOS

São Luís - MA
2025

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Tese de doutorado apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Biodiversidade e Biotecnologia da Rede BIONORTE, na Universidade Estadual do Maranhão, como requisito para a obtenção do Título de Doutor em Biodiversidade e Biotecnologia.

Orientador: Prof. Dr. Fábio Afonso Mazzei Moura de Assis Figueiredo

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Diego Pereira Santos (Discente)

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“Minha terra tem palmeiras,
Onde canta o Sabiá;
As aves, que aqui gorjeiam,
Não gorjeiam como lá.

Nosso céu tem mais estrelas,
Nossas várzeas têm mais flores,
Nossos bosques têm mais vida,
Nossa vida mais amores.

Em cismar, sozinho, à noite,
Mais prazer eu encontro lá;
Minha terra tem palmeiras,
Onde canta o Sabiá.” [...]

— Gonçalves Dias, *Canção do Exílio* (1843)

SANTOS, Diego Pereira. **Aspectos biogeográficos e ecológicos de palmeiras de babaçu**. 2025. 151 f. Tese (Doutorado em Biodiversidade e Biotecnologia) – Universidade Estadual do Maranhão, São Luís, 2025.

RESUMO

A Mata dos Cocais, formação vegetal emblemática do Meio-Norte brasileiro, constitui um mosaico ecológico singular em que as palmeiras representam elementos estruturantes da paisagem, estendendo-se por diversos estados e abrigando notável diversidade sociobiológica. Apesar de sua relevância ecológica e cultural, sua delimitação espacial permanece marcada por incertezas conceituais e cartográficas, um desafio biogeográfico, pois afeta diretamente a forma como se compreende, se planeja e se conserva a paisagem. Entre suas espécies mais representativas, destacam-se as palmeiras do Complexo Babaçu (*Attalea* spp.), reconhecidas por sua ampla distribuição e dominância ecológica, além de sua importância social, econômica e simbólica para comunidades tradicionais que delas dependem. Contudo, tanto os babaçuais quanto a própria Mata dos Cocais estão sob crescente pressão antrópica decorrente da conversão do uso da terra, da fragmentação de habitats e dos efeitos das mudanças climáticas. Assim, compreender esses sistemas requer integrar abordagens espaciais, ecológicas e sociais capazes de traduzir incertezas em instrumentos aplicáveis à conservação. Neste contexto, o presente trabalho buscou preencher lacunas de conhecimento sobre as incertezas biogeográficas que permeiam a Mata dos Cocais e o Complexo Babaçu. Inicialmente, foi realizada uma revisão sistemática de delimitações espaciais existentes atribuídas a Mata dos Cocais. Dentre os principais resultados, foram descobertas sete fontes que apresentaram divergências significativas quanto à sua extensão territorial e critérios de definição. O delineamento de Nascimento e Lima (2016) abrangeu a maior área, e a sobreposição dos diferentes mapas permitiu identificar uma zona de consenso, a qual foi denominada de “região núcleo”, composta por 14 municípios do estado do Maranhão. Essa síntese cartográfica resultou em uma área potencial de ocorrência que abrange 392 municípios distribuídos em cinco estados brasileiros. Em sequência, empregamos a Modelagem de Distribuição de Espécies (SDMs) para sete espécies do Complexo Babaçu e para o grupo como um todo, utilizando os algoritmos *Maximum Entropy* (MaxEnt), *Random Forest* (RF), *Boosted Regression Trees* (BRT) e *Generalized Linear Models* (GLM). Dados de ocorrência provenientes do GBIF foram combinados com variáveis bioclimáticas do CHELSA 2.1 sob o cenário atual (2011-2040) e cenários futuros de alta emissão (SSP3-7.0 e SSP5-8.5) para 2041–2070 e 2071–2100. Os resultados indicaram que RF e BRT geraram projeções mais conservadoras, enquanto MaxEnt e GLM apresentaram distribuições mais amplas. A sazonalidade da temperatura foi o principal preditor bioclimático. *Attalea maripa*, *A. phalerata* e *A. speciosa* exibiram faixas de adequabilidade mais amplas, ao passo que *A. funifera* e *A. vitrivir* apresentaram distribuições mais restritas. Os cenários futuros projetaram aumento de alta adequabilidade, particularmente nas regiões amazônicas e do Cerrado. Apenas *A. funifera* e *A. vitrivir* apresentaram declínios. Ao revelar como as incertezas cartográficas e preditivas limitam o planejamento territorial e a conservação de ecossistemas, este estudo reforça a importância da biogeografia da conservação como campo estratégico para compreender e intervir em paisagens socioecológicas complexas, especialmente em regiões tropicais sujeitas a múltiplas pressões ambientais.

Palavras-chave: Conservação da Terra; Floresta de Palmeiras; Distribuição Espacial; Modelagem de Distribuição de Espécies; Projeção Ecológica.

SANTOS, Diego Pereira. **Biogeographic and ecologic aspects of babassu palm**. 2025. 151 f. Thesis (PhD in Biodiversity e Biotechnology) – State University of Maranhão, São Luís, MA-Brazil, 2025.

ABSTRACT

The Cocais Forest, an emblematic vegetation formation in the Brazilian Mid-North, constitutes a unique ecological mosaic in which palm trees represent structural elements of the landscape, extending across several states and harbouring remarkable sociobiological diversity. Despite its ecological and cultural relevance, its spatial delimitation remains marked by conceptual and cartographic uncertainties, a biogeographical challenge, as it directly affects how the landscape is understood, planned and conserved. Among its most representative species are the palms of the Babassu Complex (*Attalea spp.*), recognised for their wide distribution and ecological dominance, as well as their social, economic and symbolic importance to the traditional communities that depend on them. However, both the babassu palm forests and the Cocais Forest itself are under increasing anthropogenic pressure due to land use conversion, habitat fragmentation and the effects of climate change. Thus, understanding these systems requires integrating spatial, ecological and social approaches capable of translating uncertainties into instruments applicable to conservation. In this context, this study sought to fill gaps in knowledge about the biogeographical uncertainties that permeate Cocais Forest and the Babassu Complex. Initially, a systematic review of existing spatial delimitations attributed to the Cocais Forest was carried out. Among the main results, seven sources were discovered that presented significant divergences in terms of their territorial extension and definition criteria. The delineation by Nascimento and Lima (2016) covered the largest area, and the overlap of the different maps allowed us to identify a zone of consensus, which was named the ‘core region,’ comprising 14 municipalities in the State of Maranhão. This cartographic synthesis resulted in a potential area of occurrence covering 392 municipalities distributed across five Brazilian states. Next, we employed Species Distribution Modelling (SDMs) for seven species of the Babassu Complex and for the group overall, using the Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT) and Generalised Linear Models (GLM) algorithms. Occurrence data from GBIF were combined with bioclimatic variables from CHELSA 2.1 under the current scenario (2011-2040) and future high-emission scenarios (SSP3-7.0 and SSP5-8.5) for 2041–2070 and 2071–2100. The results indicated that RF and BRT generated more conservative projections, while MaxEnt and GLM presented broader distributions. Temperature seasonality was the main bioclimatic predictor. *Attalea maripa*, *A. phalerata*, and *A. speciosa* exhibited broader ranges of suitability, while *A. funifera* and *A. vitrivir* presented more restricted distributions. Future scenarios projected an increase in high suitability, particularly in the Amazon and Cerrado regions. Only *A. funifera* and *A. vitrivir* showed declines. By revealing how cartographic and predictive uncertainties limit territorial planning and ecosystem conservation, this study reinforces the importance of conservation biogeography as a strategic field for understanding and intervening in complex socio-ecological landscapes, especially in tropical regions subject to multiple environmental pressures.

Keywords: Land conservation; Palm forest; Spatial distribution; Species distribution modelling; Ecological projection.

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SUMÁRIO

INTRODUÇÃO

O desenvolvimento de pesquisas sobre os padrões de ocorrência e distribuição dos organismos em ecossistemas de alta biodiversidade é essencial para a ecologia e biologia da conservação, e fundamental para compreender os fatores que norteiam tais padrões (KUJALA; MOILANEN; GORDON, 2018; COELHO et al., 2023). Quando aliados a ferramentas como o sensoriamento remoto, geotecnologias e modelagem preditiva, podem ampliar a precisão das análises ecológicas e oferecer bases científicas para a formulação de políticas públicas direcionadas à conservação ambiental (FERRIER, 2002; ZIZKA et al., 2020).

Apesar dos avanços, ainda existem lacunas significativas sobre a distribuição de plantas em diferentes regiões. SOUSA-BAENA et al. (2014) destacam que muitas políticas conservacionistas permanecem restritas a abordagens generalistas ou pouco aprofundadas, em parte pela escassez de informações taxonômicas e biogeográficas robustas. Essa limitação restringe a eficiência das estratégias de manejo e conservação, o que cria um desafio que requer ações e informações mais assertivas, sobretudo ao considerarmos ecossistemas complexos e de grande importância socioambiental (BOULINIER et al., 1988; KUJALA; MOILANEN; GORDON, 2018; COELHO et al., 2023).

Um exemplo emblemático é a “Mata dos Cocais”, uma formação vegetal de transição do Meio-Norte brasileiro caracterizada pela predominância de palmeiras (TEIXEIRA, 2008; MORAES; MACHADO; ARAÚJO, 2015). Essa região apresenta inconsistências cartográficas e conceituais quanto à sua delimitação em diversas literaturas (BARRETO; PARISE; DE ALMEIDA, 2019; IMESC (Brasil), 2021; LAPIG (Brasil), 2019; NASCIMENTO; LIMA, 2016; OLSON et al., 2001; ROCHA et al., 2011; SANTOS-FILHO; ALMEIDA JÚNIOR; SOARES, 2013). Tais incertezas dificultas o planejamento territorial e a implementação de ações de conservação, num contexto em que a expansão agrícola e pecuária exerce forte pressão sobre a paisagem (GEHRING et al., 2020; MITJA et al., 2018; SANTOS et al., 2022).

Nesse mosaico, destacam-se as espécies do Complexo Babaçu (*Attalea spp.*), que apresentam altas densidade populacionais e desempenham funções ecológicas, econômicas e culturais relevantes (LIMA et al., 2003; PORRO, 2019). Os babaçuais sustentam práticas de subsistência, fornecem recursos energéticos e alimentares e compõem identidades culturais de comunidades tradicionais, como as quebradeiras de coco. No entanto, a fragmentação e a degradação resultantes da conversão de habitats têm alterado a distribuição dessas populações e comprometido a manutenção do ecossistema (GEHRING et al., 2020; MITJA et al., 2018; SANTOS et al., 2022).

Além do uso da terra, os babaçuais estão sujeitos aos efeitos das mudanças climáticas, que interagem de forma sinérgica com a expansão agropecuária. O aumento das temperaturas, a alteração dos regimes de chuva e a intensificação de eventos extremos podem afetar a reprodução, a fenologia e a sobrevivência dessas palmeiras (BLOIS et al., 2013; PETERSON et al., 2011). Estudos recentes já apontam que cenários climáticos futuros podem restringir a adequabilidade de habitat de algumas espécies de *Attalea* em regiões como Caatinga e Mata Atlântica (DE LIMA et al., 2022; MENEZES et al., 2023). Entretanto, os efeitos sobre o Complexo Babaçu como um todo ainda permanecem pouco compreendidos.

Diante desse contexto, torna-se necessário investigar simultaneamente as incertezas biogeográficas e espaciais associadas à Mata dos Cocais e os potenciais impactos das mudanças climáticas sobre as espécies de babaçu. Compreender esses sistemas requer integrar abordagens espaciais, ecológicas e sociais capazes de traduzir incertezas em instrumentos aplicáveis à conservação. Por meio de uma abordagem interdisciplinar que alia ecologia, geotecnologias e modelagem bioclimática, este trabalho parte das seguintes hipóteses: (1) as delimitações espaciais da Mata dos Cocais apresentam variações significativas entre diferentes fontes cartográficas; (2) apesar dessas divergências, existe uma área de sobreposição entre os mapas analisados, o que pode ser considerada como uma "região núcleo"; (3) a distribuição das espécies do Complexo Babaçu é fortemente influenciada por fatores associados à temperatura e disponibilidade hídrica; e (4) os cenários climáticos futuros podem alterar a extensão das áreas de alta adequabilidade de habitat, ampliando-as para algumas espécies e restringindo-as para outras.

Para testar essas hipóteses, este trabalho teve como objetivos específicos: realizar uma revisão sistemática das delimitações espaciais da Mata dos Cocais, comparando mapas existentes e propondo uma síntese cartográfica, e; modelar a distribuição bioclimática potencial das espécies do Complexo Babaçu utilizando os métodos da *Maximum Entropy*, *Random Forest*, *Generalized Linear Models* e *Boosted Regression Trees*, sob cenário atual (2011-2040) e dois cenários de mudanças climáticas para os períodos de 2041-2070 e 2071-2100, avaliando a contribuição relativa das variáveis ambientais.

Por fim, foi buscada a produção de resultados que possam ser utilizados como base informativa a ser potencialmente consultada para o planejamento de políticas públicas, estratégias de manejo sustentável, ações de planejamento socioeconômico, dentre outros, alinhando-se a metas globais como os Objetivos de Desenvolvimento Sustentável (ODS), em especial os ODS 13 (Ação Climática) e 15 (Vida Terrestre). Ao reconhecer o papel estratégico do babaçu para a bioeconomia e para a segurança socioambiental de comunidades tradicionais, este trabalho também dialoga com os ODS 1 (Erradicação da Pobreza), 2 (Fome Zero) e 12 (Consumo e Produção Sustentáveis).

REFERENCIAL TEÓRICO

A Mata dos Cocais e o Complexo Babaçu

A Mata dos Cocais, também chamada de Zona dos Cocais ou Floresta de Babaçu, é uma formação vegetal localizada no Meio-Norte brasileiro (REIS et al., 2018; SANTOS-FILHO; ALMEIDA JÚNIOR; SOARES, 2013). Esta formação é caracterizada como um ecótono complexo, pois se trata de uma zona de transição que engloba em grande escala os biomas da Floresta Amazônica a oeste, do Cerrado ao sul e, em menor extensão, a Caatinga a leste e a Mata Atlântica na porção costeira, o que lhe confere elevada diversidade florística e funcional (TEIXEIRA, 2008; MORAES; MACHADO; ARAÚJO, 2015). Sua fitofisionomia é marcada pela predominância de palmeiras, sobretudo do Complexo Babaçu (*Attalea spp.*). Palmeiras como a carnaúba (*Copernicia prunifera*), o buriti (*Mauritia flexuosa*) e o tucum (*Bactris setosa*) também são elementos fitofisionômicos importantes, possuindo papel relevante na estrutura ecológica e nas práticas socioeconômicas na região (ARGIBAY; SPARACINO; ESPINDOLA, 2020; FEITOSA; TROVÃO, 2006; SARAIVA et al., 2020).

Embora as formações de palmeiras estejam incluídas em classificações globais, como os mapas globais de ecorregiões (OLSON et al., 2001) ou o produto de cobertura do solo da *European Space Agency* (HARPER et al., 2023), a delimitação espacial da Mata dos Cocais é marcada por fortes incertezas conceituais e cartográficas. A ausência de critérios padronizados para sua caracterização estrutural e funcional, levaram a diferentes interpretações cartográficas (BARRETO; PARISE; DE ALMEIDA, 2019; IMESC (Brasil), 2021; LAPIG (Brasil), 2019; NASCIMENTO; LIMA, 2016; OLSON et al., 2001; ROCHA et al., 2011; SANTOS-FILHO; ALMEIDA JÚNIOR; SOARES, 2013).

Enquanto alguns autores a classificam como uma formação secundária resultante de processos antrópicos, outros a reconhecem como uma unidade ecológica com dinâmica e composição próprias (BARRETO; PARISE; DE ALMEIDA, 2019; NASCIMENTO; LIMA, 2016; SANTOS-FILHO; ALMEIDA JÚNIOR; SOARES, 2013). Essa falta de consenso entre as informações compromete o planejamento territorial e as políticas de conservação, uma vez que a ausência de fronteiras claramente definidas dificulta a gestão integrada de ecossistemas (ACOSTA-VELÁZQUE0,Z et al., 2023;

DELAROCHE; LE TOURNEAU; DAUGEARD, 2022; MARQUES et al., 2019; RECHCIŃSKI; TUSZNIO; GRODZIŃSKA-JURCZAK, 2019).

Dentro desse mosaico paisagístico da Mata do Cocais, o Complexo Babaçu, um agrupamento de espécies do gênero *Attalea* que exibem características morfológicas em comum, hibridização natural frequente e limites taxonômicos não resolvidos, assume um papel central (CAVALLARI; TOLEDO, 2016; MATA et al., 2022; PINTAUD, 2008). A taxonomia de *Attalea* permanece um dos desafios mais persistentes da botânica neotropical. O número de espécies reconhecidas variou amplamente ao longo do tempo (de 29 a 73), e apenas cerca de vinte alcançaram consenso entre especialistas (PINTAUD, 2008). Essa instabilidade resulta de uma combinação de fatores, incluindo a ampla variação morfológica intraespecífica, a escassez e perda de espécimes-tipo e a ocorrência frequente de híbridos naturais, que dificultam a delimitação precisa entre táxons (HENDERSON, 2020).

HENDERSON (2020) analisaram 902 espécimes de herbário utilizando 21 variáveis quantitativas e 33 qualitativas, reconhecendo 30 espécies válidas. Esses resultados evidenciam a complexidade intrínseca do gênero e a expressiva sobreposição morfológica entre grupos próximos. Estudos filogenéticos recentes (FREITAS et al., 2016) ampliam essa discussão ao revelar que alguns agrupamentos tradicionalmente reconhecidos não são monofiléticos, o que desafia os enquadramentos taxonômicos clássicos e reforça a necessidade de revisões que integrem dados moleculares, anatômicos e morfológicos.

Complementarmente, MATA et al. (2022) demonstraram que a anatomia foliar pode fornecer caracteres diagnósticos relevantes para diferenciar espécies do Complexo Babaçu. O estudo identificou que traços como a disposição dos estômatos, a organização dos feixes vasculares e a espessura do parênquima paliçádico oferecem suporte anatômico à distinção taxonômica, embora possuam muitas características anatômicas comuns, como epiderme unisseriada, cicatrizes glandulares e mesofilo dorsiventral, justificando seu reconhecimento como taxas distintas e reforçando que as avaliações ecológicas sejam feitas também em nível de espécie.

As espécies atualmente reconhecidas no Complexo Babaçu incluem *Attalea barreirensis* Glassman, *A. eichleri* (Drude) A.J. Hend, *A. funifera*, *A. maripa* (Aubrl) Mart., *A. phalerata* Mart. ex Spreng., *A. speciosa* Mart. ex Spreng. e *A. vitrivir*, além de dois híbridos *A. x teixeirana* (Bondar) Zona (*A. eichleri* x *A. speciosa*) e *A.* ×

dahlgreniana (Bondar) Wess. Boer (*A. speciosa* x *A. maripa*). Por mais que as diferenças morfológicas e anatômicas revelem a diversidade interna do gênero, todas as espécies de *Attalea* compartilham atributos ecológicos que as tornam elementos estruturantes dos ecossistemas tropicais. Assim, as incertezas taxonômicas do gênero não constituem apenas uma questão de nomenclatura, mas refletem lacunas mais amplas no conhecimento evolutivo e ecológico. É precisamente nesse ponto que a perspectiva taxonômica se conecta à ecológica: compreender as variações morfológicas e funcionais entre espécies é essencial para interpretar o papel que desempenham nas comunidades vegetais e nos processos ecológicos em múltiplas escalas.

As palmeiras, no geral, são componentes estruturais de destaque nos ecossistemas tropicais e desempenham múltiplas funções ecológicas. Elas influenciam a ciclagem de nutrientes, regulam o microclima do solo, abrigam fauna associada e contribuem para a regeneração natural após distúrbios (ARAÚJO et al., 2016; BLACH-OVERGAARD et al., 2010; CORRÊA et al., 2023; PORRO, 2019; RESSIORE; LIMA; TURNHOUT, 2024). No caso das espécies do Complexo Babaçu, destacam-se a alta produtividade de frutos, a dispersão zoocórica (principalmente por mamíferos e aves), a capacidade de rebrota após o fogo ou corte, e a estruturação de ecossistemas abertos e semiabertos, o que explica sua ampla distribuição e resiliência frente a distúrbios (REIS et al., 2018; SANTOS-FILHO; ALMEIDA JÚNIOR; SOARES, 2013; SILVA et al., 2014; TEIXEIRA, 2008). Essas características fazem dos babaçuais formações-chave na manutenção da conectividade ecológica e dos serviços ecossistêmicos regionais.

Indo além dos seus valores ecológicos, as espécies do Complexo Babaçu são um pilar para a manutenção de práticas culturais e valores identitários (RESSIORE; LIMA; TURNHOUT, 2024). A exploração do babaçu é uma atividade extrativista de grande importância socioeconômica e cultural para milhares de famílias, especialmente as quebradeiras de coco, quilombolas e indígenas, que dependem em diferentes graus de seus produtos para a segurança alimentar e subsistência (ALMEIDA CAMPOS et al., 2015; LIMA et al., 2003; PORRO, 2019). O coco babaçu é o principal produto dessas palmeiras. Altamente versátil, a partir do coco podem ser originados diversos subprodutos, como farinha de mesocarpo (CARDOSO VIEIRA et al., 2023), óleo (NETO et al., 2021), carvão vegetal, biocombustível (CORRÊA et al., 2023), aditivos químicos (VIEIRA et al., 2011), além de farelos para alimentação animal (PORTELA et al., 2024).

Dessa forma, a pluralidade de usos do babaçu o posiciona como um elemento-chave para a sustentabilidade econômica e cultural de comunidades.

Apesar de toda importância socioambiental e econômica, os babaçuais e a Mata dos Cocais como um todo estão sob intensa pressão antrópica decorrente do processo de transformação do uso da terra. De modo geral, as mudanças contínuas no uso e na cobertura do solo já afetaram a distribuição geográfica de muitas espécies, perturbando os fluxos gênicos e taxonômicos globalmente, com impactos diretos à diversidade biológica (JUNG; ROWHANI; SCHARLEMANN, 2019; NEWBOLD et al., 2015; PANTHI et al., 2019). A diminuição da densidade populacional do babaçu não apenas afeta os modos de vida das comunidades tradicionais e a disponibilidade de recursos, mas, de forma geral, fragiliza o equilíbrio ecossistêmico (MITJA et al., 2018, 2019; PORRO; VEIGA; MOTA, 2011).

As mudanças no uso da terra associadas aos efeitos das mudanças climáticas intensificam as pressões sobre os babaçuais, afetando sua regeneração e distribuição. O avanço agropecuário, a fragmentação florestal e a conversão de habitats reduzem a conectividade das populações, enquanto o aumento das temperaturas e a alteração nos regimes de precipitação afetam processos ecológicos como germinação, frutificação e dispersão (ADHIKARI et al., 2022; BELLARD et al., 2012; HOLYOAK; HEATH, 2016; KATUWAL et al., 2023; TRAUTMANN, 2018). Essa sinergia entre uso da terra e clima representa uma ameaça crescente à persistência dos babaçuais, especialmente em ecossistemas de transição onde pequenas variações ambientais podem redefinir limites de adequabilidade. Adicionalmente, as mudanças nos regimes de chuva, o aumento das temperaturas e a ocorrência de eventos climáticos extremos podem afetar a fenologia, a reprodução e a sobrevivência das palmeiras (BLOIS et al., 2013; DE KORT et al., 2021; EISERHARDT et al., 2011; PETERSON et al., 2011).

Pesquisas recentes sugerem que os cenários climáticos futuros previstos podem desfavorecer a expansão de áreas de alta adequabilidade para algumas espécies do gênero *Attalea* em regiões como a Caatinga e Mata Atlântica (DE LIMA et al., 2022; MENEZES et al., 2023). Estudos sobre outras espécies de palmeiras ou ecossistemas similares, como os de BLACH-OVERGAARD et al. (2010) e EISERHARDT et al. (2011), já haviam demonstrado a sensibilidade das Arecaceae às variações climáticas. Entretanto, os efeitos das mudanças climáticas sob as espécies do Complexo Babaçu ainda são insuficientemente compreendidos. Compreender os potenciais mecanismos pelos quais as mudanças climáticas podem afetar essas palmeiras é crucial para antecipar o efeito desses cenários e auxiliar no desenvolvimento de estratégias de adaptação e mitigação de seus impactos (ELLIOTT et al., 2024; LANNUZEL et al., 2021; VOLIS; TOJIBAEV, 2021).

Biogeografia e Ecologia Espacial

Das diversas disciplinas que compõem as ciências naturais, a biogeografia busca, por essência, explicar os processos que norteiam a distribuição dos organismos em determinado espaço, bem como os fatores que moldam a dinâmica de seus padrões ao longo do tempo (RECODER, 2011; COX; MOORE; LADLE, 2016; LOMOLINO; RIDDLE; WHITTAKER, 2016). Trata-se de uma ciência interdisciplinar que integra aspectos ecológicos, evolutivos, geográficos e históricos, visando determinar espacialmente a distribuição das espécies e identificar padrões cruciais para o levantamento, reconhecimento e conservação de táxons em ecossistemas (LOMOLINO; RIDDLE; WHITTAKER, 2016; WEN; NIE; ICKERT-BOND, 2019).

De forma complementar, a ecologia espacial emerge com uma abordagem mais direta aos efeitos do espaço e da escala sobre os processos ecológicos, o que permite análises mais robustas sobre ocupação, conectividade e dinâmica das espécies (FLETCHER; FORTIN, 2018). A integração entre biogeografia e ecologia espacial tem se tornado essencial para a ecologia da conservação, especialmente em regiões tropicais onde a incerteza ecológica e informacional é elevada, representando um avanço metodológico significativo para o enfrentamento dos desafios socioambientais contemporâneos.

Essa sinergia pode fornecer bases sólidas para pesquisas ecológicas, permitindo uma abordagem holística na compreensão da distribuição da biodiversidade e na formulação de soluções sustentáveis para sua conservação, o que viabiliza abordagens interdisciplinares e multiescalares necessárias para lidar com os desafios ambientais emergentes (COBB; NALAU; CHAUVENET, 2024; MAGDALENA; DE SOUZA; AMORIM, 2023). Essa abordagem é fundamental para informar decisões em planejamento ambiental e políticas públicas de conservação, sendo mais urgente diante das rápidas transformações ambientais (FERRIER, 2002; OSHIMA et al., 2021).

Um dos aspectos teóricos centrais para a biogeografia, a abordagem determinística da teoria do nicho ecológico define que a amplitude geográfica de uma espécie depende diretamente da atuação dos fatores ambientais, os quais estabelecem os limites de tolerância para sua sobrevivência, desenvolvimento e reprodução (COELHO et al., 2023; KUJALA; MOILANEN; GORDON, 2018; PETERSON et al., 2011). A partir desse princípio, a distribuição geográfica observada das espécies pode ser compreendida como o resultado da interação entre suas exigências ecológicas e a disponibilidade de condições ambientais adequadas (HUTCHINSON, 1991; PETERSON et al., 2011).

Entre os fatores que mais influenciam a distribuição natural das espécies, destacam-se as variações climáticas e edáficas, que influenciam estrutura, funcionamento e composição dos ecossistemas (FURLEY; RATTER, 1988; PUNYASENA; ESHEL; MCELWAIN, 2007). As variáveis climáticas apresentam-se como um fator particularmente importante para as palmeiras, na medida em que a sua distribuição está frequentemente associada à umidade e temperatura (DE KORT et al., 2021; EISERHARDT et al., 2011). Alterações nesses componentes podem induzir profundas transformações nas comunidades biológicas.

A intensificação do uso da terra para agricultura e pecuária, juntamente com o uso irracional dos recursos naturais, são vetores de transformação que, em sinergia com as mudanças climáticas, fragilizam o meio ambiente e comprometem a biodiversidade e a estabilidade dos serviços ecossistêmicos (LUINTEL; SCHELLER; BLUFFSTONE, 2018). Na extensão da Mata dos Cocais, por exemplo, a fragmentação de habitats causada pela expansão agrícola afeta diretamente a distribuição espacial e a densidade das populações de babaçu (BARRETO; PARISE; DE ALMEIDA, 2019; GEHRING et al., 2020; SANTOS et al., 2022), o que ressalta a urgência de estudos para subsidiar ações de manejo e conservação. A fragmentação dos habitats compromete o fluxo gênico e a resiliência de ecossistemas, colocando em risco a diversidade biológica (ADHIKARI et al., 2022; BELLARD et al., 2012; TRAUTMANN, 2018). A degradação ambiental resultante diminui a resiliência desses ambientes a perturbações, colocando em risco a manutenção das espécies a longo prazo (VELAZCO et al., 2019).

É crucial considerar, ainda, que os efeitos das mudanças ambientais não se manifestam de maneira homogênea no espaço. As regiões tropicais, por exemplo, são particularmente vulneráveis às alterações na temperatura e nos regimes de chuvas, fatores que afetam drasticamente a fenologia das espécies e sua distribuição geográfica

(CORREA-LIMA et al., 2019). Entretanto, compreender e mitigar esses efeitos exige um conhecimento técnico e científico sólido sobre os ecossistemas e suas espécies, algo ainda incipiente em muitos ambientes de transição do Brasil.

Nesse contexto, a biogeografia da conservação se estabelece como um campo aplicado que utiliza princípios e métodos biogeográficos para priorizar áreas e estratégias de conservação eficazes (FERRIER, 2002; ZIZKA et al., 2020). A distribuição das espécies deixa de ser vista apenas como um produto de gradientes ambientais, e passa a ser compreendida como um campo de interação entre história evolutiva, dinâmica ecológica e pressões antrópicas (ACEVEDO et al., 2016; WHITTAKER et al., 2005). Além disso, a biogeografia da conservação pode incorporar, ainda, componentes sociais e culturais, reconhecendo que a conservação efetiva depende da integração entre natureza e sociedade (TEEL et al., 2018). Sua abordagem, entretanto, depende fortemente da disponibilidade e qualidade das informações, o que torna a incerteza informacional um desafio central.

A incerteza informacional engloba tanto a escassez de dados ecológicos, taxonômicos e climáticos quanto as imprecisões associadas à sua representação espacial (MEYER; WEIGELT; KREFT, 2016). Em ecossistemas de transição, como a Mata dos Cocais, essa condição se manifesta como incerteza espacial: fronteiras entre biomas difusas, delimitações cartográficas inconsistentes e ausência de critérios padronizados para definir a extensão e a funcionalidade ecológica da paisagem. Essas incertezas refletem não apenas limitações de dados, mas também a natureza contínua e gradativa dos sistemas ecológicos, cuja variabilidade desafia classificações rígidas e generalizações simplificadas (CRESSIE et al., 2009; ROCCHINI et al., 2011). Compreender a biogeografia sob essa perspectiva implica reconhecer que as fronteiras ecológicas são zonas de transição probabilísticas e contextuais, cuja definição depende da escala, das variáveis utilizadas e dos métodos empregados (KENT et al., 1997).

Nesse cenário, a identificação de refúgios climáticos, áreas que permanecem relativamente estáveis mesmo sob cenários de mudança climática, tem se mostrado uma estratégia eficaz para a persistência das espécies, devendo ser prioritárias nos esforços de conservação (BARROWS et al., 2020; BAUMGARTNER; ESPERÓN-RODRÍGUEZ; BEAUMONT, 2018; MORELLI et al., 2020). Das diversas estratégias que podem ser adotadas, a construção de cenários espaciais preditivos baseados em modelagens bioclimáticas surge como uma alternativa concreta para contornar as lacunas informacionais e espaciais e antecipar as possíveis consequências de diferentes trajetórias de desenvolvimento, possibilitando a proposição de medidas preventivas e adaptativas que contribuam com a resiliência dos sistemas socioecológicos (GARCÍA; MARTÍNEZ FERNÁNDEZ; FITZ, 2020; ZAAR, 2023).

O avanço das tecnologias de geoprocessamento e modelagem estatística tem permitido o refinamento dos estudos biogeográficos, possibilitando a análise de grandes volumes de dados ambientais e biológicos (HOBAN et al., 2019; WEN; NIE; ICKERT-BOND, 2019). A avaliação da vulnerabilidade das espécies baseada, por exemplo, em modelos de adequabilidade de habitat e dados de história de vida, dispersão e plasticidade fenotípica, permite hierarquizar os esforços de conservação de maneira mais eficiente (FLEURY et al., 2024; HUNTER-AYAD et al., 2020; ROSS; WORT; HOWELL, 2019). Esses avanços resultaram no desenvolvimento de modelos preditivos cada vez mais precisos sobre a distribuição das espécies e os efeitos de variáveis ambientais sobre seus padrões de ocorrência (ELITH; FRANKLIN, 2013; FRANKLIN, 2023).

Modelagem da Distribuição Potencial de Espécies

A construção de mapas de predição dos padrões geográficos de distribuição das espécies e da adequabilidade de habitats de áreas pouco amostradas e a projetação de respostas a cenários de mudanças climáticas tem se mostrado essencial para o planejamento e manejo da conservação de ecossistemas, sendo chave para a biogeografia da conservação (ELITH; LEATHWICK, 2009; FERRIER, 2002; PALACIO et al., 2021; ZIZKA et al., 2020). As modelagens de distribuição de espécies (*Species Distribution Modelling* - SDMs), especificamente, têm sido amplamente empregadas para investigar questões fundamentais da biogeografia, como a identificação de áreas de maior diversidade, a compreensão de padrões históricos de distribuição e a previsão de impactos das mudanças ambientais (ELITH; FRANKLIN, 2013; FRANKLIN, 2023).

O cerne dos SDMs reside no pressuposto de que as condições ecológicas, tanto bióticas quanto abióticas, moldam a distribuição potencial das espécies, influenciando diretamente processos demográficos fundamentais como crescimento, sobrevivência e reprodução (LIAN et al., 2022; PAGEL et al., 2020; PEARCE-HIGGINS et al., 2015). Como nota-se, os SDMs fundamentam-se nos princípios da teoria do nicho ecológico, permitindo a identificação de regiões potencialmente habitáveis por meio da correlação entre pontos de ocorrência georreferenciados e variáveis ambientais preditoras (BRUN et al., 2020; ELITH; FRANKLIN, 2013; FRANKLIN, 2023; NAIMI; ARAÚJO, 2016; PETERSON et al., 2011). As áreas com maior probabilidade de ocorrência para uma determinada espécie são aquelas que oferecem as condições ideais para a maximização do seu *fitness*.

Dessa forma, os padrões de distribuição de uma espécie refletem a complexa interação entre suas exigências ecológicas e os gradientes ambientais em que está inserida. Essa abordagem contribui não apenas com a compressão da presença atual de uma espécie, mas também seu potencial de ocorrência em outras regiões diante de condições favoráveis (COELHO et al., 2023; KUJALA; MOILANEN; GORDON, 2018; LIAN et al., 2022; PETERSON et al., 2011).

Entre suas diversas aplicações, os SDMs permitem avaliar como fatores ecológicos e climáticos afetam a biodiversidade, mapear a distribuição futura de espécies sob cenários de mudanças climáticas e prever a expansão de espécies invasoras (ALVES et al., 2023; BARBET-MASSIN et al., 2018). Suas projeções são essenciais para antecipar desafios de manejo e estabelecer estratégias de mitigação de impactos (PECCHI et al., 2019). Contudo, os modelos não eliminam a incerteza, eles a formalizam e a tornam mensurável. A qualidade dos resultados depende da resolução das variáveis ambientais, da representatividade das ocorrências e da robustez dos algoritmos empregados, sendo essencial tratá-los como representações probabilísticas e não determinísticas (BEALE; LENNON, 2012; SRIVASTAVA; LAFOND; GRIESS, 2019).

Essa ferramenta é particularmente valiosa para espécies com dados de ocorrência escassos ou em risco de extinção, possibilitando o delineamento de áreas prioritárias para conservação (LANNUZEL et al., 2021; VOLIS; TOJIBAEV, 2021). A aplicação dos modelos de distribuição são bastante relevantes, também, para espécies de ampla distribuição ou com grande importância ecológica e socioeconômica. Nesses casos, a identificação de áreas de alta densidade populacional pode guiar ações de manejo, conservação e uso sustentável, contribuindo para a formulação de políticas públicas ambientalmente fundamentadas (AVOLIO et al., 2019; OSHIMA et al., 2021).

No caso do Complexo Babaçu, essa perspectiva ganha especial relevância. A combinação de limites taxonômicos imprecisos, lacunas de amostragem e processos ecológicos complexos, como a síndrome de dispersão zoocórica na maioria de suas espécies e regeneração pós-distúrbio, impõe desafios adicionais à modelagem bioclimática. Dessa forma, compreender sua distribuição potencial não é apenas um exercício estatístico, mas uma oportunidade de explorar como a incerteza se manifesta simultaneamente no espaço ecológico e geográfico, moldando tanto a compreensão científica quanto as decisões de conservação.

A modelagem também oferece suporte para a avaliação de impactos decorrentes de alterações no uso e cobertura da terra, a inclusão de variáveis antropogênicas nos modelos tem se mostrado cada vez mais relevante (FRANS et al., 2022; NUÑEZ-PENICHET; MAITA; SOBERON, 2024; ZUQUIM et al., 2023). Fatores como densidade populacional, proximidade de áreas agrícolas, infraestrutura viária e índices de pressão antrópica se mostram determinantes na busca por distribuições mais reais das espécies e devem ser incorporados para aumentar a acurácia dos modelos (FRANS; LIU, 2024; PANTHI et al., 2019; REQUENA-MULLOR et al., 2019).

Os SDMs tem sido muito utilizados em contextos de mudanças climáticas, especialmente em regiões tropicais. Ao simular diferentes cenários futuros de mudanças climáticas, é possível prever como tais mudanças podem afetar a distribuição das espécies e a estabilidade dos ecossistemas (FRANKLIN, 2023). Espécies da família Arecaceae, como as do Complexo Babaçu, têm sido amplamente estudadas por sua sensibilidade às variações climáticas e por sua importância ecológica na manutenção da integridade dos ecossistemas tropicais (BLACH-OVERGAARD et al., 2010; COSTA et al., 2022; EISERHARDT et al., 2011; GÖLDEL; KISSLING; SVENNING, 2015).

Nesse cenário, os modelos possibilitam identificar áreas que permanecerão adequadas para essas espécies no futuro, mesmo sob cenários climáticos adversos. Tais áreas podem funcionar como refúgios climáticos, devendo, assim, serem consideradas prioritárias para a conservação, restauração ecológica e manutenção de serviços ambientais (CHHETRI; BADOLA; BARAT, 2021; FOIS et al., 2016; KATUWAL et al., 2023).

Ao associar os resultados da modelagem à análise de vulnerabilidade ecológica, por exemplo, os SDMs podem subsidiar políticas de adaptação às mudanças climáticas. Isso inclui, por exemplo, o redirecionamento de unidades de conservação, a priorização de corredores ecológicos e o apoio a comunidades tradicionais dependentes dos recursos naturais (BLAIR; LE; XU, 2022; FERRAZ et al., 2021; IANNELLA et al., 2021; PECCHI et al., 2019). A falta de conhecimento sobre a sensibilidade específica de cada espécie do Complexo Babaçu a essas variáveis climáticas representa uma lacuna crítica que pode ser abordada no âmbito da modelagem bioclimática preditiva.

A flexibilidade metodológica dos SDMs permite a utilização de diferentes algoritmos estatísticos e de aprendizado de máquina, como os modelos de Máxima Entropia (MaxEnt), *Random Forest* (RF), Modelos Lineares Generalizados (GLM), *Boosted Regression Trees* (BRT), dentre outros (KARGER et al., 2023; PHILLIPS; DUDÍK, 2008; ZHANG et al., 2019). O MaxEnt, por exemplo, é amplamente utilizado devido à sua robustez com dados apenas de presença e sua capacidade de modelar relações complexas entre espécies e variáveis ambientais (JHA; J; NAMEER, 2022; VENNE; CURRIE, 2021). O RF é um método de aprendizado de máquina que se destaca pela alta precisão preditiva e pela capacidade de lidar com interações não-lineares e multicolinearidade, sendo menos propenso a *overfitting* (DE MARCO; NÓBREGA, 2018). Os GLMs, por sua vez, oferecem uma abordagem estatística mais tradicional, permitindo a interpretação direta da relação entre as variáveis preditoras e a probabilidade de ocorrência (NORBERG et al., 2019; VALAVI et al., 2022). Os BRTs combinam a flexibilidade das árvores de decisão com a capacidade de melhorar a precisão por meio do *boosting*, sendo eficazes na captura de padrões complexos e na identificação de variáveis importantes (IRVING; JÄHNIG; KUEMMERLEN, 2020).

Cada um desses métodos possui características distintas que os tornam adequados para diferentes tipos de dados e perguntas de pesquisa. Contudo, a utilização de um conjunto de modelos, em vez de um único, pode permitir uma avaliação mais abrangente da adequabilidade de habitat e uma maior confiança nas projeções, mitigando as incertezas inerentes a cada método individual (HAO et al., 2019; KAKY et al., 2020; MARMION et al., 2009; VALAVI et al., 2022).

AUSTIN (2002) destacou que o conhecimento ecológico das espécies modeladas é um elemento crucial no processo de modelagem. Os SDMs têm sido utilizados em estudos comparativos entre diferentes espécies ou grupos taxonômicos, permitindo análises de sobreposição de nicho, complementaridade de distribuição e potenciais interações ecológicas (MURPHY; SMITH, 2021; STIELS; SCHIDELKO, 2018). Tais análises contribuem para o delineamento de estratégias integradas de conservação. A interpretação dos resultados e a seleção das variáveis ambientais devem estar fundamentadas em informações biológicas sólidas, evitando inferências equivocadas e reforçando a robustez dos modelos gerados (FOURCADE; BESNARD;

SECONDI, 2017). Fatores como interações bióticas, capacidade de dispersão das espécies e processos evolutivos adaptativos são difíceis de incorporar nos modelos, mas podem ter um papel crucial na determinação da distribuição real das espécies (DORMANN et al., 2018; RECORD et al., 2018).

Cabe reconhecer, contudo, as limitações intrínsecas aos SDMs. Seus modelos baseiam-se em premissas simplificadoras, como a de que a distribuição atual das espécies reflete seu nicho ecológico completo e que as relações espécie-ambiente permanecerão constantes no futuro (PEREZ-NAVARRO et al., 2021; PETERSON et al., 2011; PIIRAINEN et al., 2023). Além disso, a qualidade dos dados de ocorrência e das variáveis ambientais (ex: viés de amostragem e resolução espacial) pode influenciar significativamente a acurácia das predições (LAKE; BRISCOE RUNQUIST; MOELLER, 2020; LEE et al., 2022). Em adição, a extrapolação para condições ambientais fora do domínio de calibração do modelo (climas futuros, por exemplo) introduz incertezas consideráveis (BRODIE et al., 2022; FRANKLIN, 2023; PASSOS et al., 2024; THOMAS et al., 2024).

Outro ponto importante é a necessidade de validação empírica dos modelos gerados. A verificação em campo, o uso de métricas de desempenho como AUC (Área sob a Curva) e TSS (*True Skill Statistic*) e a avaliação com dados independentes são estratégias que fortalecem a confiabilidade das projeções, apesar de que, na ausência de dados de qualidade sobre presença e ausência, podem ser falhos na avaliação de significado ecológico (ALLOUCHE; TSOAR; KADMON, 2006; FOURCADE; BESNARD; SECONDI, 2017; SWETS, 1988; VALAVI et al., 2022).

A Mata dos Cocais e o Complexo Babaçu representam um sistema socioecológico de alta complexidade e importância, que enfrenta desafios com muitas facetas, decorrentes da expansão agrícola e das incertezas climáticas. A integração de dados ecológicos, modelagem preditiva e cartografia, é essencial para uma delimitação mais precisa da Mata dos Cocais e para a compreensão das dinâmicas de distribuição das espécies do Complexo Babaçu. Essa abordagem inter e transdisciplinar é fundamental para a construção de políticas públicas eficazes que buscam a promoção de justiça ambiental e resiliência ecológica, garantindo a conservação desse patrimônio natural e sociocultural, e revela que lidar com a incerteza é parte intrínseca do processo de conservar, não apenas um obstáculo técnico, mas uma condição epistemológica da ciência da paisagem tropical.

Esta tese foi desenvolvida no formato de artigos científicos, redigidos de acordo com as normas editoriais das respectivas revistas, conforme previsto no regulamento do programa. Os resultados apresentados nos capítulos estão diretamente associados à produção científica derivada da tese, contribuindo para o avanço do conhecimento na área de Biogeografia da Conservação, com ênfase na análise de incertezas espaciais, informacionais e ecológicas aplicadas às palmeiras de babaçu (*Attalea* spp.) e seus ecossistemas.

CAPÍTULO 1 - THE PROBLEM OF CONSERVING AN ECOSYSTEM THAT HAS NOT BEEN COMPLETELY DELINEATED AND MAPPED: the case of the Cocais Palm Forest

O presente capítulo corresponde a um artigo científico desenvolvido no âmbito desta tese, redigido e apresentado a seguir integralmente de acordo com as normas editoriais da revista *Environmental, Monitoring and Assessment*, no qual é discutido o desafio da conservação de ecossistemas caracterizados por elevada incerteza espacial, tomando a Mata dos Cocais como estudo de caso. O artigo encontra-se publicado desde **01 de junho de 2023**, com o seguinte identificador digital: DOI: https://doi.org/10.1007/s10661-023-11345-z.

THE PROBLEM OF CONSERVING AN ECOSYSTEM THAT HAS NOT BEEN COMPLETELY DELINEATED AND MAPPED: THE CASE OF THE COCAIS PALM FOREST

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Abstract

Land-cover changes threaten biodiversity and alter the geographic distribution of forests worldwide. Studies on this topic are important to establish conservation strategies and public policies. However, different studies may propose different spatial representations due to differences when identifying, classifying, and/or mapping the same vegetation formation, as observed for the Cocais Forest region. This palm-dominated ecosystem predominates the Brazilian Mid-north region in an ecotone region with 3 of the 6 Brazilian biomes. In this study, we conducted a literature review of studies that delineated and mapped the Cocais Forest, aiming to compare different mapped regions and to establish a new distribution map integrating these spatial data. We found seven sources that revealed spatial divergences in identifying the spatial distribution of Cocais Forest, including its characteristics in terms of size and shape, which could affect the conservation, socioeconomic, and cultural policies and studies carried out on this emblematic vegetation formation and influence area. The delineation proposed by de Sousa Nascimento and Lima (2016) encompassed the largest area. In addition, there was a lack of consensus regarding the nomenclature for this ecosystem, and few works offered a detailed description of the mapping process. Despite the different spatial distributions found for the Cocais Forest, we succeeded in establishing a common area by overlapping individual maps, resulting in the identification of a core region exclusive located in the State of Maranhão.

Keywords: cartography, spatial distribution, palm trees, babassu, forest conservation, Maranhão.

Introduction

Climate change, land use and land cover change, the irrational use of natural resources, and biodiversity loss are major contemporary global crises. These factors act synergistically to increase the vulnerability of the environment, endanger ecosystem balance and human life, and modify the global distribution of ecosystems (Allen et al., 2010; Newbold et al., 2015; Luintel et al., 2018; Ma et al., 2019; Silvério et al., 2019; Arroyo-Rodríguez et al., 2020; Jain et al., 2021). Conservation and restoration of forest ecosystems are essential approaches in addressing biodiversity loss and enhancing their capacity as carbon sinks. Disturbances in forest dynamics are highly variable based on factors such as forest type and location, resilience, and disturbance type and intensity, which require the analysis of a set of spatial-temporal data (Díaz-Yáñez et al., 2016; Ojha et al., 2019).

Knowledge regarding the nature and territorial delimitation of ecosystems is essential for the effective management and conservation of biodiversity (Marques et al., 2019). The ecological security of a landscape requires an adequate planning and design to optimize the spatial representation of its heterogeneity and diversity (Wang et al., 2019). Thus, information on the biodiversity of an environment, characterization of its occurrence patterns in the landscape, and mapping of vegetation extent and land cover are the main prerequisites for ecology and conservation biology studies, as well as for the formulation of public policies aimed at conservation, environmental zoning, and land use management (Frederico et al., 2021; Marques et al., 2019).

Avoiding divergences in land cover delineation could contribute to provide the good quality spatial information required to support environmental conservation strategies. To increase the success of these strategies, it is necessary to prevent the discrepancy between the spatial scale of environmental management and ecological processes that often hamper environmental conservation goals (Nguyen et al., 2022).

Tropical forests have been highlighted as priority management areas owing to their high ecological complexity, diversity of species and hotspots, and for being the largest carbon sinks in terrestrial environments (Phillips et al., 1998; Pan et al., 2011; LeFevre et al., 2020). Transition zones between large tropical biomes, also known as ecotones, are rich in complexity and community interactions. Thus, these ecotones require more complex and in-depth research for the adoption of appropriate biodiversity conservation strategies (Torello-Raventos et al., 2013; Marques et al., 2019). Among the various forest formations in central-northern Brazil, the Cocais Forest or Cocal Zone (also known locally as Mata dos Cocais or Zona dos Cocais) is a palm-dominated transition zone between the humid Amazon forests in the north, the Cerrado Savannas in the south and east, and the semi-arid Caatinga regions in the northeast. These transition regions are hotspots of diversity and could serve as refuge for endemic species from the surrounding biomes (Saraiva et al., 2020, Argibay et al., 2020). This region occurs across tropical, equatorial, and semi-arid climates (Nunes et al., 2012), and is also known as babassu forest because of the predominance of the emblematic palm tree species *Attalea spp.* (locally known as babassu palms). This palm tree is primarily found in tropical countries such as Mexico, Bolivia, Colombia, and Suriname (Teixeira, 2008; Silva et al., 2013; Santos-Filho et al., 2013; Reis et al., 2018).

Several studies have presented results on Brazilian land cover at various scales (IBGE, 2012; Batistella et al., 2013; LAPIG, 2019; Alencar et al., 2020, Project MapBiomas, 2021). However, there are several differences concerning the nomenclature, classes, and its spatial extensions, which are important criteria in boundary delimitation and spatial distribution. Although palm tree formations are included in global classifications such as the global ecoregions maps (Olson et al., 2001) or the European Space Agency Climate Change Initiative land cover product, there is currently no official maps for the distribution of Cocais Forest. This region has been scientifically neglected or misunderstood in the context of large-scale floristic characterization or mapping (Batistella et al., 2013), despite its great importance for local traditional people and communities, such as the babassu breakers, who depend on the sustainable extraction of the babassu coconut (Porro et al., 2011; Porro & Porro, 2015; Mitja et al., 2019; de Oliveira et al., 2022).

Because of the great significance of coconut babassu extraction for local communities and regional economies, as well as the need to conserve the remnants of Cocais Forest, here we performed a literature review aiming to analyze divergences on its spatial delineation from different sources, and to propose an official map that will serves as reference to improve conservation policies, ecological studies, and socioeconomic planification in the Mid-north Region of Brazil.

Methods

Study region

The Cocais Forest region has great landscape heterogeneity and is considered a type of secondary vegetation with tree clusters that form dense forests or more open regions with the presence of palm trees, such as in pasture or savannah areas (Santos-Filho et al., 2013; Barreto et al., 2019). It is estimated that this region comprises approximately 500 plant species. Palm trees such as *Attalea speciosa* Mart. ex Spreng, *Bactris setosa* Mart., *Copernicia prunifera* (Mill.) H. E. Moore, *Euterpe edulis* Mart., and *Mauritia flexuosa* L. F. are predominant and have a great socioeconomic value to local communities that depend on sustainable extraction activities (Pinheiro, 2011; Campos et al., 2015). Despite initiatives to detect palm trees formations through remote sensing approach, there are still uncertainties about the real extent of these formation and its conservation status (Vieira et al., 2017).

Systematic bibliographic research

In this study, we performed a literature review to gather spatial information on the distribution and delineation of the Cocais Forest by comparing several cartographic delineations. First, we conducted a systematic bibliographic research on different databases such as Scielo, Scopus, Web of Science (WoS), and Wiley Online Library (WOL). The search was performed considering studies involving the Cocais Forest with no defined date range. Based on the different nomenclature observed in English and Portuguese, we searched for the terms “Mata dos Cocais” OR “Cocal Forest” OR “Floresta de Babaçu” OR “Babassu Forest”, limiting the search to titles, abstracts, and keywords in the Scopus database, and to any field category in the other databases. In addition, we searched for other grey literature in online and print formats to supplement the data from the systematic bibliographic research. We considered all studies that included a map of the Cocais Forest, additional information is given in the PRISMA flow diagram in Online Resource 1.

Shapefiles with State and municipal boundary data were obtained from IBGE (2020b).

Geoprocessing procedures

For each study selected from the systematic review, we extracted the following information: mapping and publishing year; the nomenclature used by the authors to classify the Cocais Forest region (e.g., biome, ecoregion, and phytoregion); the spatial range and references used for mapping; the number of municipalities within the region attributed to Cocais Forest per State considering all municipalities that cross the shapefiles; and the size of the mapped region in square kilometers (km^2).

We gathered these data from shapefiles whenever available, and for studies that had no spatial information in shapefile format, we georeferenced the maps using QGis software version 3.18 Zurich® and the Georeferencer tool in a SIRGAS 2000 projection-based coordinate system. Next, using the georeferenced maps, we manually delineated the polygon defined for this vegetation formation from the figure map presented in each analyzed source, at a scale of 1:4,000,000, with the vertices corrected for a scale of 1:2,000,000, generating the respective vector (shapefile) of its boundaries.

We calculated the total area and other features based on the number of municipalities included and their areas inside each Cocais Forest boundaries. In addition, we overlapped the shapefile layers derived from the different maps to create a single boundary map for this vegetation formation based on all the collated sources. Then, vector files were rasterized with a 1-km spatial resolution to ensure compatibility with the spatial resolution of other climate and environmental products derived from remote sensing (e.g. 1 km for precipitation data derived from CHIRPS, 500 m to 1km for MODIS derived products) and to facilitate the processing and evaluation of future analyses. We used the raster calculator to sum the individual layers created by each study using map algebra functions. Based on the overlapped map, we determined the following information: the total region attributed to the Cocais Forest by combining the areas of all maps, and a core region defined by the intersection between all maps.

Results and discussion

Systematic bibliographic research

The systematic review on databases returned a total of 116 papers, being 16 from Scielo, 54 from Scopus, 46 from WoS and none from WOL (Online Resource 1). However, none of studies presented explicit figures or maps of the Cocais Forest extent, for this reason we could not use them to accomplish our goal. Thus, we searched for the grey literature which yielded seven maps of the Cocais Forest extent, that served as cartographic data for this study (Table 1): World Wildlife Fund for Nature Brazil (WWF Brasil, 2004), Rocha et al. (2011), Santos-Filho et al. (2013), de Sousa Nascimento and Lima (2016), Barreto et al. (2019), Deforestation Polygon Assessment Tool (DEPAT) of the Image Processing and Geoprocessing Laboratory (LAPIG) of the Federal University of Goiás (UFG) (LAPIG, 2019), and Maranhense Institute of Socioeconomic and Cartographic Studies (IMESC) (2021).

Table 1 Compilation of the cartographic data extracted from the selected sources.

Reference	**Year of publication**	**Mapping year(s)**	**Mapping reference(s)**	**Spatial range used for mapping**	**Nomenclature used to define Cocais Forest**	**Number of municipalities incorporated, by State**	**Cocais Forest Area (km^2)**
WWF Brazil	2004	*i.n.f*	IBGE (1993); Olson et al. (2001)	Global	Ecoregion	CE: 12; MA: 125; PI: 57	141,628.98
Rocha et al.	2011	*i.n.f*	*i.n.f*	Northeast	Type of vegetation	MA: 129; PI: 74; TO: 17	219,219.49
Santos-Filho et al.	2013	2006	WWF and IBGE	Maranhão and Piauí	Zone	MA: 126; PI: 54	149,361.81
De Sousa Nascimento; Lima	2016	*i.n.f*	Diversos autores	Ceará, Maranhão, Pará, Piauí and Tocantins	Babassu ecological region	CE:1; MA: 168; PA: 12; PI: 86; TO: 33	260,039.07
Barreto et al.	2019	2015	IBGE (2015)	Maranhão, Piauí and Tocantins	Landscape	MA: 108; PI: 53; TO: 25	164,994.67
LAPIG	2019	*i.n.f*	Sano et al. (2019)	Cerrado Biome	Ecoregion	MA: 87; PI: 21	74,129.07
IMESC	2021	*i.n.f*	ZEE/MA (2021)	Maranhão	Zone	MA: 14	27,905.24

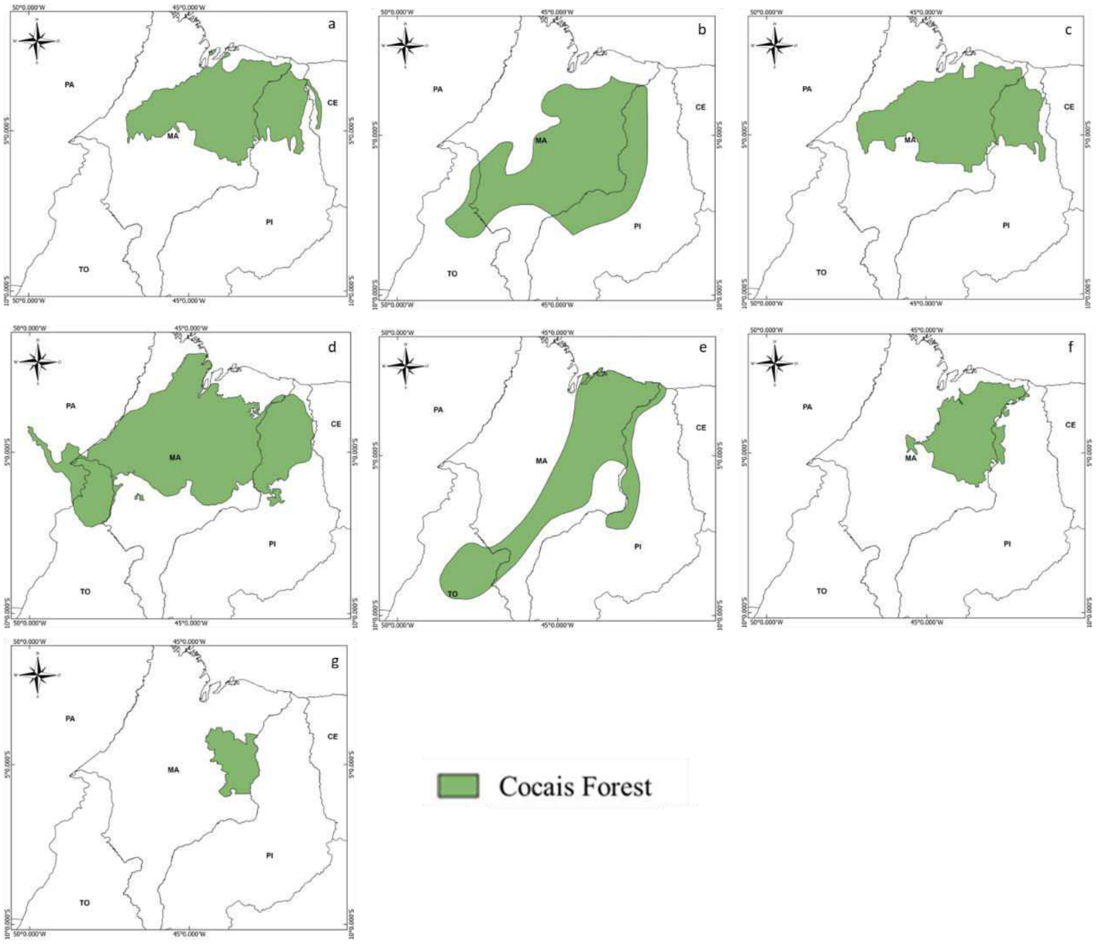
i.n.f Information not found, *CE* Ceará State, *MA* Maranhão State, *PA* Pará State, *PI* Piauí State, *TO* Tocantins State.

Cartographic surveys of Cocais Forest and its implications for nature conservation

Maps from the identified studies revealed spatial divergences of the Cocais Forest region (Figs. 1a to 1g). Each map depicted a unique representation of the spatial delimitation of the Cocais Forest, both in terms of its size and shape, as well as the

Brazilian States encompassed. Considering the analyzed sources (Fig. 1), Cocais Forest was identified in five of the 27 Brazilian States: Ceará (CE), Maranhão (MA), Pará (PA), Piauí (PI), and Tocantins (TO), most located in the northeastern region of Brazil. The absence of a cartographic consensus among the references may have a direct impact on studies that guide the landscape characterization process and the implementation of public policies aimed at managing and conserving this plant formation (Colten, 2018; de Almeida et al., 2019; Barreal & Jannes, 2020). Anything that has not been rightly delimited or identified cannot be protected or conserved properly, as has been the case for other ecosystems such as the Asian savannas, which have been misclassified in global and local research, resulting in controversies over conservation efforts (Ratnam et al., 2016). In the case of the Cocais Forest in Brazil, misclassification or inaccurate definitions of its spatial distribution could affect related research. For example, the extend and correct delineations of land cover is important to determine the effects of fire regime changes and how that affect the flammable and fire adapted ecosystems (e.g Cerrado savannas) and the more fire sensitive forest ecosystems (e.g. gallery forest, amazon forest) where fire could cause forest fragmentation or degradation (Silva-Junior et al., 2022). Accurate spatial information serves as a cartographic basis for burned areas analyses (Alves & Alvarado, 2019; Argibay et al., 2020; Syphard & Keeley 2020, Silva et al., 2021), particularly in these transition zones as the Cocais Forest region characterized by a mosaic of patches of palms forest into a matrix of anthropic areas and savannas.

Fig. 1 The main spatial delimitations of Cocais Forest. Maps were adapted from the Cocais Forest distributions reported by a) WWF Brasil (2004), b) Rocha et al. (2011), c) Santos-Filho et al. (2013), d) de Sousa Nascimento and Lima (2016), e) Barreto et al. (2019), f) LAPIG (2019); and g) IMESC (2021).



The spatial information obtained from mapping a region is essential for establishing and applying spatial indices and landscape metrics for structural quantification, forest landscape management, and diagnosing and measuring spatial changes in landscape composition and configuration (Herold et al., 2003; Feng et al., 2018; Dadashpoor et al., 2019; Jia et al., 2019; Mandal & Chatterjee, 2021). These metrics require different types of land-mapping data for their equations and algorithms, such as area and perimeter data (Kupfer, 2012). Thus, maps with distinct spatial delimitations produce divergent geometric information and location vectors, implying that different results are produced for aspects associated with landscape changes at various scales. In addition, research on landscape metrics has demonstrated a correlation between landscape metrics and ecosystem services (Zhang et al., 2011; Duarte et al., 2018; Wang et al., 2019; Hou et al., 2020), making it important to properly and accurately delineate vegetation formations.

In areas with a high degree of anthropization, such as the Cocais Forest region (Santos-Filho et al., 2013), landscape metrics are essential for predicting habitat restrictions when considering the movement and potential for species dispersion and other aspects associated with population dynamics (Jackson & Fahrig, 2015; Rezende et al., 2020; Santos et al., 2020), and population genetics (Wan et al., 2018). The forest cover of a landscape is inextricably linked to the availability of natural resources and consequently to the richness, abundance, perpetuation, and population density of species (Fahrig, 2003; Godefroid & Koedam, 2003; Gignac & Dale, 2007; Fahrig, 2013; Jackson & Fahrig, 2015; Uroy et al., 2019). The number of studies analyzing the influence of landscape connectivity on biodiversity has increased considerably since the early part of the 21st century (Ayram et al., 2016). Thus, as biodiversity patterns vary widely (Bridgewater et al., 2004; Milliken et al., 2010; Soares et al., 2020), forest managers require highly accurate forest cover information (Unger et al., 2014).

Regarding the States encompassed in each single maps (Fig. 1), the area established by de Sousa Nascimento and Lima (2016) (Fig. 1d) contained the greatest number of Brazilian States (Ceará, Maranhão, Pará, Piauí, and Tocantins), whereas the region defined by the IMESC (2021) was the most limited and restricted exclusively to the State of Maranhão. Highly restrictive classifications might prevent the spatial characterization of areas on official maps by disregarding or inadequately identifying its actual characteristics. A map that underestimates the extent of a landscape may not encompass all its economic and ecological heterogeneity and multifunctionality. For example, landscape heterogeneity has the potential to mitigate the detrimental effects of habitat fragmentation (Tscharntke et al., 2012; Uroy et al., 2019) and is essential for the perpetuation of biological diversity, provision of ecosystem services, and conservation of endangered species (Dorresteijn et al., 2015; László et al., 2018).

The differences in spatial delimitation observed in the analyzed maps (Figs. 1a to 1g) have a substantial impact on the quality of the sustainability assessment of the Cocais Forest ecosystem, which has great social, economic, scientific, and ecological interest (Porro & Porro, 2015; Mitja et al., 2019; de Oliveira et al., 2022), and has historically been impacted by anthropogenic activities (Santos-Filho et al., 2013), needing strategic plans for ecological protection and recovery. By estimating the spatial delimitation of the Brazilian Caatinga biome, Antongiovanni et al. (2018) quantified its spatial structure and assessed the extent to which the remaining areas were susceptible to anthropogenic disturbances. Thus, mapping properly an area makes it possible to understand the complexity of mosaic landscape dynamics, including its composition, changes, and the intensity and potential effects of human disturbances that can influence ecological processes and conservation strategies (Marques et al., 2019; Souza-Filho et al., 2019; Yang et al., 2019; Wang et al., 2019). Marques et al. (2019) obtained different values for estimated deforested areas in the Caatinga biome compared to the mapping performed by IBGE, demonstrating one of the effects associated with different spatial delimitations for the same region.

Another associated issue is the inconsistency between maps in terms of its distribution and quantification of potential forest biomass along forest landscapes. For example, spatial differences influence the estimation of the above-ground biomass and its potential carbon sequestration of the region, causing under- or overestimations of these values (Wang et al., 2019). This scenario makes it difficult to develop and implement a green (low-carbon) economy and adopt strategies targeted at efficient natural resource management, green investment, technological innovation, and poverty eradication (Brand, 2012). Furthermore, it prevents the acquisition of economic incentives for the land organization and management, and landscape-scale conservation efforts such as payments for ecosystem services (Hartig & Drechsler, 2009; Muradian et al., 2010; Ruggiero et al., 2019; Nguyen et al., 2019; Nguyen et al., 2022).

Implications of the criteria and methods used to delimit the Cocais Forest region

Assessment of the identified maps in the analyzed studies revealed that the mapping year was the most unreported information since it was only reported by Santos-Filho (2013) and Barreto et al. (2019). The absence of a temporal record affects the evaluation of spatial and temporal dynamics in the short and long term and the analysis of land cover change dynamics (Turner & Gardner 2015). It is the baseline to know the current status, reconstruct the past history, quantify the degradation level, or predict the future trajectory of Cocais Forest vegetation. In addition, to achieve an accurate interpretation of the landscape, it is important that the temporal and spatial scales are well-defined, allowing for the separation between the effects associated with landscape connectivity from other factors, such as dispersal mode (Uroy et al., 2019).

It is important to emphasize the lack of information about the mapping process or methodological approaches used in all analyzed studies, such as the descriptive information on the primary sources (e.g., satellite images, other sources of bibliographic references, and field data) and variables (e.g., vegetation reflectance, topography, rainfall, and temperature) used by these authors to map the Cocais forest region. This prevented us from discussing the key variables in the biogeographic delimitation of this formation. In general, the recurring absence of information throughout our literature review indicated the need to better characterize the methodological procedures used in the studies on Cocais Forest to clarify the criteria and variables used to delimit this region, which can serve as a foundation for future research on this plant formation.

The problem involved with the definition of the Cocais Forest is not exclusive to this region. In the Brazilian Caatinga biome and its phytophysiognomies, a similar discrepancy between the information from multiple maps is observed, particularly regarding the semiotic choices made during the preparation of the map classification system (Bontempo et al., 2020). The absence or inadequacy of this information exacerbated the issue raised by Sousa-Baena et al. (2014), who analyzed primary data on angiosperm biodiversity in Brazil. The authors identified knowledge gaps regarding this primary data and reported that most biodiversity data is not available in digital format and not georeferenced or is limited to the extent that makes them unusable. In the context of conservation-oriented public policies, this directly affects their implementation because the available digital knowledge employed is limited, biased, or insufficient. According to Frederico et al. (2021), primary data are required to develop knowledge that can be applied more diligently. The limited methodological information restricts the use of these cartographic materials to develop biogeographical research and, consequently, to establish environmental conservation strategies or to explain landscape dynamics.

Another controversial issue is the various nomenclature used by authors to refer to the Cocais Forest formation. Some publications used similar terms, such as WWF Brazil (2004) and LAPIG (2019), which referred to Cocais Forest as an “ecoregion”, whereas Santos-Filho et al. (2013) and IMESC (2021) used “zone.” The remaining studies applied different nomenclatures (landscape, type of vegetation, and babassu ecological region). However, even among references that employing similar terminology, distinct cartographic delimitations were observed (Figs. 1c and 1e, and 1b and 1f). Regarding the conceptual aspects of landscape ecology, the various terms used to represent the spectrum of approaches used by the authors, ranging from a geographic approach that focuses on the anthropogenic effects on geographic areas to an ecological approach that emphasizes the relationship between the area and its ecological processes (Pickett & Cadenasso, 1995; Turner & Gardner, 2015). This confirms the lack of consistency about the nomenclature used, even among studies employing the same methodological approach (geographical or ecological). Using terminology better suited to characterize the Cocais Forest is essential for the development of studies in this field, especially in terms of formulating public policies aimed at the specificities of this research to reinforce the core objectives of environmental standards. More concrete notions can guide decision-makers in developing initiatives with a more integrated perspective, thereby facilitating the adaptation of the normative framework and management of available resources (Sposati, 2016).

Among the references analyzed in this study, only Barreto et al. (2019) used the term “landscape” to refer to the Cocais Forest. Given the notion underlying this term, as described by Wu and Qi (2000) and Siqueira et al. (2013), who considered a landscape as a dynamic product of physical, biological, and anthropogenic factors, this nomenclature appears more biogeographical than the other afore mentioned terms. Landscapes are identified as areas exhibiting considerable spatial differences, which are sometimes expressed in the form of mosaics of patches with distinct shapes, sizes, histories, and compositions, and the Cocais Forest fits this definition. Although this region comprises naturally dense areas, it also has fragmented anthropogenic areas across States in the Brazilian Mid-north region (Santos-Filho et al., 2013).

Regarding the spatial range utilized for mapping, different scales have been used in previous studies. WWF Brazil used the widest scale, with global-scale vegetation mapping based on studies by IBGE (1993) and Olson et al. (2001), whereas the IMESC (2021) used the smallest scale, performing mapping at the State level only for State of Maranhão using the Maranhão Ecological-Economic Zoning database process (2021), which represents a political bias. Establishing a suitable scale for landscape analyses is highly relevant for accomplishing biogeographic delimitations and ecological analyses because living organisms respond to environmental gradients rather than political boundaries. The differences observed in this information may result in spatial data with distinct spatial arrangement patterns and precision, and most important, excluding regions where this formation is present. The scale used could compromise the characterization of environment, such as the heterogeneity of its systems, owing to changes in how its varying nature is perceived (Wu & Qi, 2000). Interestingly, the map presented by LAPIG (2019) (Fig. 1e), based on the study by Sano et al. (2019), was developed exclusively for the Cerrado ecoregions. Thus, according to the criteria of these authors, it is believed that the Cocais Forest area could have been larger than it appeared on the map if the same information had been available for the Amazon biome.

Sousa Nascimento and Lima (2016) reported the largest area (260,039.07 km^2) including the largest number of municipalities (n = 300, 56% of which were in State of Maranhão). The study of Rocha et al. (2011) reported the second largest area with 219,219.49 km^2, contained the second-highest number of municipalities (n = 220, with 58.6% of these located in State of Maranhão). In contrast, the IMESC study (2021) restricted to a single State (Maranhão), presenting the smallest area with 27,905.24 km^2 and consequently the smallest number of municipalities (n=14). The IMESC data (2021) (Fig. 1f) resulted from a local sociopolitical approach, from the technical work carried out by the State of Maranhão government to define zones for management and territorial planning (Maranhão Ecological-Economic Zoning – ZEE project), limiting the extent of the studied area to the geographical State boundaries rather than following the natural distribution of Cocais Forest formation (Barros, 2020; SEATI, 2020). This approach has been criticized by several researchers who affirm that it favors the socioeconomic interests over the environmental interests on the conservation of the forest remnants in the State (Silva-Junior et al. 2020; Silva-Junior et al., 2021; Celentano et al., 2017).

Restringing the studies to a geographical boundary may also have contributed to a more limited spatial definition by excluding areas in other States or other palm formation regions, such as those occupied by carnauba palms (known as *carnaubais* in Portuguese) in Piauí State (Santos-Filho et al. 2013). Piauí is divided into 12 so-called Development Areas (*Territórios de Desenvolvimento* in Portuguese), one of which is referred to as the Cocais Development Area, comprising 22 municipalities in the north of the State, and a second one referred as the Carnaubais Development Area encompassing 16 municipalities in the Mid-North of the State (SEPLAN-PI, 2019). Although the geographic boundaries of the States were the primary criteria for limiting the mapping area in these studies, the Cocais Forest was delineated in each one using different classification criteria.

The new proposed Cocais Forest area delimitation

The sum of the raster layers of the single analyzed maps (Figs 1a to 1g) indicated that the total area allocated to Cocais Forest encompassed 425,529.30 km^2 and comprised five Brazilian States (Ceará, Maranhão, Pará, Piauí, and Tocantins) (Fig. 2). In terms of total area, the largest portion (270,591.13 km^2) was in Maranhão State, accounting for

63.59% of the total area and 82% of the State (Table 2). The Cocais Forest region included a total of 392 municipalities, 51.28% of which were in Maranhão, which also corresponded to the most representative State in the new proposed Cocais Forest delimitation, with 92.63% of its municipalities (201 from 217) included in this formation. In contrast, Ceará State had the smallest percentage of municipalities (6.52%). All studies indicated that the largest area of occurrence designated as Cocais Forest were in Maranhão State (Figs. 1a to 1g), corroborating the findings of Batistella et al. (2013), who characterized this forest formation as a typical landscape of Maranhão.

Fig. 2 Overlay map of the areas attributed to Cocais Forest in the reviewed studies, highlighting the total area and core region.

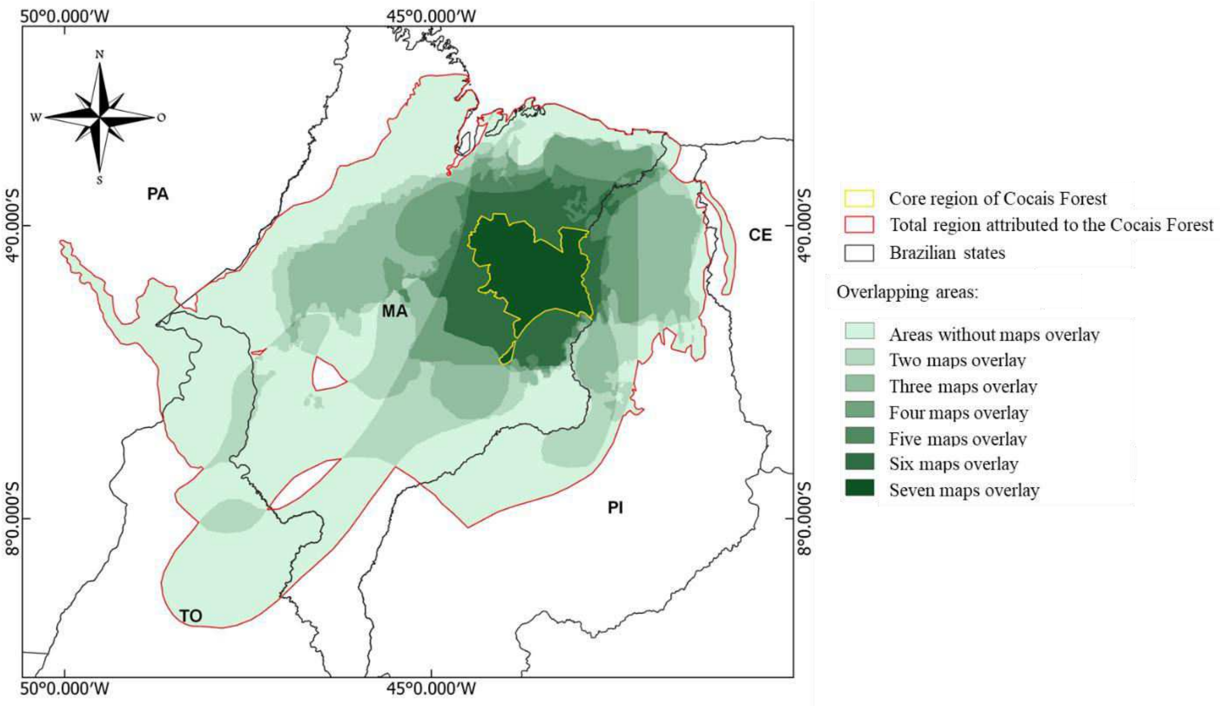


Table 2 Geographic aspects of the States included in the total area attributed to Cocais Forest. The values in parentheses represent the proportions of municipalities within the total region that are attributed to Cocais Forest relative to the total number of municipalities in that State.

Brazilian State	**Area of the State (km^2)**	**Area of the State within the total Cocais Forest region (km^2)**	**Percentage area of the State within the total Cocais Forest region (%)**	**Percentage area of the State in relation to the total region attributed to Cocais Forest (%)**	**Number of municipalities incorporated**
Maranhão	329,651.56	270,591.13	82.08	63,59	201 (92.63%)
Piauí	1,245,870.28	79,166.09	6.35	18,60	108 (48.21%)
Tocantins	277,423.57	60,169.46	21.69	14,14	59 (42.25%)
Pará	251,755.48	13,321.82	5.29	3,13	12 (8.33%)
Ceará	148,894.44	2,280.80	1.53	0,54	12 (6.52%)
TOTAL	**2,253,595.33**	**425,529.30**	**-**	**-**	**392 (43.17%)**

The overlapping of different layers made it possible to determine the intersection between the 7 analyzed maps, resulting in a core region that proved to be exclusively within Maranhão State and predominantly in the eastern region. This core region contained 14 Maranhão municipalities and occupied an area of 20,643.94 km² where 95.5% (4,975.85 km²) of the Caxias municipality belongs to this core area and the other nine municipalities are entirely situated within the core (Online Resource 2). In terms of environmental aspects, based on information from the IBGE database (2012; 2020a), the entire core region was in the Cerrado biome, and a considerable portion of this area was situated in the Brazilian semi-arid region (Caatinga biome), in areas where seasonal deciduous and semi-deciduous forests occurred.

Considering the consensus between the cartographic data analyzed, and reinforced by the presence of a region whose plants are indicative of Cocais Forest, the IMESC (2018) defined a Development Area denominated “Cocais” in Maranhao State based on a socioeconomic classification. This reinforced the close relationship between the local communities in the region and these palm trees that constitute this forest formation and that contribute to its domination in the landscape, particularly babassu tree palm (Porro et al., 2011; Porro & Porro, 2015; Mitja et al., 2019; de Oliveira et al., 2022).

Based on the identified studies, the overlay map of the locations attributed to Cocais Forest could be regarded as a new proposed area for its occurrence. Thus, it could be inferred that the larger the number of overlay maps, the greater the possibility of a region being classified as a Cocais Forest region. However, studies about the potential species distribution and niche distribution modeling are strongly recommended to perform a robust analysis based on field occurrence data of the dominant tree palms.

Regarding environmental conservation strategies, mapping that underestimates the breadth of a landscape similarly affected the definition of priority areas for conservation (Rezende et al., 2020). Based on this interpretation and utilizing this new proposed map as a cartographic reference, the vulnerabilities that permeate this environment can be studied more assertively (Wang et al., 2019). Consequently, the initial areas for management and conservation plans for their communities and sustainability can be identified.

Conclusions

The analyzed data confirmed the existence of spatial and nomenclatural divergence in the Cocais Forest region, as evidenced by the various spatial delimitations from the selected studies, which highlighted the necessity to better characterize and report the methodological procedures employed to perform these classifications. The lack of consensus regarding cartographic boundaries could impact the characterization of geographic areas and biogeographical analyses necessary for the implementation of public policies to manage and conserve the Cocais Forest region.

Considering the challenges in characterization and nomenclature, a fundamental issue in biogeographical studies, ecologists bear a considerable amount of responsibility for appropriately defining this type of ecosystem. In addition, a highly anthropized environment requires interdisciplinary action to integrate aspects intrinsic to landscape ecology and geography in an approach that encompasses physical and biotic components as well as anthropogenic and social factors.

Combining the different maps resulted in a new proposed occurrence delimitation for Cocais Forest, which included 392 Brazilian municipalities across five States and could be regarded as a potential delimitation area. Although more studies are needed to better understand the potential species distribution of the dominant and emblematic tree palms and its niche distribution. Despite the various spatial delimitations of Cocais Forest, a common area was established by overlapping the single selected maps, resulting in the identification of a core zone located on Maranhão State, which may be used as a priority area to focus conservation efforts.

This study offered key insights for researchers, policymakers, and practitioners. Future studies based on field work and remote sensing techniques are required to provide scientifically robust data and assess the practical impacts of these divergences on this ecosystem, as a basis for multidisciplinary researchers in the conservation of this relevant landscape.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors. The authors approved the manuscript, and there are no ethical issues to declare.

Consent to participate

The authors have agreed on the manuscript, and there are no issues to disclose.

Consent for publication

The authors have no issues on this matter and agreed to publish the content of the paper.

Conflict of interest

The authors declare no competing interests.

Author Contribution

Santos, D.P was responsible for surveying the database and formatting the figures and tables. All authors participated in writing and revising the manuscript.

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Electronic Supplementary Material

A NEW CONSENSUS MAP OF THE COCAIS PALM FOREST TO GUIDE CONSERVATION EFFORTS

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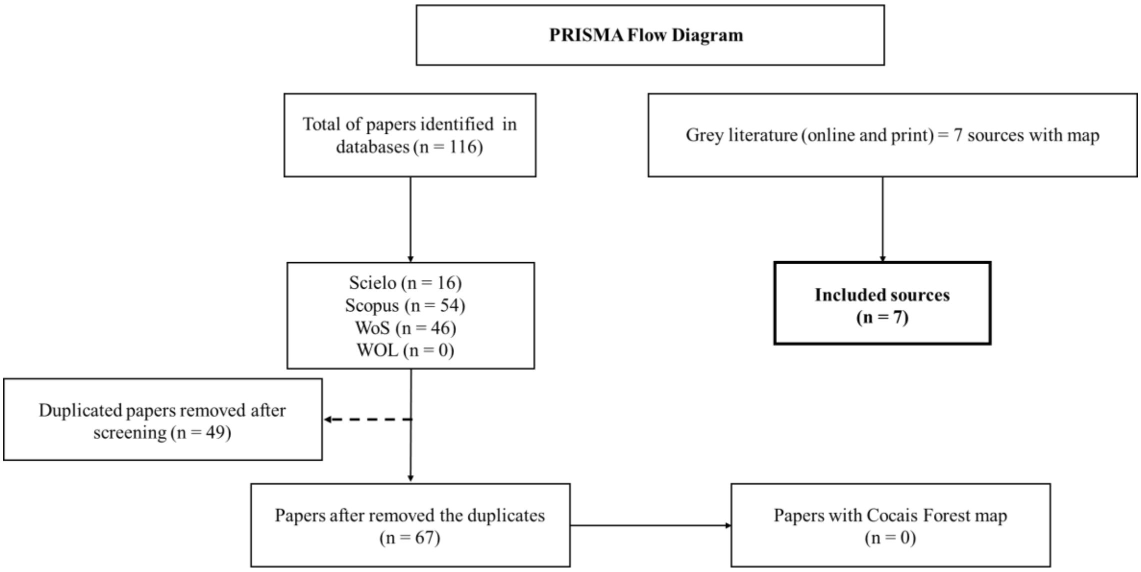
Online Resource 1 PRISMA flow diagram for the systematic review, which includes searches of databases and other sources.



Online Resource 2 Geographic aspects of the states incorporated in the core region of Cocais Forest.

Municipality	Area of the municipality (km2)	Area incorporated int the core (km2)	Percentage of the area of the municipality incorporated in the core (%)	Percentage of the area of the municipality incorporated in relation to the total core (%)
Caxias	5,201.93	4,975.85	95.65	24.10
Codó	4,361.61	4,361.61	100.00	21.13
Coroatá	2,263.69	2,263.69	100.00	10.97
Aldeias Altas	1,942.12	1,942.12	100.00	9.41
Timbiras	1,486.58	1,486.58	100.00	7.20
São João do Soter	1,438.07	1,438.05	100.00	6.97
Coelho Neto	977.08	977.07	100.00	4.73
Timon	1,763.22	928.44	52.66	4.50
Peritoró	824.73	824.72	100.00	3.99
Alto Alegre do Maranhão	392.75	392.75	100.00	1.90
Buriti Bravo	1,582.55	327.49	20.69	1.59
Duque Bacelar	317.49	317.49	100.00	1.54
Parnarama	3,244.75	309.80	9.55	1.50
Matões	2,108.67	98.28	4.66	0.48
TOTAL	**27,905.24**	**20,643.94**	**-**	**100.00**

CAPÍTULO 2 - CLIMATE CHANGE MAY INCREASE ENVIRONMENTAL SUITABILITY OF THE BABASSU COMPLEX (*Attalea spp.*, ARECACEAE)

O presente capítulo corresponde a um artigo científico desenvolvido no âmbito desta tese, redigido e apresentado a seguir integralmente de acordo com as normas editoriais da revista *Journal of Biogeography*, no qual são apresentados e discutidos os principais resultados relacionados à biogeografia do Complexo Babaçu (*Attalea spp.*). O artigo encontra-se publicado desde **04 de agosto de 2025**, com o seguinte identificador digital: DOI: https://doi.org/10.1111/jbi.70027.

CLIMATE CHANGE MAY INCREASE ENVIRONMENTAL SUITABILITY OF THE BABASSU COMPLEX (*Attalea spp.,* ARECACEAE)

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Author contribution

D.P. Santos was responsible for compiling the database, conducting the modelling procedures, analysing the results, and preparing the figures and tables, under the guidance of the co-authors. All authors contributed to the conceptualization, writing, and revision of the manuscript.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Biosketch

The authors operate at the intersection of forest ecology, conservation, and environmental modelling. Their collective expertise includes forest resources, silviculture, ecophysiology, and ecological modelling, with a strong focus on understanding species distribution, ecosystem dynamics, and responses to climate change. The team combines field-based research with geospatial analysis, remote sensing, and machine learning to explore patterns of biodiversity and ecosystem function.

Abstract

Aim

This study aimed to identify the key bioclimatic factors driving the distribution of the Babassu Complex across the Neotropics in current scenario (2011-2040), and to project their range shifts under future climate scenarios (2041-2070 and 2070-2100).

Taxon

Babassu Complex (Arecaceae): *Attalea barreirensis*, *A. eichleri*, *A. funifera*, *A. maripa*, *A. phalerata*, *A. speciosa*, and *A. vitrivir*.

Location

Neotropical region.

Methods

We employed Species Distribution Modelling using four algorithms: Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT), and Generalized Linear Models (GLM) for the seven babassu species and for the combined Babassu Complex dataset. GBIF presence-only data was combined with CHELSA 2.1 bioclimatic variables from current and future scenarios to fit the models. Projections for 2041–2070 and 2071–2100 were derived for two high-emission climate scenarios (SSP3 7.0 and SSP5 8.5), using an ensemble of five global climate models.

Results

The RF and BRT algorithms provided more conservative predictions for the current scenario, while MaxEnt and GLM projected broader distributions. Temperature seasonality was the most important suitability predictor. *Attalea maripa*, *A. phalerata*, and *A. speciosa* showed broadest suitability ranges, while *A. funifera* and *A. vitrivir* were most constrained. Future scenarios projected major suitability increases (up to 871.80% for the Complex under SSP5-8.5 by 2071-2100), particularly in Amazonian and Cerrado regions. Only *A. funifera* and *A. vitrivir* showed declines (-8.55% and -20.97% respectively under SSP3-7.0).

Main conclusions

We anticipate that climate change may favour babassu species that tolerate warmer and more variable conditions, promoting their expansion. While this may support restoration and livelihoods, unmanaged spread could disrupt local ecosystems. It is recommended that future research focus on incorporating anthropogenic variables, validating predictions with field data, and exploring species-specific ecological responses to climate change.

Keywords: Species Distribution Modelling (SDM); Habitat Suitability; Tropical Forests; Bioclimatic Predictors; Ecological Forecasting; Neotropical Palm; Babaçu.

Introduction

The Arecaceae family represents one of the largest and most ecologically significant tropical botanical families, contributing with the nutrients cycling, providing habitat structure, food, and materials for both biodiversity and local communities (Eiserhardt et al., 2011). Within this family, the genus *Attalea* is recognised as a major component of the Neotropical flora (Freitas et al., 2016; Pintaud, 2008). From the c.a. 40

species in the genus, at least seven recognised species and two hybrids form the “Babassu Complex”: *Attalea barreirensis* Glassman, *A. eichleri* (Drude) A.J. Hend, *A. funifera*, *A. maripa* (Aubrl) Mart., *A. phalerata* Mart. ex Spreng., *A. speciosa* Mart. ex Spreng., *A. vitrivir*, *A. x teixeirana* (Bondar) Zona (a hybrid of *A. eichleri* and *A. speciosa*), and *A. × dahlgreniana* (Bondar) Wess. Boer (a hybrid of *A. speciosa* and *A. maripa*). Known locally as "babassu" or "babaçu," these palms are predominantly found in tropical countries such as Brazil, Mexico, Bolivia, Colombia, and Suriname (Teixeira 2008; Santos-Filho, Almeida Júnior, Soares 2013; Silva et al. 2014; Reis et al. 2018).

The Babassu Complex refers to a group of closely related *Attalea* species that exhibit overlapping morphological traits, frequent natural hybridization, and unresolved taxonomic boundaries (Cavallari; Toledo, 2016; Mata et al., 2022b; Pintaud, 2008). Although its species share many anatomical features such as uniseriate epidermis, glandular scars, and dorsiventral mesophyll, they also show diagnostic differences in traits like stomatal distribution, vascular bundle organization, and palisade parenchyma layers (Mata et al., 2022b), justifying their recognition as distinct taxa and supporting species-level ecological assessment.

From an ecological perspective, babassu palms are foundational species that influence forest structure, microclimate regulation, nutrient cycling, and soil stabilization across various Neotropical biomes (see Araújo et al., 2016; Corrêa et al., 2023; Porro, 2019; Ressiore C. et al., 2024). Socioeconomically, they support the livelihoods of traditional communities (Almeida Campos et al., 2015; Lima et al., 2003), such as the communities of babassu coconut breakers, women who rely on artisanal harvesting and processing of its fruit given their broad range of uses (De Oliveira et al., 2022; Mitja et al., 2019; Porro et al., 2011; Shiraishi Neto, 2017), . These species can be utilised for handicrafts, construction, and human consumption. The babassu species provide a diverse range of products, the babassu nuts are the most prominent, which have the potential to be processed into various by-products with different levels of processing complexity, including mesocarp flour (Cardoso Vieira et al., 2023), oil (Neto et al., 2021), adsorptive material for chemical molecules (Vieira et al., 2011), biofuel, charcoal (Corrêa et al., 2023), and animal feed (Portela et al., 2024).

Comprehension of the ecological dynamics and distribution patterns of babassu is, therefore, imperative to ensure the sustainability of such socio-ecological systems and to support conservation and spatial planning efforts across the Neotropics. Climatic variables are especially relevant for palms, whose distributions are often closely tied to thermal and moisture regimes (De Kort et al., 2021; Eiserhardt et al., 2011; Peterson et al., 2011). While variables such as water availability and temperature seasonality are recognized as key determinants for many tropical palms (Kissling et al., 2012 the specific climatic thresholds that shape the distribution of babassu species remain unresolved.

As a powerful tool in conservation biogeography, the emergence of Species Distribution Modelling (SDM) has been instrumental in bridging knowledge gaps related to the geographic distribution of species and identifying species–climate relationships (Elith; Franklin, 2013; Guisan; Thuiller, 2005; Guisan; Zimmermann, 2000), encompassing historical biogeography, diversity patterns, ecosystem conservation, and the impacts of climate change (Brun et al., 2020; Franklin, 2023; Freer et al., 2018; Maltby et al., 2020; Volis; Tojibaev, 2021). The employment of advanced SDM techniques, involving bioclimatic variables and multiple algorithms, furnishes valuable insights into species distributions and potential niche shifts under prevailing and future climate scenarios (Alves et al., 2019; Brun et al., 2020; Katuwal et al., 2023; Valavi et al., 2022). This is of particular importance for palms and its pivotal ecological roles in tropical ecosystems and economical importance for local communities (Blach-Overgaard et al., 2010; Costa et al., 2022; Mitja et al., 2019).

Previous SDM studies have assessed the climatic suitability of *Attalea* species. Menezes et al. (2023) projected future distributions of *A. pindobassu* in the Brazilian biome Caatinga under the scenarios SSP2-4.5 and SSP5-8.5, finding drastic losses of suitable habitat, especially under pessimistic scenarios. Likewise, De Lima et al. (2022) modelled 15 palm species in the Atlantic Forest, including *A. dubia* (Mart.) Burret and *A. humilis* Mart. Ex Spreng., revealing conservation gaps and spatial mismatches between suitable habitats and protected areas. However, no comprehensive multi-species SDM has been conducted for the Babassu Complex. These previous efforts have either focused on single species or specific regions, limiting their relevance for broader-scale conservation and land-use planning, what represents a critical gap. The lack of spatially explicit, climate-based assessments at the group level hinders our ability to anticipate range shifts, identify conservation priorities, and develop adaptation strategies under climate change.

Given their ecological dominance, socioeconomic importance, and biogeographic significance, the Babassu Complex is a high-priority group for climate impact assessments. Thus, the objective of this study is to identify the key bioclimatic factors driving the distribution of the Babassu Complex and its species across the Neotropical region, and project their range shifts under future climate scenarios (SSP3-7.0 and SSP5-8.5) across two periods (2041–2070 and 2071–2100), thereby contributing to a more nuanced understanding of their vulnerability and resilience in a changing climate.

Material and Methods

Data Collection

This study focused on species distribution modelling (SDM) for the seven species of the *Attalea* genus identified as part of the Babassu Complex and for the combined dataset. The species selection was based on their taxonomic inclusion in the Babassu Complex, supported by anatomical and morphological evidence (Cavallari; Toledo, 2016; Mata et al., 2022b), the availability of sufficient georeferenced occurrence data for ecological modelling, and their ecological and socioeconomic importance across the region. Presence-only occurrence data were obtained from the Global Biodiversity Information Facility (GBIF) database, totalling 19,204 records distributed among species as follows: *A. phalerata* (n = 15,170), *A. maripa* (n = 3,580), *A. eichleri* (n = 142), *A. speciosa* (n = 129), *A. funifera* (n = 84), *A. barreirensis* (n = 52), and *A. vitrivir* (n = 47) (Figure 1).

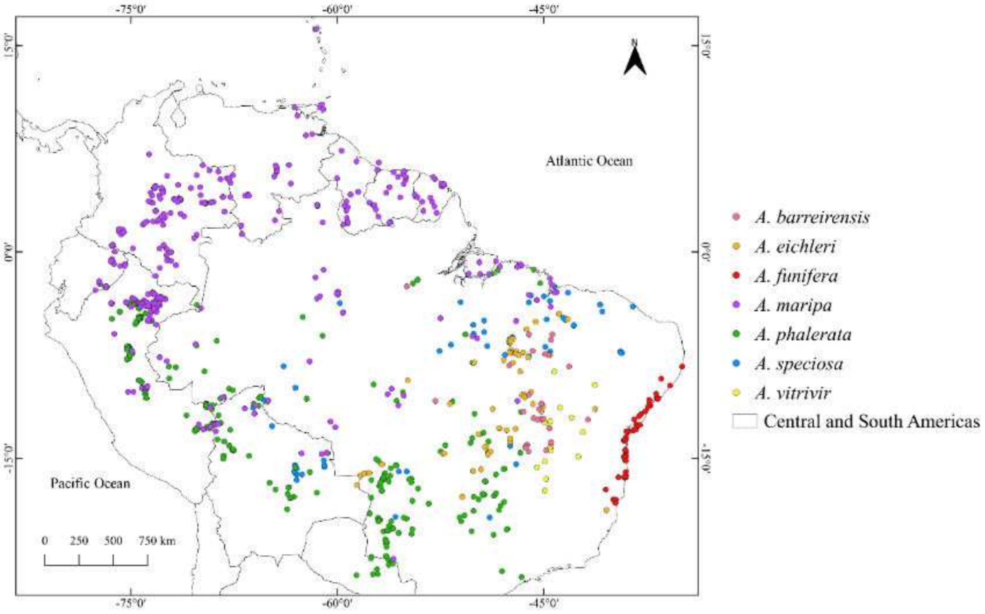


Figure 1. Distribution map of occurrence points obtained from the GBIF database for the Babassu Complex species: *A. phalerata* (n = 15,170), *A. maripa* (n = 3,580), *A. eichleri*

(n = 142), *A. speciosa* (n = 129), *A. funifera* (n = 84), *A. barreirensis* (n = 52), and *A. vitrivir* (n = 47).

To minimise spatial sampling bias, duplicate and spatially clustered, occurrences were filtered from the dataset so that only one occurrence per 20 km grid cell was retained. This filtering procedure was used to reduce the influence of highly sampled cluster, often associated with accessible or well-surveyed areas, while preserving broader landscape-level occurrence patterns (Lake; Briscoe Runquist; Moeller, 2020; Lee et al., 2022). After filtering, the number of retained occurrence points per species was: *A. barreirensis* (n = 41), *A. eichleri* (n = 79), *A. funifera* (n = 65), *A. maripa* (n = 570), *A. phalerata* (n = 431), *A. speciosa* (n = 84), *A. vitrivir* (n = 27), and the combined dataset (n = 1,269).

Bioclimatic Variables

For both current and future scenarios, bioclimatic variables were sourced from the Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) database, version 2.1 (Table S1.2), which incorporates orographic corrections (e.g. wind fields, valley exposure) to enhance the accuracy of temperature and precipitation estimates in complex terrains (Brun et al., 2022; Karger et al., 2017, 2020, 2021). Each variable was obtained as a georeferenced TIFF file (GeoTIFF) with an original resolution of 30 arc-second (~1 km^2), using a geographic coordinate system referenced to the WGS 84 horizontal datum.

The predictor variables employed to model the current climate scenario covered the baseline period of 2011-2040. For future scenarios, the bioclimatic predictors were obtained from the *Scenario Model Intercomparison Project* (SMI), part of the *Coupled Model Intercomparison Project Phase 6* (CMIP6), accessed via the CHELSA V2.1 database. We considered two Shared Socioeconomic Pathways (SSPs) of high greenhouse gas emission: SSP3 7.0 and SSP5 8.5, and two time periods: 2041–2070 and 2071–2100. These scenarios were chosen to represent upper-bound climate change trajectories relevant for ecological risk assessments and stress-testing conservation planning. While recent studies have questioned the global plausibility of SSP5-8.5 due to evolving energy and policy trends (Hausfather; Peters, 2020; Scafetta, 2023), both SSP3-

7.0 and SSP5-8.5 remain valuable for identifying potential biodiversity impacts in regions where mitigation policies are less consistent or delayed, such as parts of the Neotropics. SSP3-7.0 assumes a fragmented world with low international cooperation, while SSP5-8.5 represents a fossil-fueled development trajectory with high energy demand (Riahi et al., 2017). In this context, these scenarios were not used as predictions, but as boundary conditions to explore the vulnerability and resilience of the Babassu Complex under contrasting high-risk futures. The projections were based on all five Global Climate Models (GCMs) available in the CHELSA database: National Oceanic and Atmospheric Administration - Geophysical Fluid Dynamics Laboratory (GFDL-ESM4), Met Office Hadley Centre (UKESM1-0-LL), Max Planck Institute for Meteorology (MPI-ESM1-2-HR), Institut Pierre Simon Laplace (IPSL-CM6A-LR), and Meteorological Research Institute (MRI-ESM2-0).

Pre-processing and modelling

The occurrence of palms has been primarily observed in tropical regions (Eiserhardt et al., 2011); moreover, the distribution of babassu species appears to be centred in the Neotropics (Teixeira 2008; Santos-Filho, Almeida Júnior, Soares 2013; Silva et al. 2014; Reis et al. 2018). Thus, all models were generated for the Neotropical region, encompassing Central and South America and the Caribbean. The SDMs were implemented using an integration of the sdm (Naimi; Araújo, 2016) and dismo (Hijman et al., 2024) packages in R 4.3.2. The models were trained using 70% of the retained occurrence points, with the remaining 30% being allocated for model testing.

Species distribution models based on presence-only data rely on recorded occurrences and do not account for confirmed absences. To compensate, researchers have employed various strategies to refine model predictions and improve ecological inference, such as the use of background points (Renner et al., 2015). To minimise sampling bias and acted as 'pseudo-absence' data in the models, ten thousand background points were randomly generated across the Neotropical region, which corresponds to the biogeographic extent of the Babassu Complex and reflects the broad ecological amplitude of the *Attalea* genus. This number is frequently recommended in SDMs studies to ensure sufficient environmental coverage while maintaining computational efficiency (Radomski et al., 2022; Valavi et al., 2022; Whitford; Shipley; McGuire, 2024) . The selection of background points in SDMs varies considerably (Steen et al., 2024; Whitford;

Shipley; McGuire, 2024), and it is well known that using large background extents can inflate environmental gradients and potentially compromise model realism, particularly for species with narrow distributions and few occurrence records (Vasquez et al., 2021). In our case, species such as *A. vitrivir* (n = 27) and *A. barreirensis* (n = 41) are restricted in space (see Figure 1), which could increase sensitivity to this issue. However, because no detailed information exists on their climatic tolerances or dispersal constraints, defining a more ecologically precise background would be speculative. As such, the Neotropical background was retained for all species to maintain consistency and support comparative and ensemble analyses. Moreover, benchmark studies show that presence-background models can still achieve reliable performance for rare species, provided that background points are well-distributed and model complexity is appropriately managed (Valavi et al., 2022; Whitford; Shipley; McGuire, 2024). Our approach thus seeks to balance ecological realism and methodological consistency, while acknowledging the limitations of modelling poorly known and geographically restricted species.

Multicollinearity is a common issue in ecological modelling, as it complicates the estimation of variable effects and reduces model extrapolation accuracy (Brun et al., 2020; Graham, 2003). To address this, a multicollinearity analysis was conducted (Dormann et al., 2013), for the seven species and Babassu Complex overall using all the bioclimatic variables considered for constructing the bioclimatic models. Variance inflation factors (VIF) were calculated using the *vifstep* function from the *usdm* package (Naimi et al., 2014), utilising default specifications, with variables showing VIF > 10 considered highly collinear and excluded to prevent overfitting.

Given the unavailability of evapotranspiration and vapour pressure deficit data for future climate scenarios in the CHELSA database, a correlation analysis was conducted utilising Spearman's coefficient (See Figure S1.1) on the complete set of current bioclimatic variables. This analysis, performed with the *rcorr* function from the *Hmisc* package (Hijman et al., 2024), identified the most strongly correlated variables to substitute for missing predictors. To avoid redundancy, each missing predictor was replaced only by its single most correlated variable, ensuring that a given predictor was not associated with multiple replacements. All the remaining predictors used for current and future scenarios can be found in Table S1.3. For the current scenario, multicollinearity analysis resulted in 8 to 12 variables being kept in model formulations. The most frequently retained predictors included mean diurnal temperature range

(MDTR), mean monthly precipitation amount of the warmest quarter (MMPAWaQ), mean daily mean air temperatures of the wettest quarter (MDTWeQ), and precipitation amount of the wettest month (PAWM), which appeared in at least seven of the eight models (Figure S1.2). Conversely, annual precipitation amount (APA) (*A. speciosa* model), mean monthly potential evapotranspiration (PPMean) (*A. eichleri* model), mean monthly vapour pressure deficit (VPDMean) (*A. funifera* model), and mean daily mean air temperatures of driest quarter (MDTDQ) (*A. maripa* and *A. phalerata* models) were less frequently selected.

To generate the SDMs for all the datasets in current and future scenarios, models were implemented using the sdm package, employing four algorithms with complementary modelling approaches: Boosted Regression Trees (BRT) (Friedman, 2001), Generalised Linear Models (GLM) (McCullagh; Nelder, 1989), Maximum Entropy (MaxEnt) (Phillips; Anderson; Schapire, 2006) and Random Forest (RF) (Breiman, 2001). These algorithms were chosen because they represent a diverse spectrum of statistical and machine learning methods, ranging from parametric (GLM), semi-parametric (MaxEnt), to non-parametric (BRT, RF), and are widely benchmarked in ecological niche modelling (Norberg et al., 2019; Qiao et al., 2019; Shabani; Kumar; Ahmadi, 2016). This diversity helps capture varying species–environment relationships while mitigating algorithm-specific biases in ensemble predictions (Valavi et al., 2022). To evaluate the mean performance of the algorithms, the k-fold cross-validation technique was implemented through the sdm function from the sdm R package. In this process, the occurrence data were divided into five folds, and the cross-validation procedure was repeated five times. This approach yielded 25 models (5 folds × 5 repetitions) per species–algorithm combination, thereby providing a robust assessment of model performance, utilising multiple random partitions as opposed to a single one (Phillips; Anderson; Schapire, 2006). The performance of the models was evaluated using the receiver operating characteristic (ROC) curve (Phillips; Anderson; Schapire, 2006), assessed based on area under the curve (AUC) values (Swets, 1988), True Skill Statistics (TSS) (Allouche; Tsoar; Kadmon, 2006), and deviance measures. AUC or TSS values of 1 indicate perfect predictive performance, while values of ≤ 0.5 suggest random prediction (Allouche; Tsoar; Kadmon, 2006; Swets, 1988). According to these metrics, all models showed good performance (AUC: 0.95–1.00; TSS: 0.85–0.99; Deviance: 0.08–0.37; Table S1.4a-c).

To assess the contribution of individual variables to the presence-absence of Babassu Complex species, we calculated relative variable importance (IR%), based on the mean AUC metric as implemented in the R package sdm (Naimi; Araújo, 2016). These values were then visualised using the *getVarImp* function. Both model performance metrics and IR% values are available in the metadata of the SDM objects.

Habitat suitability and presence-absence maps

Habitat suitability maps were generated for each of the four modelling algorithms (MaxEnt, RF, GLM, and BRT), for each individual species and for the Babassu Complex overall, using the predict function from the dismo package. For the current scenario (2011-2040), an ensemble suitability map was created by integrating the outputs from the four algorithms using a weighted average based on TSS performance criteria (Boali et al., 2024; Marmion et al., 2009). This ensemble approach balance interpretability and predictive power, following best practices for ecological forecasting, and ensures that better-performing models contribute more heavily to the final prediction (Valavi et al., 2022). For the future scenarios (2041-2070 and 2071-2100) under both SSP3-7.0 and SSP5-8.5, the ensemble suitability maps for each species and the Babassu Complex were generated by combining all individual model outputs (i.e. all four algorithms across each of the five GCMs) into a single ensemble per scenario for period, using TSS-weighted averages. All GCMs (GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, IPSL-CM6A-LR, and MRI-ESM2-0) were given equal representation, but individual model contributions were weighted by algorithmic performance (TSS). This method reflects ensemble modelling practices recommended for ecological forecasting under climate change, helps mitigate model-specific biases and offers a pragmatic balance between robustness and interpretability (Brun et al., 2020).

The resulting ensemble habitat suitability map for all scenarios were then transformed into binary presence-absence maps, delineating the potential distribution of the seven individual species and the Babassu Complex. This was achieved using the maximum thresholding method (maxSSS), which optimises the trade-off between sensitivity (true positive rate) and specificity (false positive rate) and is not affected by the use of pseudo absences (Liu; White; Newell, 2013).

Finally, the ensemble maps for both current and future scenarios were reprojected to a Universal Transverse Mercator (UTM) coordinate system and resampled to a spatial resolution of 1 km to allow area calculations, and to assess the change in suitable area between classes across scenarios. The suitability maps were classified into four categories: unsuitable (suitability ≤ 0.05), low suitability (0.05 < suitability ≤ 0.33), medium suitability (0.33 < suitability ≤ 0.66), and high suitability (suitability > 0.66). The cutoff for unsuitability corresponds to the lower 5th percentile of predicted suitability values, excluding areas environmentally equivalent to background conditions (Almpanidou et al., 2016; Liu; White; Newell, 2013). The thresholds for low and medium suitability follow widely used ENM classifications and represent a gradient of environmental favourability (Jiménez-Valverde, 2014). Low suitability includes marginal habitats, often corresponding to the lower quantiles of predicted suitability (Liu; White; Newell, 2013; Sillero, 2011), while medium suitability includes suboptimal but viable environments for species persistence, consistent with transitional habitat categories in SDM frameworks (Franklin, 2010). High suitability reflects optimal conditions, defined here as the upper tercile (>0.66) of predictions based on robust threshold-selection methods (Liu; Newell; White, 2016), and aligning with core climatic niches in Neotropical species distributions (Costa et al., 2022). For the current scenario, area calculations were conducted independently for each of the following algorithms: BRT, GLM, MaxEnt, and RF, in addition to the ensemble map. For future scenarios, area calculations were performed for each emission scenario (SSP3 7.0 and SSP5 8.5) across distinct periods (2041–2070 and 2071–2100) for the ensembles only. A detailed methodological workflow is provided in a flowchart (See Figure S1.3). All image processing and map generation were conducted using QGIS Desktop 3.18.2 and R 4.3.2.

Results

Relative importance of variables

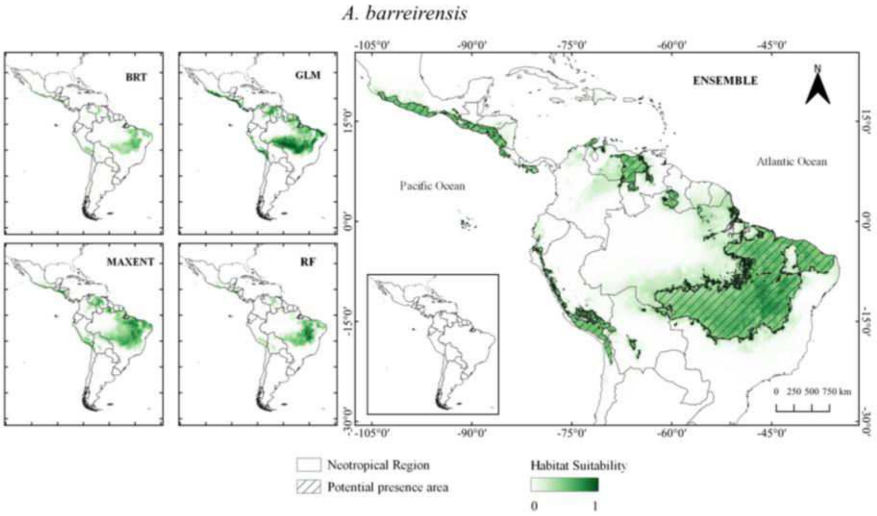
Most variables demonstrated low importance across the majority of SDMs and models (Table S1.5a-h). Results varied significantly among SDMs, resulting in high standard deviations in the mean importance per predictor (n=100) and, consequently, high coefficients of variation. The highest mean Im% values were observed for GLM, while the lowest were found for RF.

Among all predictors, temperature seasonality (TS) emerged most frequently as the variable with the highest Im%, showing a notable association with the distribution of *A. barreirensis* (53.0%), *A. eichleri* (43.6%), *A. maripa* (20.6%), and the Babassu Complex overall (34.5%). Furthermore, *A. eichleri* exhibited robust responses to annual range of monthly vapour pressure deficit (VPDrange) and mean monthly vapour pressure deficit (VPDmean), *A. speciosa* to Isothermality (Iso), and *A. vitrivir* to minimum monthly potential evapotranspiration (PPmin) and precipitation amount of the driest month (PADM).

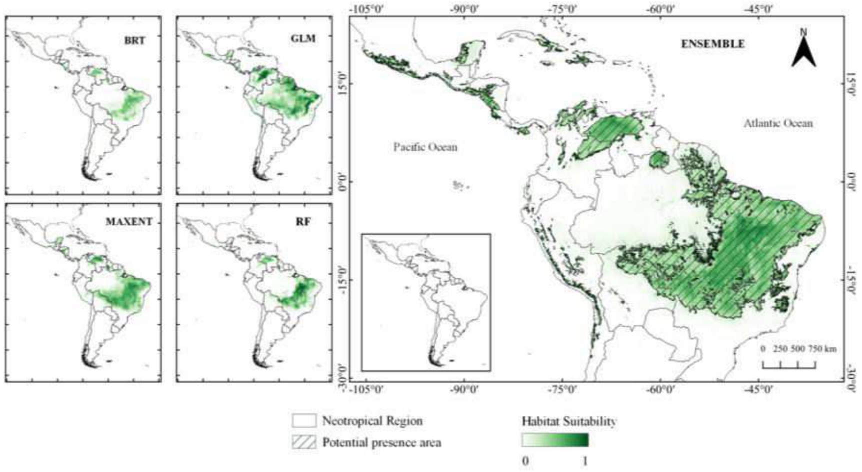
Predicted current habitat suitability and potential distribution of the Babassu Complex

The spatial distribution of habitat suitability areas was found to be consistent across SDM predictions (Figure 2a-h), with variations primarily observed in suitability levels (Table S1.6). The GLM algorithm identified the largest areas of high habitat suitability across models (See Table S1.7), while BRT predicted the smallest high-suitability areas but the most extensive low-suitability regions, with a maximum suitability value of approximately 0.53. RF and BRT models had the most conservative estimates of habitat suitability for the babassu species, while MaxEnt and GLM projected broader areas in the medium and high suitability classes.

a)

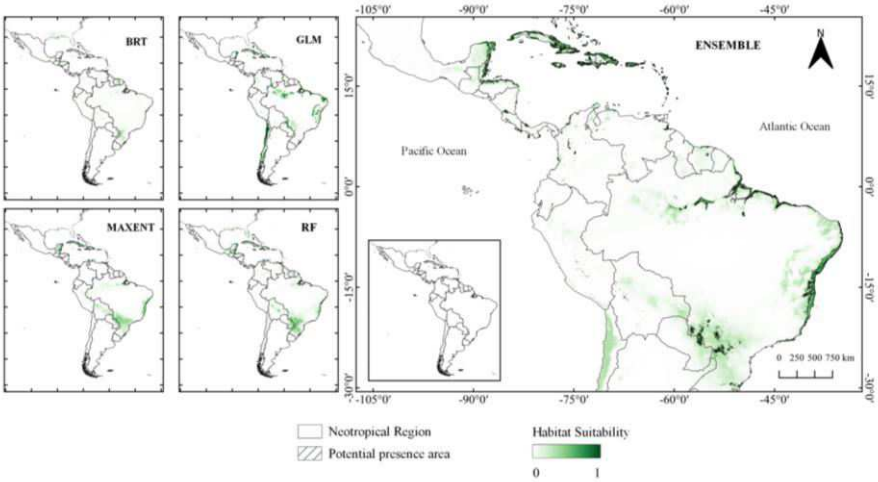


b)



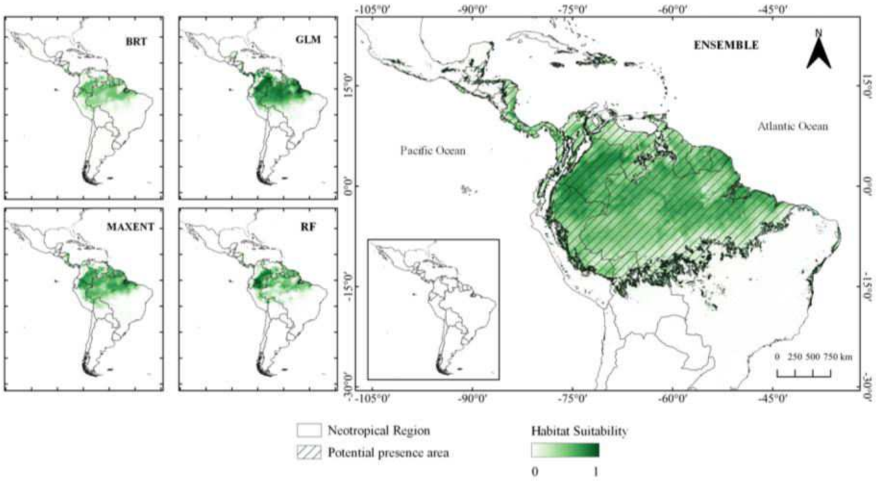
A. eichleri

c)



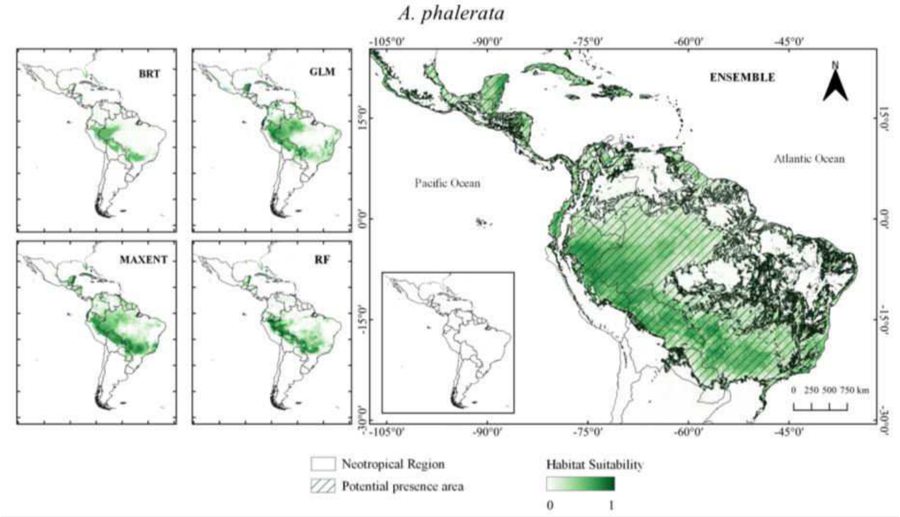
A. funifera

d)

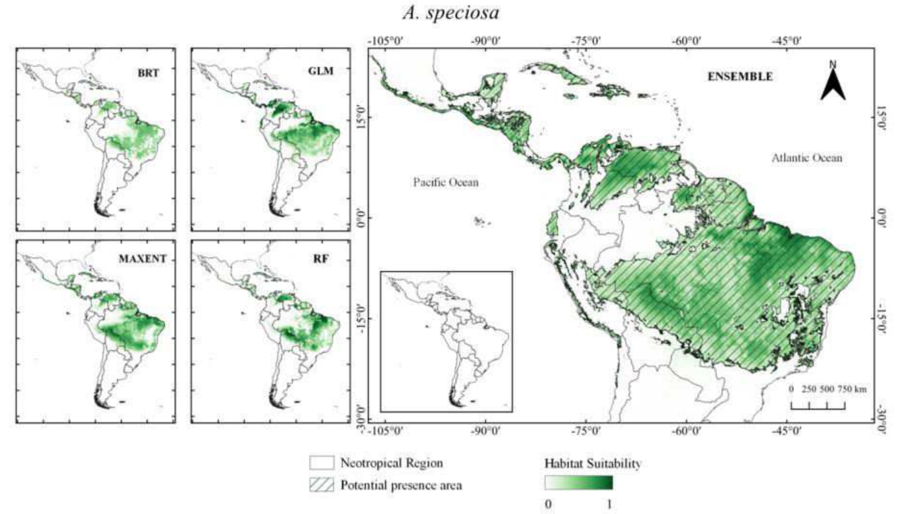


A. maripa

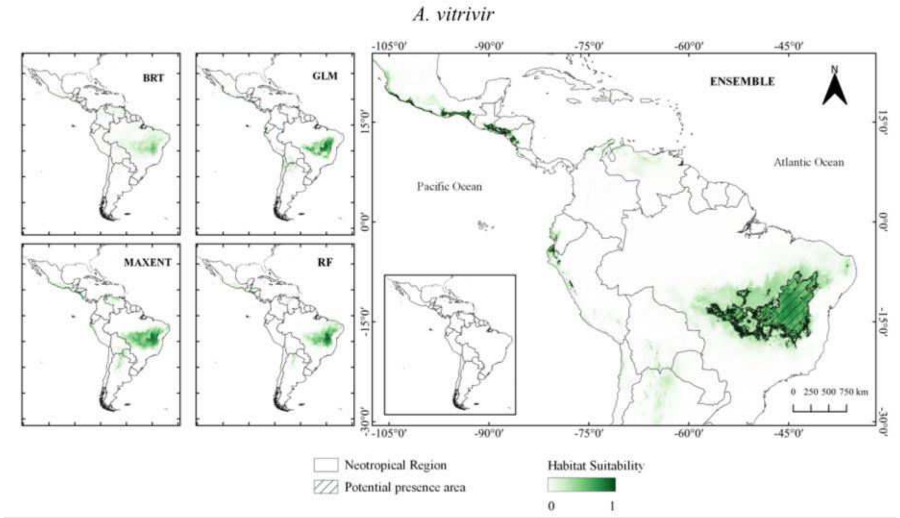
e)


A. phalerata
BRT
GLM
MAXENT
RF
ENSEMBLE
Pacific Ocean
Atlantic Ocean
-105°0'
-90°0'
-75°0'
-60°0'
-45°0'
15°0'
0°0'
-15°0'
-30°0'
N
0 250 500 750 km
Neotropical Region
Potential presence area
Habitat Suitability
0
1

f)


A. speciosa
BRT
GLM
MAXENT
RF
ENSEMBLE
Pacific Ocean
Atlantic Ocean
-105°0'
-90°0'
-75°0'
-60°0'
-45°0'
15°0'
0°0'
-15°0'
-30°0'
N
0 250 500 750 km
Neotropical Region
Potential presence area
Habitat Suitability
0
1

g)


A. vitrivir
BRT
GLM
MAXENT
RF
ENSEMBLE
Pacific Ocean
Atlantic Ocean
-105°0'
-90°0'
-75°0'
-60°0'
-45°0'
15°0'
0°0'
-15°0'
-30°0'
N
0 250 500 750 km
Neotropical Region
Potential presence area
Habitat Suitability
0
1

h)

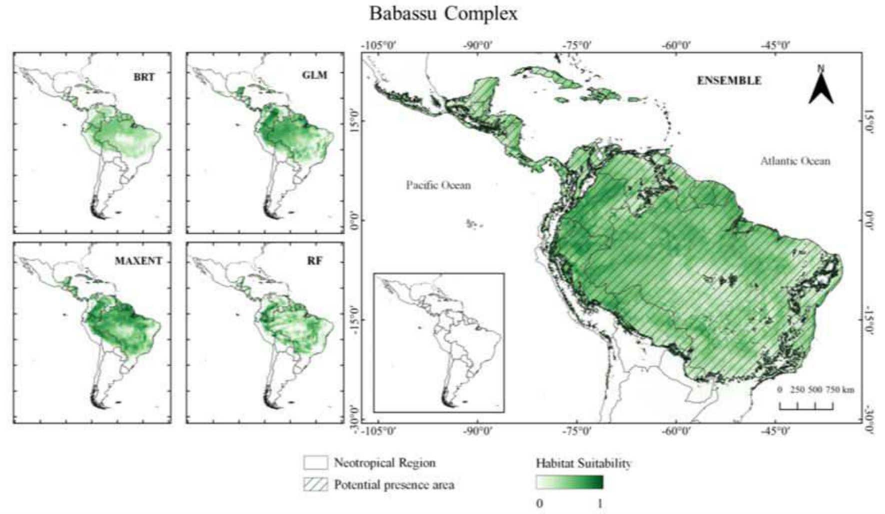


Figure 2. Habitat suitability maps for the modelled distribution of species within the Babassu Complex, based on Maximum Entropy (Maxent), Random Forest (RF), Boosted Regression Trees (BRT), Generalized Linear Models (GLM), and the ensemble map of all algorithms. The maps represent: a) *A. barreirensis*, b) *A. eichleri*, c) *A. funifera*, d) *A. maripa*, e) *A. phalerata*, f) *A. speciosa*, g) *A. vitrivir*, and h) the Babassu Complex overall, covering Neotropical region.

Among species, *Attalea speciosa* and *A. maripa* had the largest high-suitability areas, covering 927,503 km² and 915,496 km², respectively. Conversely, *A. vitrivir* (14,502,398 km²) and *A. funifera* (14,020,351 km²) had the most extensive unsuitable areas. For the Babassu Complex as a whole, the most extensive suitability class was medium suitability, covering 7,891,228 km².

Changes in habitat suitability in future climatic change emissions scenarios

The application of SDMs has revealed notable differences in the bioclimatic suitability of species from the Babassu Complex under current climate conditions, which has demonstrated significant adaptability across tropical regions of the Americas and the Caribbean, particularly in the Amazon rainforest and Cerrado (Figure 2a-h). At the species level, *A. barreirensis* and *A. eichleri* predominantly occupied savanna regions, including the Brazilian Cerrado and the Venezuelan Llanos. *A. funifera* exhibited the most restricted distribution, mainly within the tropical and subtropical moist broadleaf forests of the Brazilian Atlantic Forest, coastal Bahia, and the Brazil-Paraguay border, as well as parts of the tropical and subtropical dry broadleaf forests of the Caribbean and Central

America. *A. maripa* showed an intrinsic relationship with the Amazon rainforest in northern South America. *A. phalerata* was found in tropical and subtropical moist forests, flooded grasslands of the Chaco and Pantanal, and savanna regions. Of all the species, *A. speciosa* demonstrated the largest potential distribution, encompassing transitional zones between the Cerrado and Amazon, adjacent areas, and savanna regions across the Americas (Cerrado, Llanos) and the Caribbean. Finally, *A. vitrivir* exhibited one of the smallest distribution areas, being confined to the Brazilian Cerrado and the transition zones between the Cerrado, Caatinga, and Atlantic Forest.

The analysis revealed that the prediction maps generated by each of the algorithms, and when averaged together, indicated the Babassu Complex as having extensive potential to support its presence across South America. The areas of highest environmental suitability were found to be predominantly concentrated in the northwestern regions of the continent, significantly overlapping the Amazon rainforest. However, a substantial portion of these suitable areas was also identified within the Cerrado biome, indicating a potential intrinsic relationship with both ecosystems.

Comparison of habitat suitability areas between current and future scenarios (see Table 1 and Figure S1.4) indicate a substantial increase in high-suitability areas for most models and climate change scenarios, with the only reductions being observed in the 2071-2100/SSP3 scenario for *A. funifera* (-8.55%) and *A. vitrivir* (-20.97%). The scenario with the most significant increase in high-suitability areas for the majority of models was 2041-2070/SSP3 (Figure 3). For the Babassu Complex, the largest increases in high-suitability areas were recorded across all future scenarios, ranging from 680.78% in 2041-2070/SSP3 to 871.80% in 2071-2100/SSP5.

Table 1. Projected changes in habitat suitability for *A. barreirensis*, *A. eichleri*, *A. funifera*, *A. maripa*, *A. phalerata*, *A. speciosa*, *A. vitrivir*, and the Babassu Complex overall, under SSP3-7.0 and SSP5-8.5 Scenarios (2041-2100 and 2071-2100).

Species	**Class**	**Scenarios**							
		2041-2070				2071-2100			
		SSP3 - 7.0		SSP5 - 8.5		SSP3 - 7.0		SSP5 - 8.5	
		Future (km^2)	Relative Difference (%)	Future (km^2)	Relative Difference (%)	Future (km^2)	Relative Difference (%)	Future (km^2)	Relative Difference (%)
A. barreirensis	Unsuitable	10389998	-12.78	11222328	-5.79	10599801	-11.02	9662624	-18.89
	Low	7550859	16.80	7037553	8.86	8265168	27.85	8340284	29.01
	Medium	2922591	-1.32	2547970	-13.97	2255124	-23.86	2898266	-2.14
	High	710311	178.68	765908	200.49	453666	77.99	672586	163.88
A. eichleri	Unsuitable	10203525	0.14	9851437	-3.31	10266276	0.76	9234843	-9.37
	Low	6931939	-17.64	7564985	-10.11	7192470	-14.54	8121934	-3.50
	Medium	2990210	13.09	2956637	11.82	3092123	16.95	2954888	11.76
	High	1448086	319.90	1200700	248.17	1022890	196.61	1262094	265.97
A. funifera	Unsuitable	4114133	-70.66	6004479	-57.17	6964763	-50.32	4544225	-67.59
	Low	16657799	133.94	15181583	113.21	14352789	101.57	16447072	130.98
	Medium	764255	81.03	351878	-16.65	227706	-46.06	535694	26.89
	High	37572	20.56	35819	14.93	28501	-8.55	46769	50.06
A. maripa	Unsuitable	9145010	-22.61	9146797	-22.60	8997537	-23.86	8997711	-23.86

	Low	5799128	25.04	5650332	21.83	5878972	26.76	5713825	23.20
	Medium	4334464	2.63	4524891	7.14	4608890	9.13	4573014	8.28
	High	2295158	150.70	2251740	145.96	2088360	128.11	2289209	150.05
A. phalerata	Unsuitable	5762009	-25.74	6098864	-21.40	5855616	-24.53	6262523	-19.29
	Low	7905634	-20.43	8162661	-17.84	8303156	-16.43	6851348	-31.04
	Medium	5847963	84.71	5519804	74.35	5729364	80.97	6509678	105.61
	High	2058153	180.65	1792430	144.41	1685624	129.85	1950210	165.93
A. speciosa	Unsuitable	6270546	-33.72	7329885	-22.52	7834524	-17.19	7098530	-24.97
	Low	7670282	16.46	7065532	7.28	7171222	8.89	7443843	13.03
	Medium	5073102	9.80	5042139	9.13	5321250	15.17	4859595	5.18
	High	2559830	175.99	2136203	130.32	1246764	34.42	2171792	134.15
A. vitrivir	Unsuitable	12884926	-11.15	12859357	-11.33	13861406	-4.42	13051311	-10.01
	Low	7484122	28.60	6857590	17.84	6962269	19.63	6860189	17.88
	Medium	954730	-12.12	1562079	43.79	603198	-44.47	1435779	32.17
	High	249982	34.50	294734	58.58	146886	-20.97	226480	21.86
Babassu Complex	Unsuitable	6188662	-17.12	6515732	-12.75	6032378	-19.22	6087909	-18.47
	Low	4050732	-30.26	4004980	-31.05	4030283	-30.61	4009590	-30.97
	Medium	7997410	1.35	7431489	-5.83	7547891	-4.35	7322919	-7.20
	High	3336956	680.78	3621558	747.37	3963208	827.31	4153342	871.80

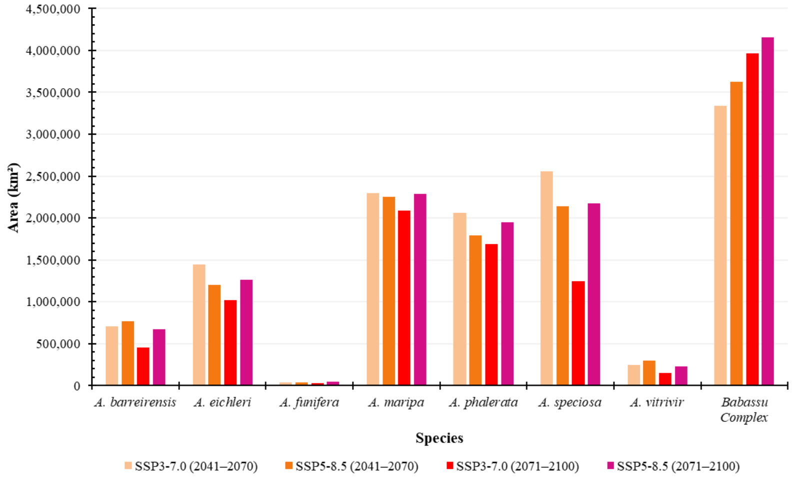


Figure 3. Projected area (km^2) of high environmental suitability for seven *Attalea* species and the Babassu Complex under SSP3-7.0 and SSP5-8.5 scenarios for 2041–2070 and 2071–2100.

Discussion

The selection of specific predictors, as observed for annual precipitation amount (APA) (*A. speciosa*), mean evapotranspiration (PPMean) (*A. eichleri*), mean vapour pression deficit (VPDMean) (*A. funifera*), and mean daily temperature in the driest quarter MDTDQ (*A. maripa* and *A. phalerata*), may indicate more species-specific environmental preferences (Brun et al., 2020; Dormann et al., 2013; Graham, 2003). However, it is important to note that the retention of these predictors does not necessarily imply a direct ecological response (Graham, 2003), underscoring the need for complementary field and physiological studies to validate these predictors' ecological significance.

The Relative Variable Importance (Im%) values demonstrated that humidity-related variables were not the most influential in modelling Babassu Complex distributions. Instead, temperature seasonality (TS), defined as the standard deviation of mean monthly temperature, exhibited a high retention frequency across species after multicollinearity removal and had the highest Im% values, identifying it as a key predictor. These results corroborate Eiserhardt et al. (2011), who emphasized palm species' sensitivity to cold and seasonal climates due to limited frost tolerance and dormancy mechanisms These findings serve to reinforce the notion of the pronounced temperature sensitivity exhibited by palms and their marked preference for tropical climates (Eiserhardt et al., 2011).

Concerning SDMs, Generalised Linear Models (GLMs) have been shown to assign higher Im% values to individual bioclimatic variables in comparison to alternative modelling methods. In the context of GLMs, the occurrence of species is assumed to be associated with environmental variables according to a predefined relationship, thereby placing greater emphasis on variables that exhibit strong statistical associations. This sensitivity may result in an overemphasis on certain predictors, potentially reducing the reliability of species distribution projections and highlighting the importance of ensemble models (Hao et al., 2019; Marmion et al., 2009; McCullagh; Nelder, 1989). Conversely, Random Forest (RF) assigned lower numerical importance to individual predictors. This is because RF is a non-parametric algorithm based on an ensemble of decision trees, which distributes variable importance across multiple trees (Antoniadis; Lambert-Lacroix; Poggi, 2021; Breiman, 2001; Zhang et al., 2019). Consequently, RF tends to yield more balanced variable importance values, which are often lower than those observed in parametric models such as GLMs.

The broad suitability ranges exhibited by *Attalea maripa*, *A. phalerata*, and *A. speciosa* suggested high levels of tolerance to present-day bioclimatic conditions, which highlights the necessity for their management. In contrast, the more limited suitability zones of *A. funifera* and *A. vitrivir*, particularly the latter, indicating higher vulnerability to environmental fluctuations. This emphasises the necessity for the formulation of targeted conservation strategies to ensure the continued viability of these species in the context of climate change (Elliott et al., 2024; Lannuzel et al., 2021; Volis; Tojibaev, 2021). The use of a uniform Neotropical background extent for all species, including range-restricted taxa like *A. funifera*, *A. barreirensis*, and *A. vitrivir*, ensured methodological consistency and allowed comparative ensemble modelling. However, this approach may overestimate bioclimatic suitability for narrowly distributed species by incorporating ecologically irrelevant areas. While justified by limited ecological information on these species, future studies should explore species-specific extents based on dispersal capacity and biogeographic context to refine predictions (Vasquez et al., 2021; Whitford; Shipley; McGuire, 2024).

The variations observed among models in the current scenario are indicative of the inherent characteristics of the algorithms used, thus reinforcing the necessity for complementary approaches to enhance projection robustness and minimise methodological uncertainties. These differences arise from the way each algorithm processes environmental information. RF and BRT likely emphasised strong environmental signals and interactions within the training data, constraining their projections to regions with highly suitable conditions while prioritising complexity and precision (Antoniadis; Lambert-Lacroix; Poggi, 2021; Breiman, 2001; Friedman, 2001; Zhang et al., 2019). Conversely, MaxEnt and GLM, with their broader statistical assumptions, projected larger continuous areas of medium to high suitability, potentially incorporating marginally suitable regions (Guisan; Zimmermann, 2000; McCullagh; Nelder, 1989; Phillips; Anderson; Schapire, 2006).

Furthermore, the ensemble modelling framework combined parametric (GLM), semi-parametric (MaxEnt), and non-parametric (BRT, RF) algorithms to leverage complementary strengths: GLMs provided interpretable relationships between predictors and responses but often produced inflated variable importance values due to model assumptions, while machine-learning methods captured complex interactions and generalized more conservatively (Norberg et al., 2019; Valavi et al., 2022). Ensemble models mitigated individual algorithm biases, improving robustness, predictive reliability, and generalization capacity, particularly when dealing with species that have varied ecological traits and data availability (e.g., widespread generalists like *A. speciosa* vs. narrowly distributed taxa like *A. vitrivir*) (Hao et al., 2019; Kaky et al., 2020; Marmion et al., 2009; Valavi et al., 2022).

It is anticipated that climate change will favour species capable of tolerating warmer and more variable climatic conditions, thereby enhancing their performance and facilitating their spread into new areas (Blois et al., 2013). Projections indicate a potential expansion of bioclimatic suitability for species of the Babassu Complex under future climate scenarios. This expansion could significantly affect savanna ecosystems such as the Brazilian Cerrado and the Venezuelan Llanos, as well as degraded areas of the Amazon rainforest (Santos et al., 2022), potentially altering ecological dynamics and species interactions (Rosenblatt; Schmitz, 2014). The presence of highly suitable habitats in these regions may allow babassu species to disperse from adjacent ecosystems and integrate into local communities (Blois et al., 2013; Gehring et al., 2020).

This ecological shift presents both opportunities and risks. On one hand, babassu expansion may support biodiversity restoration and the livelihoods of traditional communities that depend on palm products (Mitja et al., 2019; Porro et al., 2011). On the other, unmanaged expansion could lead to ecological imbalances and potential invasiveness with the potential to reshape local vegetation structure, alter resource availability for other plants and animals, and influence key ecological processes such as fire regimes and competition for space and nutrients (Alves et al., 2019; De Kort et al., 2021; Gehring et al., 2020). This dual nature calls for proactive management strategies that mitigate ecological risks while maximizing socioeconomic and environmental gains through sustainable extractivism, agroforestry integration, and community-led conservation.

Despite potential ecological concerns related to mismanagement, Babassu palms are deeply integrated into the cultural and economic fabric of traditional communities, contributing with food, oil, fiber, and income (De Oliveira et al., 2022; Mitja et al., 2019; Porro et al., 2011; Shiraishi Neto, 2017). The projected expansion of climatically suitable areas for babassu species offers practical opportunities for both conservation and sustainable use of its species. Regions such as the Cerrado-Amazon transition zone and the Venezuelan Llanos, where species like *A. speciosa*, *A. maripa*, and *A. phalerata* are projected to expand, should be prioritized for sustainable extractivism and community-based agroforestry initiatives that align with traditional livelihoods and promote biodiversity conservation (Almeida Campos et al., 2015; De Oliveira et al., 2022; Mitja et al., 2019). In contrast, species with more restricted distributions and higher vulnerability to climatic shifts, including *A. vitrivir* and *A. funifera*, demand targeted in situ conservation actions in regions identified as future climatic refugia (Lannuzel et al., 2021; Volis; Tojibaev, 2021). Integrating species distribution models with local ecological knowledge and land-use planning offers a pathway for designing resilient socioecological systems that support both biodiversity and human well-being under climate change (Porro et al., 2011; Valavi et al., 2022).

Moreover, while SDMs predict broad future suitability, actual expansion is contingent on factors like dispersal ability, landscape connectivity, and biogeographic barriers. Thus, expansion is not guaranteed and must be interpreted with caution. These results also corroborate Eiserhardt et al. (2011), who emphasized palm species' sensitivity to cold and seasonal climates due to limited frost tolerance and dormancy mechanisms. This physiological sensitivity helps explain the concentration of unsuitable habitats in arid and colder regions, where thermal stress and low humidity act as constraints on distribution.

Ongoing changes in land use and land cover have already had an impact on the geographic distribution of many species, disrupting taxonomic flows and reducing biodiversity at both present and future scales (Adhikari et al., 2022; Bellard et al., 2012; Trautmann, 2018). Given that some babassu species are associated with anthropized landscapes (Gehring et al., 2020; Santos et al., 2022), incorporating anthropogenic variables such as land use, biological interactions, topography, and edaphic conditions into modelling efforts could improve the accuracy of distribution projections (Blach-Overgaard et al., 2010; Frans et al., 2022; Nuñez-Penichet; Maita; Soberon, 2024; Silva et al., 2023; Vedel-Sørensen et al., 2013; Zuquim et al., 2023). The resilience of these species to disturbed environments (Santos et al., 2022), coupled with the interaction of ecological and anthropogenic factors, may be key determinants of their persistence and potential expansion under future scenarios.

Moreover, it is imperative to interpret SDM predictions as testable hypotheses rather than as direct substitutes for actual population parameters. To ensure reliability and applicability in ecological planning, it is essential to validate these models when utilising them to guide conservation decisions (Lee-Yaw et al., 2022).

Research limitations

While this study provides valuable insights into the climate-driven distribution shifts of the Babassu Complex, several limitations should be acknowledged. First, the use of a uniform Neotropical background extent for all species, including those with restricted distributions (e.g., *A. funifera*, *A. vitrivir*), may have overestimated suitability for rare taxa by incorporating ecologically irrelevant areas. Future studies could refine predictions by testing species-specific extents based on dispersal constraints or biogeographic barriers (Vasquez et al., 2021; Whitford et al., 2024). Second, anthropogenic factors such as land-use change, habitat fragmentation, and human-mediated dispersal were not incorporated, potentially inflating projected suitability in heavily modified landscapes (Blach-Overgaard et al., 2010; Nuñez-Penichet; Maita; Soberon, 2024). Third, the models assume unlimited dispersal, ignoring geographic barriers (e.g., deforestation, mountain ranges) that may limit range shifts (Adhikari et al., 2022; Qiao et al., 2019). Finally, while ensemble modelling mitigated algorithmic biases, field validation is needed to confirm predicted expansions, particularly for species with low occurrence records (Franklin, 2023; Lee-Yaw et al., 2022). Addressing these limitations through integrated socio-ecological frameworks will enhance the practical utility of SDMs for conservation planning.

Conclusions

The projected responses of Babassu species to climate change reveal distinct ecological strategies and potential biogeographic shifts. Generalist species such as *A. speciosa*, *A. maripa*, and *A. phalerata* show broad tolerance to warmer and more seasonal climates, suggesting potential range expansions into transitional and anthropized environments. In contrast, *A. vitrivir* and *A. funifera* show narrow climatic suitability, indicating higher sensibility to climate changes. These patterns underscore the dual role of climate as both a driver of expansion and a constraint on persistence, emphasizing the need for species-specific conservation strategies. Beyond mapping distributions, these findings contribute to a broader understanding of how tropical plant species may reorganize in response to shifting climatic envelopes. Such reorganization has implications not only for local ecosystems and community structure but also for long-distance floristic connectivity, endemism patterns, and the future configuration of Neotropical biotas.

By integrating the strengths of multiple algorithms and mitigating individual model biases, species distribution modelling (SDM) techniques provide robust insights into current and future biogeographic patterns. Within the Babassu Complex, these approaches have helped fill critical knowledge gaps, highlighting how species with different ecological traits and climatic tolerances may respond unevenly to environmental change. While ensemble species distribution models remain powerful tools for anticipating these changes, the key insight lies in their ecological interpretation: predicting not just where species might go, but how they will interact with existing communities and processes when they arrive.

A forward-looking conservation biogeography should therefore combine modelling with field validation and ecological data to better anticipate species responses. Thus, future research should focus on incorporating anthropogenic variables, validating predictions with field data, and exploring species-specific ecological responses to climate change. A multidisciplinary approach that combines species distribution modelling with ecological and socioeconomic assessments will be essential for developing effective conservation and management strategies in the face of ongoing environmental change.

Data Availability Statement

All species occurrence records are available via GBIF, and bioclimatic variables were sourced from the CHELSA database. The full set of modelling scripts and processed data has been deposited on Zenodo (https://doi.org/10.5281/zenodo.15265496), ensuring full transparency and reproducibility of all analyses and results.

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Supporting Information

Table S1.1. ODMAP protocol documenting the modelling workflow for climate change projections of seven Attalea species (Babassu Complex) in the Neotropics.

1. Overview	**1.1 Objective**	To identify the key bioclimatic drivers of the Babassu Complex (*Attalea* spp.) in the Neotropics and predict current and future habitat suitability under climate change scenarios.
	1.2 Study Taxa	Babassu Complex (*Attalea* spp.) – Seven species: *A. barreirensis*, *A. eichleri*, *A. funifera*, *A. maripa*, *A. phalerata*, *A. speciosa*, *A. vitrivir*, and Babassu Complex overall.
	1.3 Study Area	Neotropical Region
	1.4 Study Period	Current (2011-2040); Future (2041–2070 and 2071–2100).
	1.5 Hypotheses	Species distributions will shift due to climate change, expanding for climate-tolerant species and shrinking for climate-sensitive ones.
2. Occurrence Data	**2.1 Source**	GBIF.
	2.2 Data Type	Presence-only records.
	2.3 Sample Size	~19,204 raw records; *A. barreirensis* (n = 41), *A. eichleri* (n = 79), *A. funifera* (n = 65), *A. maripa* (n = 570), *A. phalerata* (n = 431), *A. speciosa* (n = 84), *A. vitrivir* (n = 27), and the combined dataset (n = 1,269), after spatial filtering.
	2.4 Filtering Methods	Spatial thinning to 20 km.
3. Environmental Data	**3.1 Variable Source**	CHELSA v2.1 bioclimatic variables; SMI-CMIP6 GCMs for future scenarios.
	3.2 Variables Used	Full list of 23 CHELSA variables (bio1–bio19, PP, VPD derivatives); reduced post-VIF.
	3.3 Resolution	30 arc-seconds (~1 km²).
	3.4 GCMs Used	GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, IPSL-CM6A-LR, MRI-ESM2-0.
	3.5 Scenarios	SSP3-7.0 and SSP5-8.5.
4. Pre-processing	**4.1 Collinearity**	VIF threshold < 10; usdm:vifstep() used.
	4.2 Replacement of Missing Predictors	Spearman correlation with current variables to substitute missing PP and VPD values.
	4.3 Spatial Mask	Entire Neotropical realm.

5. Modelling	**5.1 Algorithms Used**	Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT), Generalized Linear Models (GLM).
	5.2 Pseudo-absences	10,000 randomly selected background points per model.
	5.3 Model Calibration	70% training / 30% testing; k-fold cross-validation (5 folds × 5 repeats).
	5.4 Model Evaluation	AUC, TSS, Deviance.
	5.5 Ensemble Modelling	Weighted mean using TSS for current and future projections.
	5.6 Software	R 4.3.2 (packages: sdm, dismo, usdm, Hmisc, etc.); QGIS 3.18.2.
6. Output	**6.1 Suitability Maps**	Continuous (0–1) and classified maps: unsuitable (≤ 0.05), low (0.05–0.33), medium (0.33–0.66), high (> 0.66).
	6.2 Thresholding	maxSSS (maximizes sensitivity + specificity).
	6.3 Presence-Absence Maps	Ensemble presence-absence per species and overall complex.
	6.4 Area Calculation	Suitability maps reprojected to UTM, 1 km resolution. Area computed for all classes.
	6.5 Change Maps	Area change between current and future for each class and species.
	6.6 Variable Importance	Relative variable contribution (Im%) based on mean AUC-weighted values across repetitions.
7. Uncertainty & Validation	**7.1 Sources of Uncertainty**	Algorithmic, GCM, scenario-specific; addressed via ensembling.
	7.2 Model Robustness	High mean AUC (0.97–0.99), high TSS (0.90–0.95).
	7.3 Data Availability	Data and code archived at Zenodo: https://doi.org/10.5281/zenodo.15243376
8. Interpretation	**8.1 Ecological Implications**	Species with wider tolerance may expand, altering community composition and ecosystem function. Potential ecological disruption vs restoration opportunities.
	8.2 Conservation Relevance	Highlights climate-driven biogeographic shifts in socio-economically important species. Supports regional conservation planning in Amazon and Cerrado biomes.
9. Funding	**9.1 Funding**	FAPEMA (IECT-05539/18), CAPES (PDSE - Edital n° 44/2022).

Table S1.2. List of bioclimatic variables considered for constructing the bioclimatic models sourced from the Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) database, version 2.1.

Acronym	Code	Description
APA	bio12	Annual Precipitation Amount
ART	bio7	Annual Range of Air Temperature
Iso	bio3	Isothermality
MAAT	bio1	Mean Annual Air Temperature
MDTCQ	bio11	Mean Daily Mean Air Temperatures of the Coldest Quarter
MDTDQ	bio9	Mean Daily Mean Air Temperatures of the Driest Quarter
MDTR	bio2	Mean Diurnal Temperature Range
MDTWaQ	bio10	Mean Daily Mean Air Temperatures of the Warmest Quarter
MDTWeQ	bio8	Mean Daily Mean Air Temperatures of the Wettest Quarter
MMPACQ	bio19	Mean Monthly Precipitation Amount of the Coldest Quarter
MMPADQ	bio17	Mean Monthly Precipitation Amount of the Driest Quarter
MMPAWaQ	bio18	Mean Monthly Precipitation Amount of the Warmest Quarter
MMPAWeQ	bio16	Mean Monthly Precipitation Amount of the Wettest Quarter
PADM	bio14	Precipitation Amount of the Driest Month
PAWM	bio13	Precipitation Amount of the Wettest Month
PPMax	Pet_penman_max	Maximum monthly potential evapotranspiration
PPMean	Pet_penman_mean	Mean monthly potential evapotranspiration
PPMin	Pet_penman_min	Minimum monthly potential evapotranspiration
PPRange	Pet_penman_range	Annual range of monthly potential evapotranspiration
PS	bio15	Precipitation Seasonality
TMaxW	bio5	Mean Daily Maximum Air Temperature of the Warmest Month
TMinC	bio6	Mean Daily Minimum Air Temperature of the Coldest Month
TS	bio4	Temperature Seasonality
VPDMax	VPDMax	Maximum monthly vapor pressure deficit
VPDMean	VPDMean	Mean monthly vapour pressure deficit
VPDMin	VPDMin	Minimum monthly vapour pressure deficit
VPDRange	VPDRange	Annual range of monthly vapour pressure deficit

Table S1.3. Final predictors retained after multicollinearity testing for each babassu species and the overall Babassu Complex, used for the current scenario and adjusted through correlation analysis for future scenarios.

SPECIES															
A. barreirensis		*A. eichleri*		*A. funifera*		*A. maripa*		*A. phalerata*		*A. speciosa*		*A. vitrivir*		Babassu Complex	
Current	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**	**Current**	**Future**
Iso	Iso	Iso	Iso	Iso	Iso	Iso	Iso	MDTDQ	MDTDQ	APA	APA	MDTR	MDTR	Iso	Iso
MDTR	MDTR	MDTR	MDTR	MMPACQ	MMPACQ	MDTDQ	MDTDQ	MDTR	MDTR	Iso	Iso	MDTWeQ	MDTWeQ	MDTR	MDTR
MDTWeQ	MDTWeQ	MDTWeQ	MDTWeQ	MMPAWaQ	MMPAWaQ	MDTR	MDTR	MDTWeQ	MDTWeQ	MDTR	MDTR	MMPACQ	MMPACQ	MDTWeQ	MDTWeQ
MMPAWaQ	MMPAWaQ	MMPACQ	MMPACQ	PADM	PADM	MDTWeQ	MDTWeQ	MMPACQ	MMPACQ	MDTWeQ	MDTWeQ	MMPAWaQ	MMPAWaQ	MMPAWaQ	MMPAWaQ
PAWM	PAWM	MMPAWaQ	MMPAWaQ	PAWM	PAWM	MMPACQ	MMPACQ	MMPAWaQ	MMPAWaQ	MMPACQ	MMPACQ	PADM	PADM	PADM	PADM
PPMin	PADM	PAWM	PAWM	PPMax	MAAT	PADM	PADM	PADM	PADM	MMPAWaQ	MMPAWaQ	PAWM	PAWM	PAWM	PAWM
PPRange	MMPAWaQ	PPMean	MMPADQ	PPRange	MDTCQ	PAWM	PAWM	PAWM	PAWM	PADM	PADM	PPMin	MDTDQ	PPMin	MMPADQ
PS	PS	PPRange	PADM	VPDMean	~~MAAT~~	PPMin	PADM	PPMax	ART	PPMax	MMPADQ	PS	PS	PPRange	TS
TS	TS	PS	PS	VPDRange	ART	PPRange	MMPAWaQ	PPMin	MAAT	PPMin	MDTCQ			PS	PS
		TS	TS			PS	PS	VPDMin	TMaxW	PS	PS			TS	TS
		VPDMin	MDTWeQ			TS	TS	VPDRange	MMPADQ	VPDMin	MDTWeQ			VPDMin	MMPADQ
		VPDRange	TMaxW			VPDMin	MDTWaQ			VPDRange	TMaxW			VPDRange	TMaxW

Table S1.4. Performance values based on a) mean area under the curve (AUC), b) True Skill Statistics (TSS), and c) Deviances, for the potential species distribution modeling using Maxent, Random Forest (RF), Boosted Regression Trees (BRT), and Generalized Linear Models (GLM). Results are provided for each babassu species and the Babassu Complex overall. Values in parentheses represent the standard deviation of the mean (n = 25).

a)

Species	**Algorithms (n=25)**			
	MaxEnt	RF	GLM	BRT
A. barreirensis	0.99 (± 0.01)	0.99 (± 0.01)	0.95 (± 0.02)	0.99 (± 0.01)
A. eichleri	0.99 (± 0.01)	0.99 (± 0.01)	0.96 (± 0.01)	0.99 (± 0.01)
A. funifera	1.00 (± 0.00)	1.00 (± 0.00)	0.99 (± 0.01)	0.99 (± 0.01)
A. maripa	0.99 (± 0.00)	0.99 (± 0.00)	0.98 (± 0.00)	0.99 (± 0.00)
A. phalerata	0.99 (± 0.00)	0.99 (± 0.00)	0.97 (± 0.01)	0.98 (± 0.00)
A. speciosa	0.99 (± 0.01)	0.99 (± 0.00)	0.96 (± 0.01)	0.99 (± 0.01)
A. vitrivir	0.99 (± 0.01)	0.99 (± 0.01)	0.96 (± 0.03)	0.97 (± 0.03)
Babassu Complex	0.98 (± 0.00)	0.99 (± 0.00)	0.97 (± 0.00)	0.97 (± 0.00)
mean (n=200)	0.99 (±0.01)	0.99 (±0.01)	0.97 (±0.02)	0.98 (±0.01)

b)

Species	**Algorithms (n=25)**			
	MaxEnt	RF	GLM	BRT
A. barreirensis	0.96 (± 0.04)	0.95 (± 0.04)	0.90 (± 0.05)	0.93 (± 0.05)
A. eichleri	0.96 (± 0.03)	0.95 (± 0.03)	0.89 (± 0.04)	0.94 (± 0.02)
A. funifera	0.99 (± 0.02)	0.99 (± 0.02)	0.96 (± 0.04)	0.96 (± 0.05)
A. maripa	0.94 (± 0.01)	0.94 (± 0.01)	0.92 (± 0.01)	0.92 (± 0.01)
A. phalerata	0.90 (± 0.03)	0.94 (± 0.02)	0.85 (± 0.02)	0.86 (± 0.02)
A. speciosa	0.94 (± 0.04)	0.95 (± 0.03)	0.90 (± 0.03)	0.93 (± 0.03)
A. vitrivir	0.97 (± 0.02)	0.95 (± 0.06)	0.90 (± 0.05)	0.86 (± 0.06)
Babassu Complex	0.91 (± 0.01)	0.92 (± 0.01)	0.87 (± 0.01)	0.86 (± 0.02)
mean (n=200)	0.94 (±0.04)	0.95 (±0.04)	0.90 (±0.05)	0.91 (±0.05)

c)

Species	**Algorithms (n=25)**			
	MaxEnt	RF	GLM	BRT
A. barreirensis	0.20 (± 0.06)	0.15 (± 0.05)	0.35 (± 0.12)	0.27 (± 0.04)
A. eichleri	0.18 (± 0.05)	0.16 (± 0.04)	0.30 (± 0.05)	0.26 (± 0.02)
A. funifera	0.10 (± 0.02)	0.08 (± 0.02)	0.15 (± 0.09)	0.22 (± 0.04)
A. maripa	0.16 (± 0.01)	0.11 (± 0.01)	0.19 (± 0.02)	0.26 (± 0.01)
A. phalerata	0.19 (± 0.02)	0.12 (± 0.01)	0.25 (± 0.02)	0.29 (± 0.02)
A. speciosa	0.18 (± 0.03)	0.15 (± 0.02)	0.28 (± 0.04)	0.25 (± 0.03)
A. vitrivir	0.21 (± 0.04)	0.17 (± 0.05)	0.37 (± 0.17)	0.32 (± 0.07)
Babassu Complex	0.21 (± 0.01)	0.14 (± 0.01)	0.26 (± 0.01)	0.32 (± 0.01)
mean (n=200)	0.18 (±0.05)	0.13 (±0.04)	0.27 (±0.11)	0.28 (±0.05)

Table S1.5. Relative importance of predictor variables (Im%) per species vs. algorithm combination (n = 25) in explaining the distribution of a) *A. barreirensis*, b) *A. eichleri*, c) *A. funifera*, d) *A. maripa*, e) *A. phalerata*, f) *A. speciosa*, g) *A. vitrivir*, and h) the Babassu Complex overall. The algorithms considered include Maxent, Random Forest (RF), Boosted Regression Trees (BRT), and Generalized Linear Models (GLM). Mean and Coefficient of Variation (CV) values are provided for each bioclimatic predictor (n = 100). Values in parentheses represent the standard deviation of the mean.

a)

Predictors	**Algorithms (n=25)**				**mean (n=100)**	**CV**
	MaxEnt	**RF**	**GLM**	**BRT**		
Iso	1.05 (±1.43)	1.84 (±2.49)	7.80 (±3.24)	2.07 (±1.81)	3.19 (±3.56)	1.11
MDTR	2.28 (±1.42)	0.48 (±0.35)	3.17 (±2.16)	0.12 (±0.15)	1.51 (±1.81)	1.19
MDTWeQ	1.33 (±1.01)	0.21 (±0.21)	6.65 (±3.57)	0.13 (±0.0.25)	2.08 (±3.26)	1.57
MMPAWaQ	0.29 (±0.37)	0.21 (±0.24)	0.60 (±0.59)	0.09 (±0.16)	0.30 (±0.42)	1.41
PAWM	0.75 (±0.49)	0.36 (±0.31)	0.26 (±0.28)	0.05 (±0.13)	0.35 (±0.41)	1.17
PPMin	0.82 (±0.79)	0.40 (±0.60)	2.61 (±2.00)	0.39 (±0.89)	1.10 (±1.50)	1.42
PPRange	2.67 (±1.72)	1.07 (±1.18)	4.90 (±2.12)	0.75 (±0.55)	2.35 (±2.23)	0.95
PS	8.69 (±1.96)	1.93 (±1.09)	4.40 (±2.98)	2.42 (±1.13)	4.36 (±3.30)	0.76
TS	88.69 (±6.45)	2.55 (±3.05)	96.03 (±2.97)	24.78 (±5.87)	53.01 (±40.69)	0.77

b)

Predictors	**Algorithms (n=25)**				**mean (n=100)**	**CV**
	MaxEnt	**RF**	**GLM**	**BRT**		
Iso	0.72 (±0.76)	0.77 (±1.16)	4.19 (±1.58)	0.07 (±0.09)	1.44 (±1.92)	1.34
MDTR	4.24 (±1.21)	0.94 (±0.54)	0.31 (±0.23)	1.37 (±0.43)	1.72 (±1.67)	0.97
MDTWeQ	0.02 (±0.04)	0.09 (±0.07)	3.31 (±1.89)	0.10 (±0.11)	0.89 (±1.69)	1.92
MMPACQ	0.55 (±0.34)	0.18 (±0.15)	0.35 (±0.37)	0.09 (±0.13)	0.29 (±0.32)	1.08
MMPAWaQ	0.74 (±0.76)	0.16 (±0.23)	1.14 (±0.92)	0.04 (±0.08)	0.52 (±0.75)	1.44
PAWM	1.41 (±0.98)	0.20 (±0.16)	0.29 (±0.43)	0.09 (±0.10)	0.5 (±0.76)	1.53
PPMean	0.17 (±0.20)	0.26 (±0.22)	5.53 (±1.93)	0.06 (±0.08)	1.51 (±2.53)	1.68
PPRange	0.59 (±0.35)	0.33 (±0.36)	8.68 (±2.21)	0.16 (±0.17)	2.44 (±3.79)	1.55
PS	6.71 (±2.09)	0.96 (±0.42)	0.28 (±0.32)	2.64 (±1.07)	2.65 (±2.78)	1.05

TS	56.87 (±14.34)	3.18 (±2.06)	96.74 (±2.07)	17.66 (±6.90)	43.61 (±33.47)	0.86
VPDMin	3.28 (±1.42)	1.34 (±0.94)	14.31 (±3.30)	2.92 (±2.04)	5.46 (±5.59)	1.02
VPDRange	0.03 (±0.05)	0.41 (±0.25)	6.69 (±2.71)	0.59 (±0.45)	1.93 (±3.08)	1.60

c)

Predictors	**Algorithms (n=25)**				**mean (n=100)**	**CV**
	MaxEnt	**RF**	**GLM**	**BRT**		
Iso	1.44 (±1.01)	0,70 (±0.99)	0.15 (±0.13)	0.89 (±1.18)	0.80 (±1.02)	1.28
MMPACQ	0.90 (±1.00)	0.74 (±0.90)	5.45 (±2.43)	6.23 (±5.08)	3.33 (±3.82)	1.15
MMPAWaQ	0.05 (±0.09)	0.05 (±0.08)	1.90 (±1.32)	0.01 (±0.20)	0.50 (±1.04)	2.06
PADM	2.97 (±2.64)	1.63 (±1.38)	0.32 (±0.40)	3.18 (±2.31)	2.02 (±2.20)	1.08
PAWM	0.43 (±2.64)	0.17 (±0.25)	3.02 (±2.31)	0.05 (±0.10)	0.92 (±1.69)	1.84
PPMax	0.00 (±0.01)	0.67 (±0.64)	2.78 (±2.28)	2.46 (±1.12)	1.48 (±1.75)	1.18
PPRange	2.43 (±1.39)	0.36 (±0.43)	13.33 (±3.79)	0.48 (±0.52)	4.15 (±5.75)	1.39
VPDMean	13.14 (±4.34)	0.28 (±0.37)	63.54 (±6.28)	0.55 (±0.42)	19.38 (±26.42)	1.36
VPDRange	42.08 (±7.96)	0.58 (±0.48)	92.92 (±3.23)	1.13 (±0.63)	34.18 (±38.3)	1.12

d)

Predictors	**Algorithms (n=25)**				**mean (n=100)**	**CV**
	MaxEnt	**RF**	**GLM**	**BRT**		
Iso	30.89 (±6.17)	1.43 (±0.32)	0.26 (±0.24)	1.23 (±0.39)	8.45 (±13.38)	1.58
MDTDQ	0.41 (±0.42)	0.29 (±0.16)	38.63 (±4.70)	0.30 (±0.36)	9.91 (±16.83)	1.70
MDTR	2.65 (±0.50)	0.46 (±0.25)	0.13 (±0.13)	0.34 (±0.11)	0.9 (±1.07)	1.19
MDTWeQ	0.28 (±0.23)	0.20 (±0.13)	0.14 (±0.15)	0.12 (±0.06)	0.18 (±0.17)	0.90
MMPACQ	1.78 (±0.41)	0.61 (±0.21)	0.03 (±0.06)	0.59 (±0.48)	0.75 (±0.72)	0.96
PADM	1.40 (±0.44)	0.79 (±0.17)	0.89 (±0.24)	0.75 (±0.25)	0.96 (±0.39)	0.41
PAWM	3.85 (±0.66)	0.62 (±0.14)	0.67 (±0.22)	0.46 (±0.14)	1.40 (±1.47)	1.05
PPMin	0.70 (±0.44)	0.30 (±0.23)	9.00 (±0.79)	0.10 (±0.08)	2.53 (±3.79)	1.50
PPRange	0.99 (±0.29)	0.31 (±0.16)	3.60 (±0.50)	0.38 (±0.16)	1.32 (±1.38)	1.05
PS	1.18 (±0.27)	0.14 (±0.10)	3.61 (±0.68)	0.01 (±0.05)	1.24 (±1.49)	1.21
TS	0.24 (±0.17)	1.58 (±0.51)	73.90 (±3.47)	6.73 (±3.59)	20.61 (±31.11)	1.51
VPDMin	1.70 (±0.55)	0.13 (±0.09)	0.96 (±0.36)	0.05 (±0.06)	0.71 (±0.75)	1.05

e)

Predictors	Algorithms (n=25)				mean (n=100)	CV
	MaxEnt	RF	GLM	BRT		
MDTDQ	0.38 (±0.28)	0.38 (±0.20)	50.99 (±4.06)	0.26 (±0.19)	13.00 (±22.14)	1.70
MDTR	6.78 (±1.20)	0.39 (±0.15)	0.75 (±0.22)	0.16 (±0.07)	2.02 (±2.84)	1.40
MDTWeQ	0.72 (±0.21)	1.23 (±0.36)	17.75 (±2.68)	1.29 (±0.26)	5.25 (±7.38)	1.41
MMPACQ	5.14 (±0.71)	0.94 (±0.28)	0.23 (±0.13)	0.61 (±0.23)	1.73 (±2.03)	1.18
MMPAWaQ	0.33 (±0.47)	1.36 (±0.33)	0.31 (±0.19)	1.49 (±0.47)	0.87 (±0.67)	0.77
PADM	0.44 (±0.17)	0.40 (±0.11)	0.41 (±0.23)	0.03 (±0.05)	0.32 (±0.23)	0.72
PAWM	12.38 (±2.50)	0.90 (±0.30)	0.47 (±0.23)	7.93 (±1.36)	5.42 (±5.21)	0.96
PPMax	2.23 (±0.82)	0.39 (±0.12)	9.42 (±1.26)	0.18 (±0.09)	3.05 (±3.85)	1.26
PPMin	2.55 (±0.73)	1.03 (±0.19)	10.17 (±1.03)	1.10 (±0.27)	3.71 (±3.85)	1.04
VPDMin	44.42 (±3.83)	1.80 (±0.61)	23.30 (±4.76)	2.54 (±0.71)	18.02 (±17.87)	0.99
VPDRange	0.63 (±0.37)	0.97 (±0.24)	11.24 (±2.04)	0.83 (±0.21)	3.42 (±4.66)	1.36

f)

Predictors	Algorithms (n=25)				mean (n=100)	CV
	MaxEnt	RF	GLM	BRT		
APA	0.79 (±0.55)	0.36 (±0.24)	4.05 (±2.67)	0.04 (±0.07)	1.31 (±2.10)	1.60
Iso	9.53 (±3.30)	2.94 (±1.22)	62.00 (±13.50)	33.74 (±5.77	27.05 (±24.48)	0.90
MDTR	4.30 (±1.12)	2.60 (±0.79)	14.14 (±5.31)	5.74 (±1.50)	6.70 (±5.27)	0.79
MDTWeQ	0.50 (±0.73)	0.36 (±0.24)	27.40 (±11.30)	0.45 (±0.34)	7.18 (±12.99)	1.81
MMPACQ	3.46 (±1.18)	0.46 (±0.27)	0.19 (±0.30)	0.05 (±0.13)	1.04 (±1.54)	1.48
MMPAWaQ	0.42 (±0.38)	0.23 (±0.14)	1.68 (±0.93)	0.13 (±0.11)	0.61 (±0.80)	1.31
PADM	1.89 (±0.90)	0.17 (±0.13)	9.47 (±3.63)	0.15 (±0.17)	2.92 (±4.29)	1.47
PPMax	0.15 (±0.18)	1.00 (±0.46)	1.80 (±0.79)	1.92 (±0.71)	1.21 (±0.92)	0.76
PPMin	0.59 (±0.28)	0.27 (±0.22)	8.02 (±1.44)	0.04 (±0.06)	2.23 (±3.44)	1.54
PS	1.58 (±1.04)	1.48 (±0.71)	0.57 (±0.60)	1.91 (±0.86)	1.39 (±0.95)	0.69
VPDMin	8.92 (±3.26)	1.22 (±0.63)	1.91 (±1.84)	0.53 (±0.52)	3.15 (±3.88)	1.23
VPDRange	2.73 (±0.93)	0.18 (±0.14)	1.89 (±1.95)	0.05 (±0.07)	1.21 (±1.56)	1.29

g)

Predictors	Algorithms (n=25)				mean (n=100)	CV
	MaxEnt	RF	GLM	BRT		
MDTR	5.10 (±2.56)	1.27 (±1.43)	0.52 (±0.48)	2.37 (±1.97)	2.31 (±2.47)	1.07
MDTWeQ	0.79 (±1.37)	0.34 (±0.37)	0.82 (±0.86)	0.17 (±0.26)	0.53 (±0.88)	1.65
MMPACQ	0.98 (±1.05)	0.91 (±0.82)	0.69 (±0.47)	3.03 (±2.61)	1.40 (±1.74)	1.24
MMPAWaQ	4.19 (±2.17)	0.61 (±1.11)	12.06 (±6.41)	0.74 (±0.86)	4.40 (±5.78)	1.31
PADM	30.12 (±12.83)	1.21 (±1.57)	76.53 (±9.05)	1.00 (±1.06)	27.21 (±31.95)	1.17
PAWM	0.30 (±0.38)	0.48 (±0.47)	0.82 (±0.76)	0.37 (±0.50)	0.49 (±0.57)	1.16
PPMin	22.61 (±8.58)	3.37 (±4.75)	26.33 (±9.12)	25.47 (±7.88)	19.45 (±12.14)	0.62
PS	2.25 (±2.07)	1.10 (±1.01)	11.92 (±3.74)	2.42 (±1.52)	4.42 (±4.94)	1.12

h)

Predictors	Algorithms (n=25)				mean (n=100)	CV
	MaxEnt	RF	GLM	BRT		
Iso	7.79 (±1.24)	1.72 (±0.24)	0.72 (±0.22)	1.45 (±0.55)	2.92 (±2.93)	1.00
MDTR	7.10 (±0.69)	0.78 (±0.15)	0.08 (±0.09)	1.12 (±0.16)	2.27 (±2.85)	1.26
MDTWeQ	0.66 (±0.15)	0.89 (±0.22)	4.62 (±0.59)	1.40 (±0.20)	1.89 (±1.64)	0.87
MMPAWaQ	0.31 (±0.11)	0.42 (±0.13)	0.12 (±0.10)	0.07 (±0.09)	0.23 (±0.18)	0.78
PADM	0.32 (±0.08)	0.69 (±0.17)	0.86 (±0.30)	0.20 (±0.08)	0.52 (±0.32)	0.63
PAWM	5.83 (±0.53)	1.08 (±0.19)	0.01 (±0.03)	0.37 (±0.14)	1.82 (±2.37)	1.30
PPMin	1.24 (±0.23)	0.64 (±0.18)	10.90 (±0.60)	0.80 (±0.18)	3.40 (±4.37)	1.29
PPRange	1.54 (±0.23)	0.83 (±0.18)	4.89 (±0.35)	1.66 (±0.26)	2.23 (±1.60)	0.72
PS	3.51 (±0.42)	0.49 (±0.12)	4.42 (±0.57)	0.20 (±0.09)	2.15 (±1.88)	0.87
TS	1.02 (±0.34)	4.52 (±0.64)	99.89 (±0.14)	32.70 (±1.19)	34.53 (±39.89)	1.16
VPDMin	9.86 (±2.13)	0.89 (±0.19)	7.09 (±0.57)	0.07 (±0.07)	4.48 (±4.29)	0.96
VPDRange	0.59 (±0.18)	0.24 (±0.09)	2.56 (±0.31)	0.00 (±0.00)	0.85 (±1.03)	1.21

Table S1.6. Calculated areas of the classes of suitability for the various algorithms (BRT, GLM, MaxEnt and RF) and for *A. barreirensis*, *A. eichleri*, *A. funifera*, *A. maripa*, *A. phalerata*, *A. speciosa*, *A. vitrivir*, and the Babassu Complex overall in the current scenario.

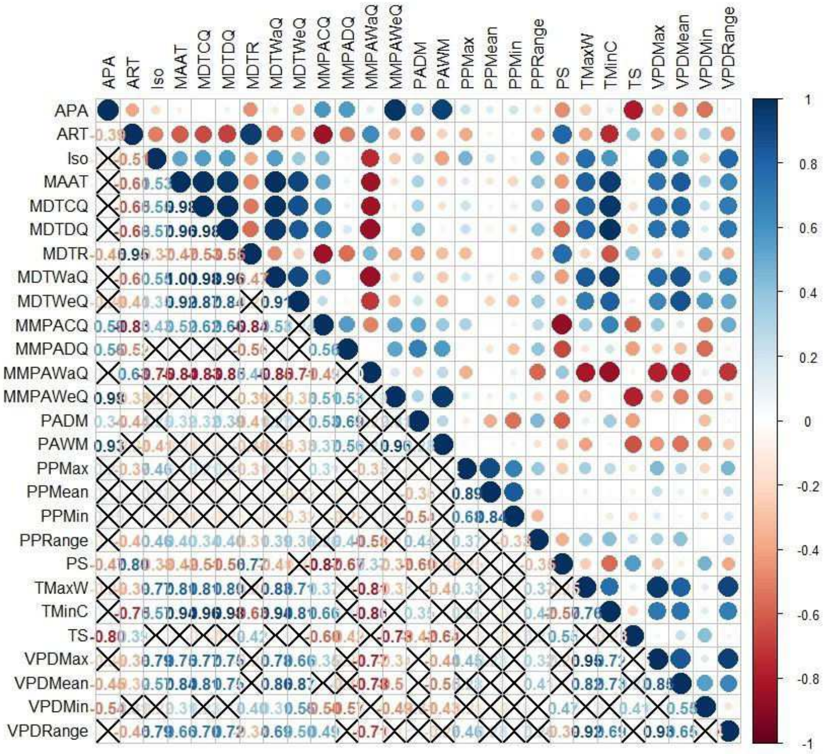
Species	**Class**	**Algorithms (km²)**				**Ensemble map (km²)**
		BRT	GLM	MaxEnt	RF	
A. barreirensis	Unsuitable	13634187	12969299	10905077	14058727	11912656
	Low	6213786	3856431	6055359	5309672	6464969
	Medium	1713127	2580292	3623780	1703246	2961686
	High	1363	2156442	978248	490818	254882
A. eichleri	Unsuitable	12429280	10206745	11682964	13369467	10189062
	Low	7518369	6255746	5409039	5697229	8416218
	Medium	1593143	3680293	3523524	1696250	2644049
	High	21671	1419680	946936	799517	344864
A. funifera	Unsuitable	11330256	17256849	14280289	14379435	14020352
	Low	10076050	2807763	6433105	6317610	7120495
	Medium	145691	773799	771506	802808	422180
	High	10467	724053	77564	62611	31166
A. maripa	Unsuitable	11967586	12243827	12177871	12459396	11817501
	Low	5954938	3499207	3760769	5199122	4637818
	Medium	3639939	2235268	4048532	2897280	4223378
	High	0	3584161	1575292	1006666	915496
A. phalerata	Unsuitable	7539385	9470269	8345042	9922433	7759199
	Low	11696008	6690289	7223609	8226021	9935641
	Medium	2327070	4056093	4044635	2160187	3165997
	High	0	1345813	1949178	1253823	733356
A. speciosa	Unsuitable	11886372	9869652	9311258	10663904	9460532
	Low	5258244	5449361	5269999	6203454	6585918
	Medium	4414489	4157888	5026396	3049355	4620239
	High	3359	2085563	1954811	1645751	927503
A. vitrivir	Unsuitable	9945873	17772173	14418881	15714232	14502398
	Low	11281382	2331444	5012342	4676827	5819594
	Medium	335209	970969	1715391	907519	1086344

	High	0	487877	415851	263885	185856
Babassu Complex	Unsuitable	7518791	7668912	7853995	8309833	7467461
	Low	8231298	5219682	3573677	7340167	5808119
	Medium	5812375	6284256	6498762	4849699	7891228
	High	0	2389614	3636030	1062765	427386

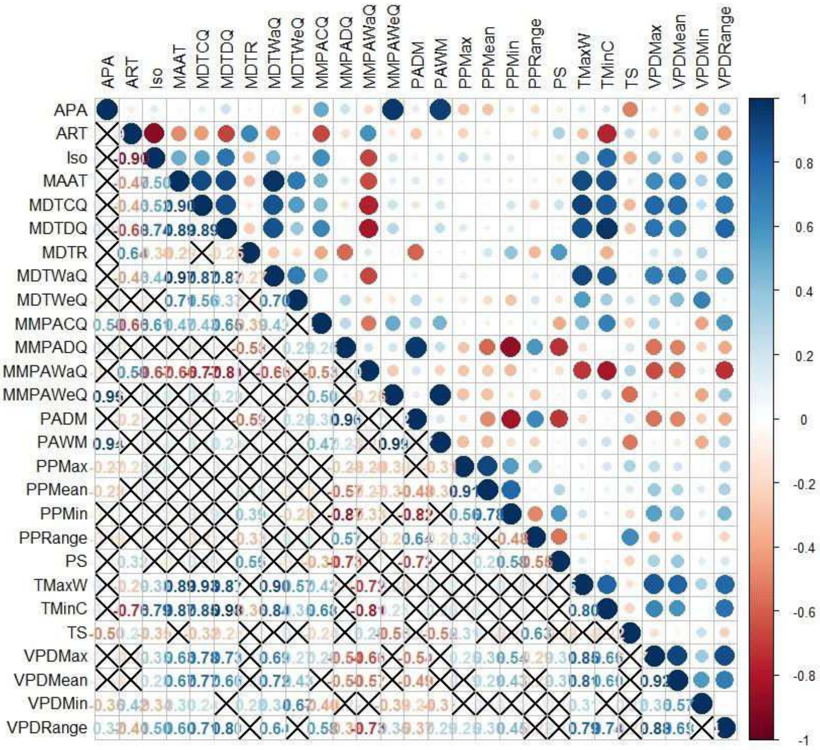
Table S1.7. The total sum of the areas of the whole species for each of the classes of suitability for the various algorithms (BRT, GLM, MaxEnt and RF) in the current scenario.

Class	**Algorithms (km²)**			
	BRT	GLM	MaxEnt	RF
Unsuitable	86251730.71	97457726.66	88975378.68	98877426.89
Low	66230075.32	36109923.49	42737898.39	48970102.14
Medium	19981044.06	24738857.10	29252525.03	18066344.11
High	36859.92	14193202.77	11533907.91	6585836.88

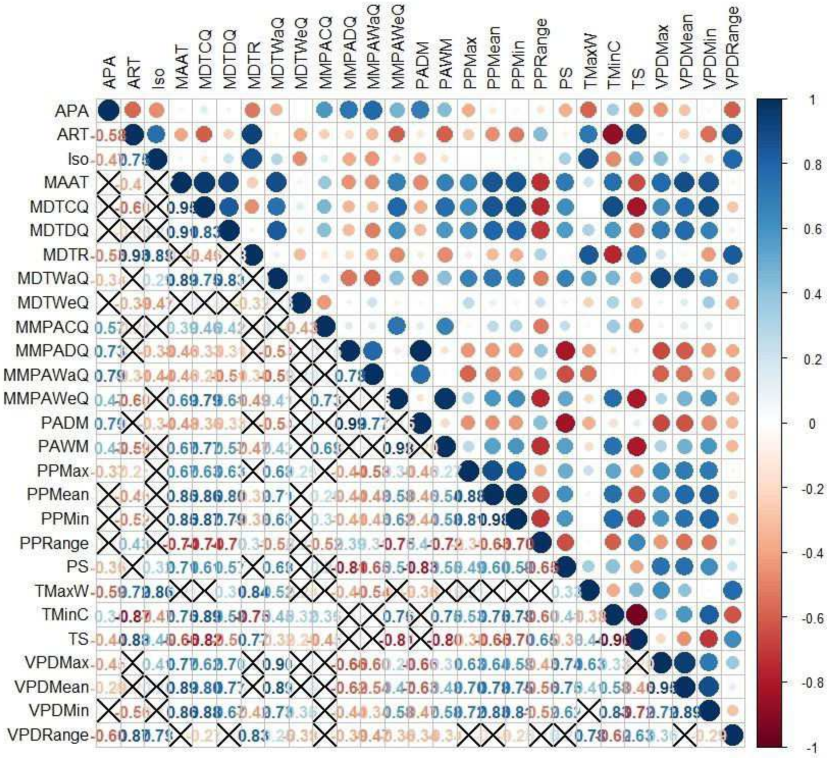
a) *Attalea barreirensis*



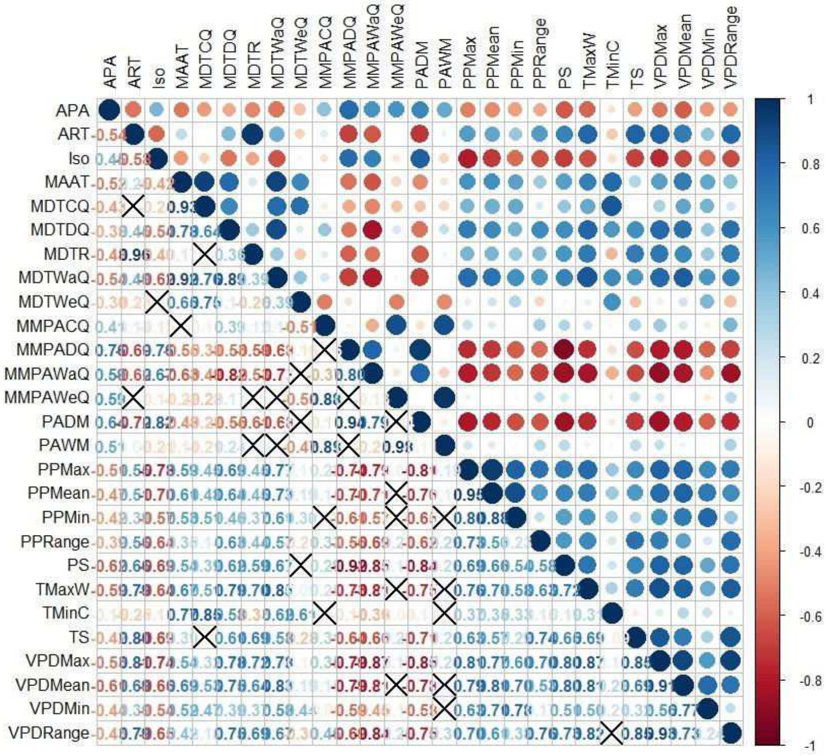
b) *Attalea eichleri*



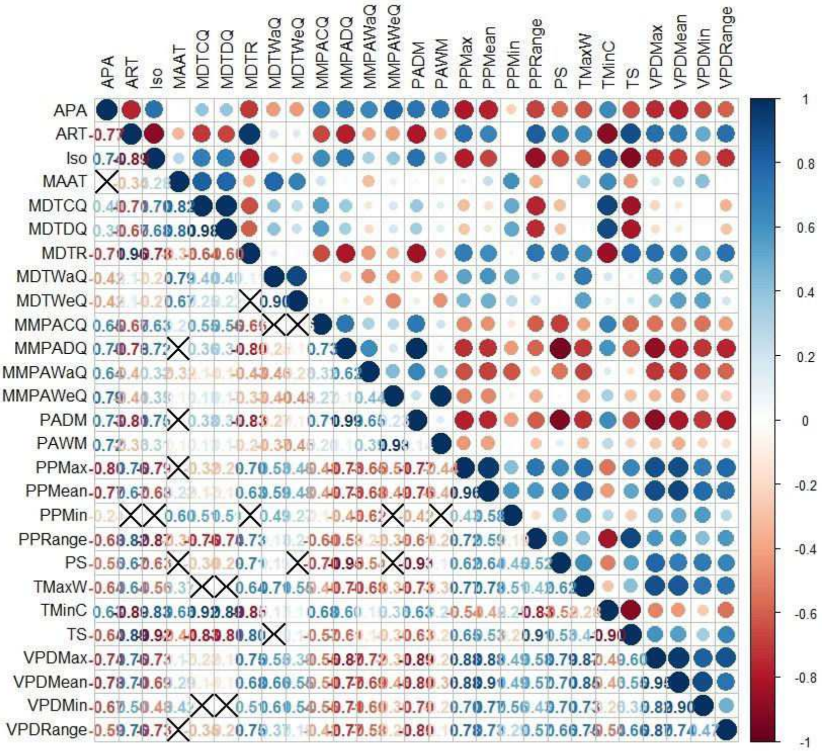
c) *Attalea funifera*



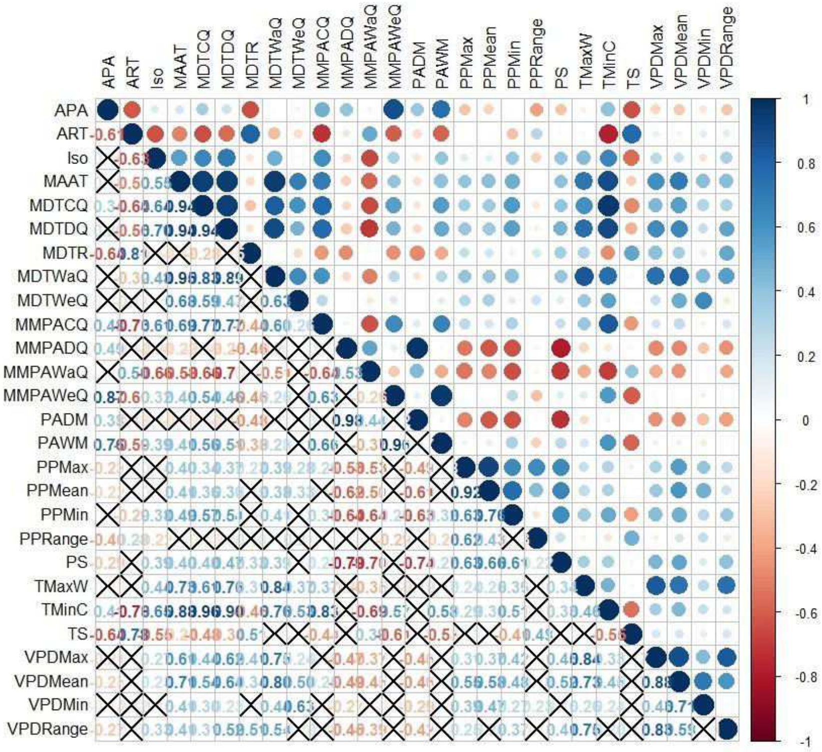
d) *Attalea maripa*



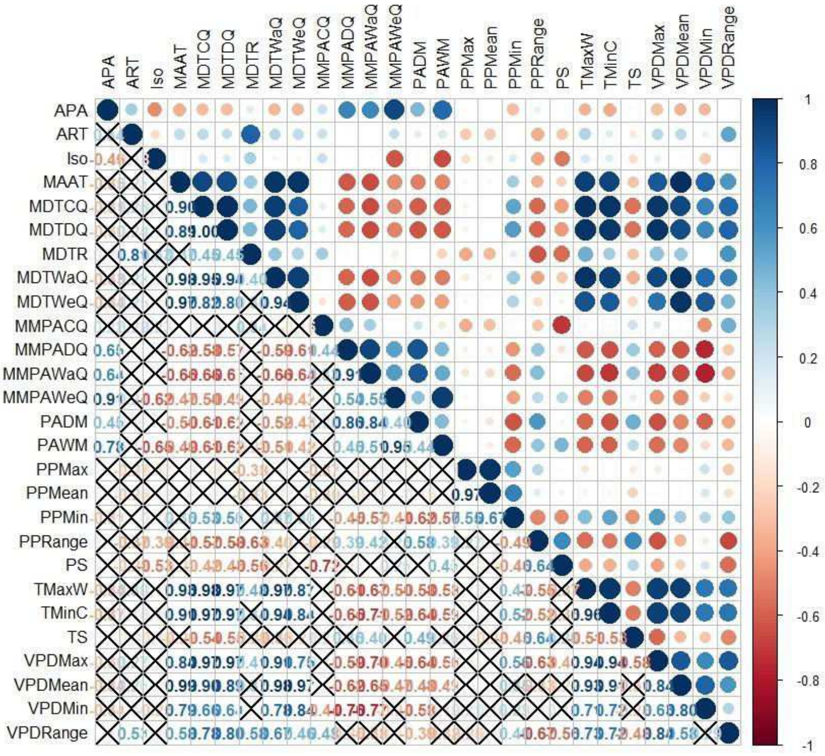
e) *Attalea phalerata*



f) *Attalea speciosa*



g) *Attalea vitrivir*



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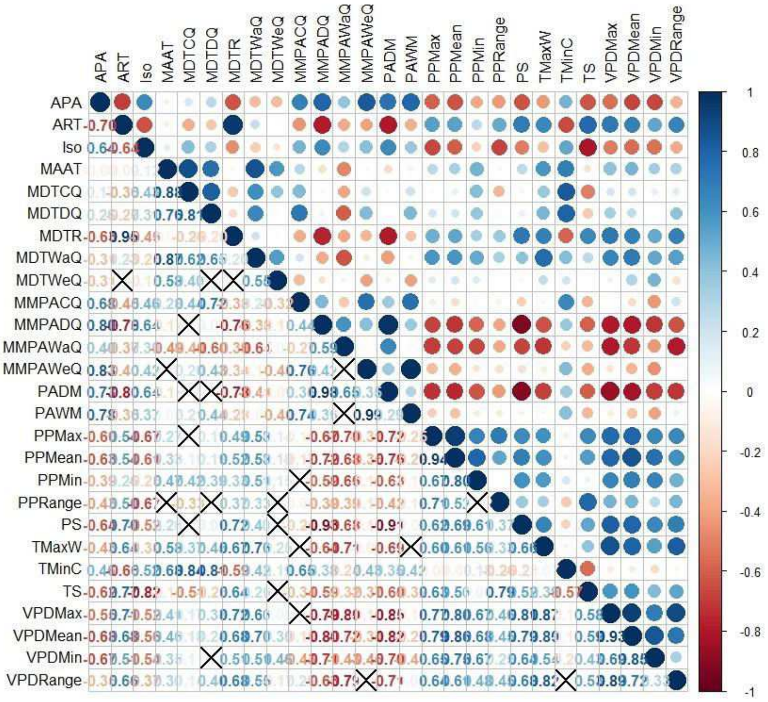


Figure S1.1. Spearman's correlation test for the set of bioclimatic variables for a) *A. barreirensis* (n = 41), b) *A. eichleri* (n = 79), c) *A. funifera* (n = 65), d) *A. maripa* (n = 570), e) *A. phalerata* (n = 431), f) *A. speciosa* (n = 84), g) *A. vitrivir* (n = 27), and h) the Babassu Complex overall (n = 1,269). Marked cells represent non-significant correlations at $p \leq 0.05$.

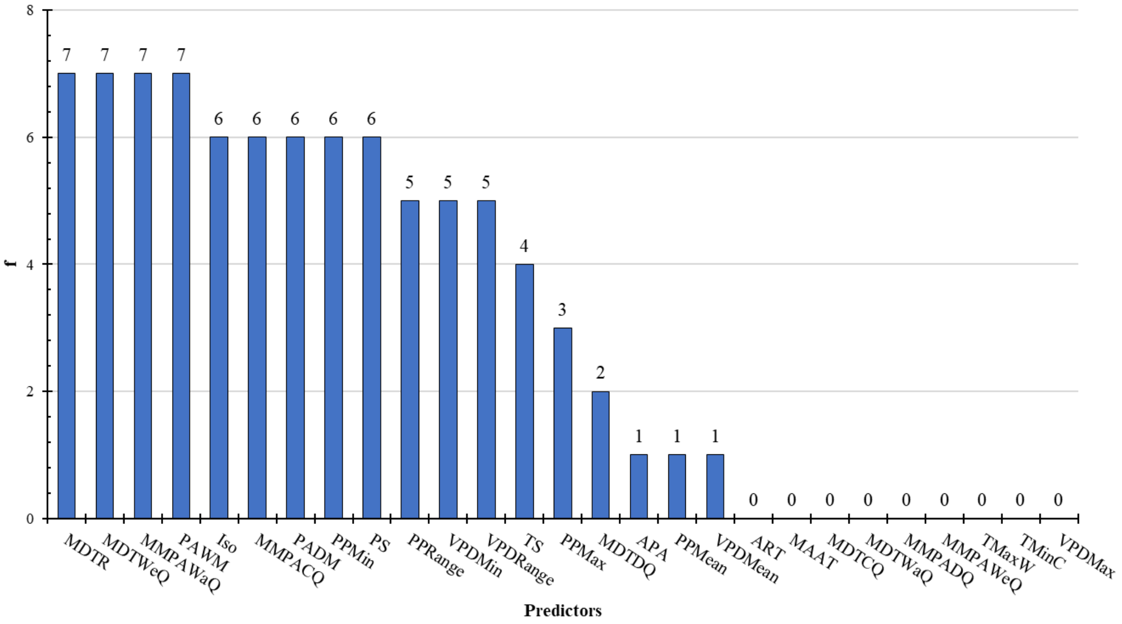


Figure S1.2. Frequency (f) of the remaining bioclimatic variables used for fitting current scenario models after multicollinearity analysis, considering all individual species and the Babassu Complex overall.

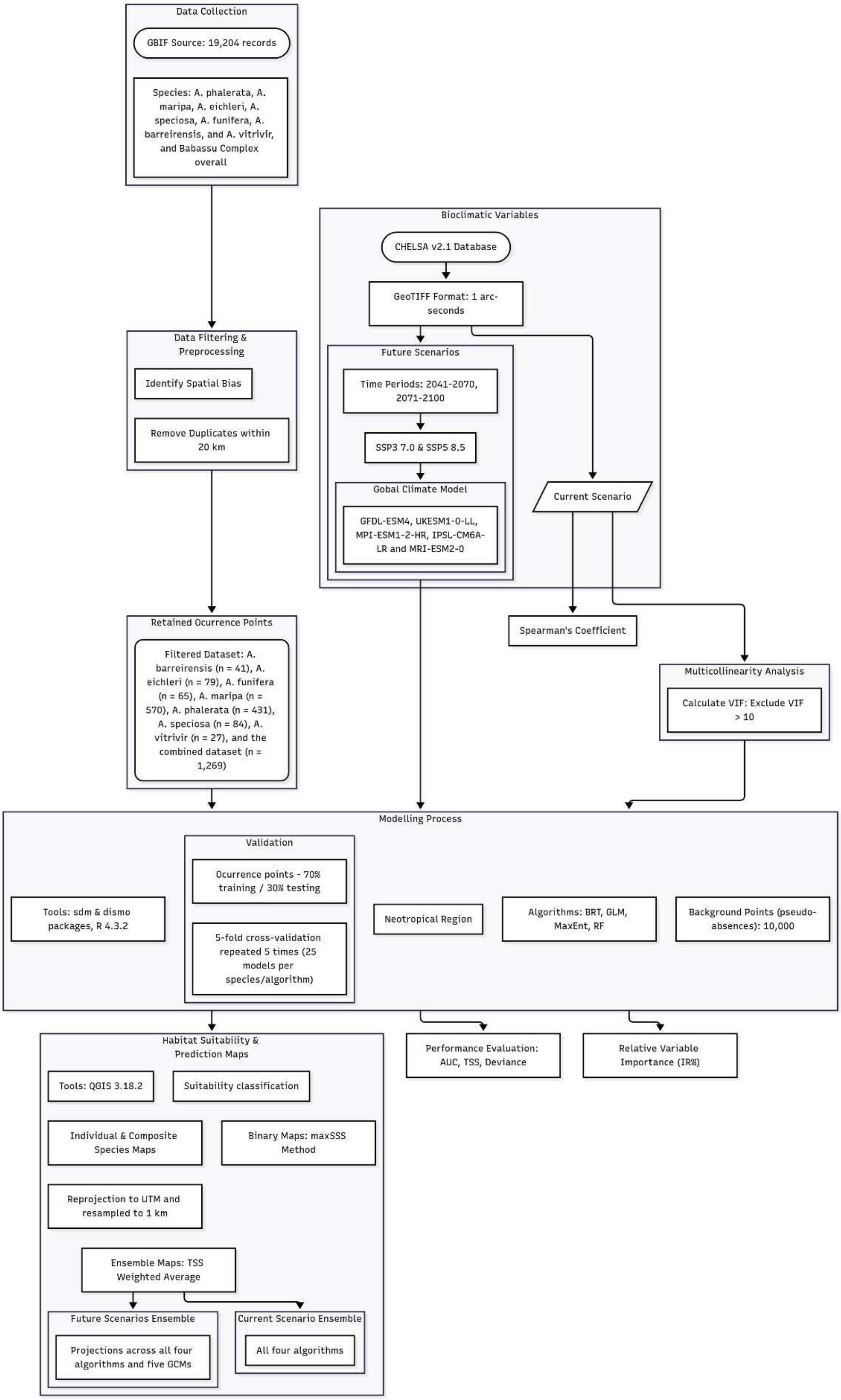
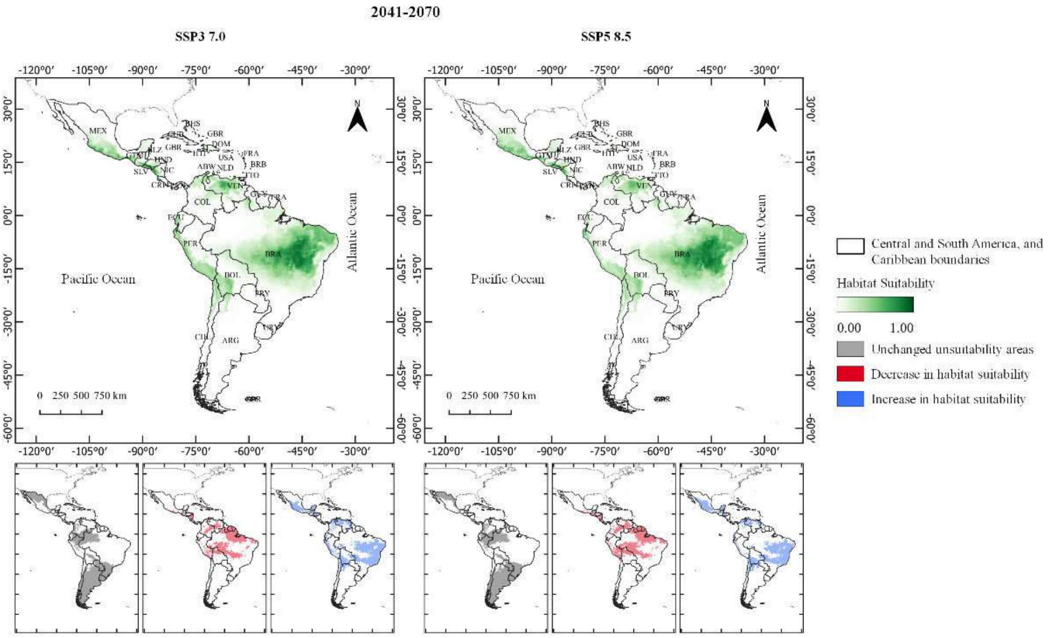
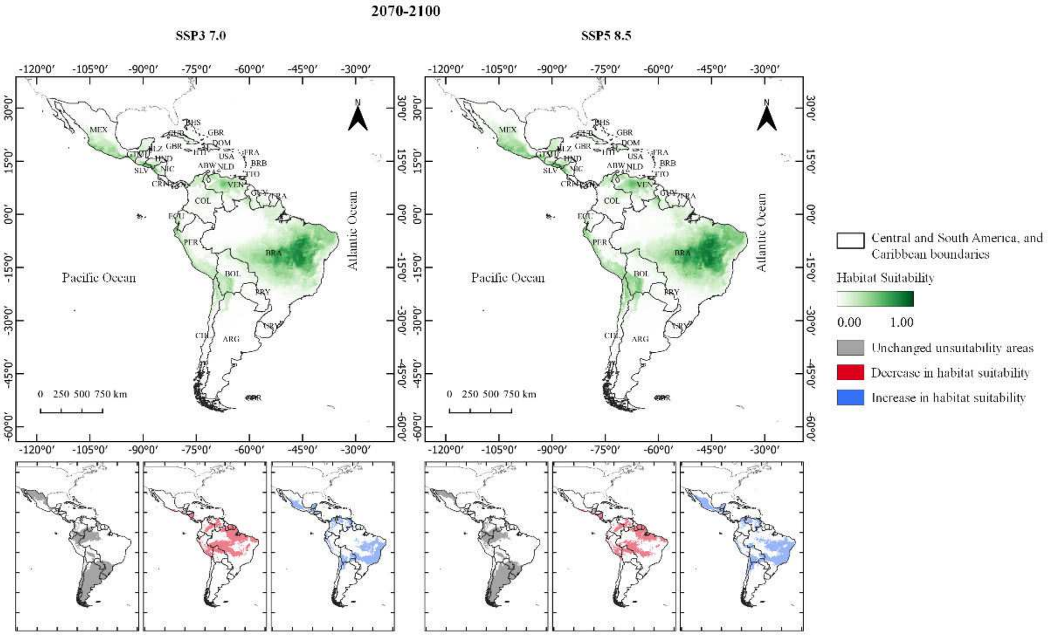


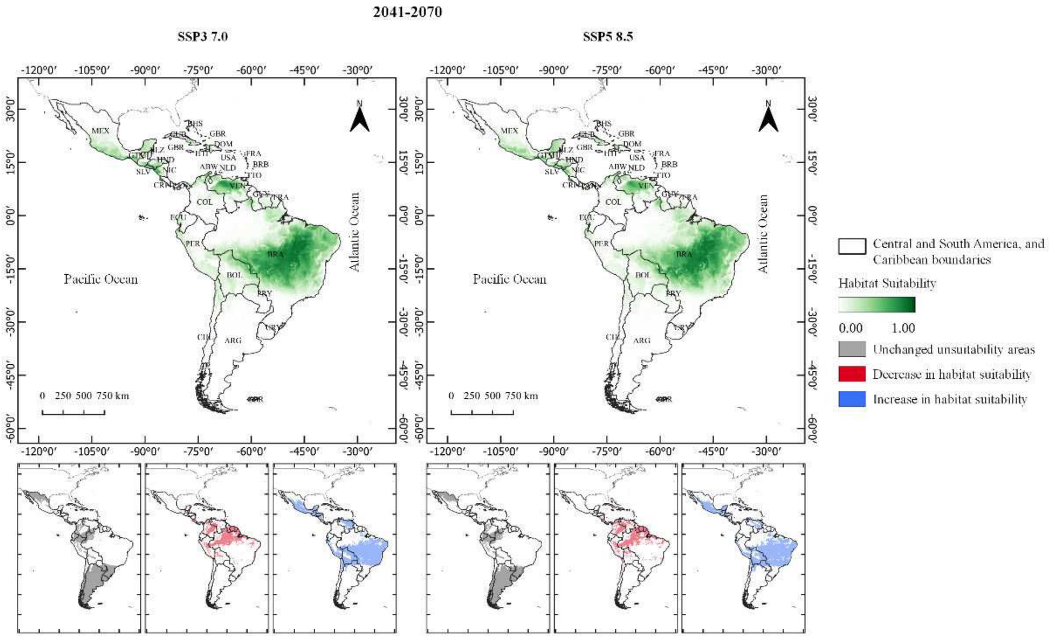
Figure S1.3. Methodological workflow for the species distribution modelling of the Babassu Complex and its species.

a) *A. barreirensis*



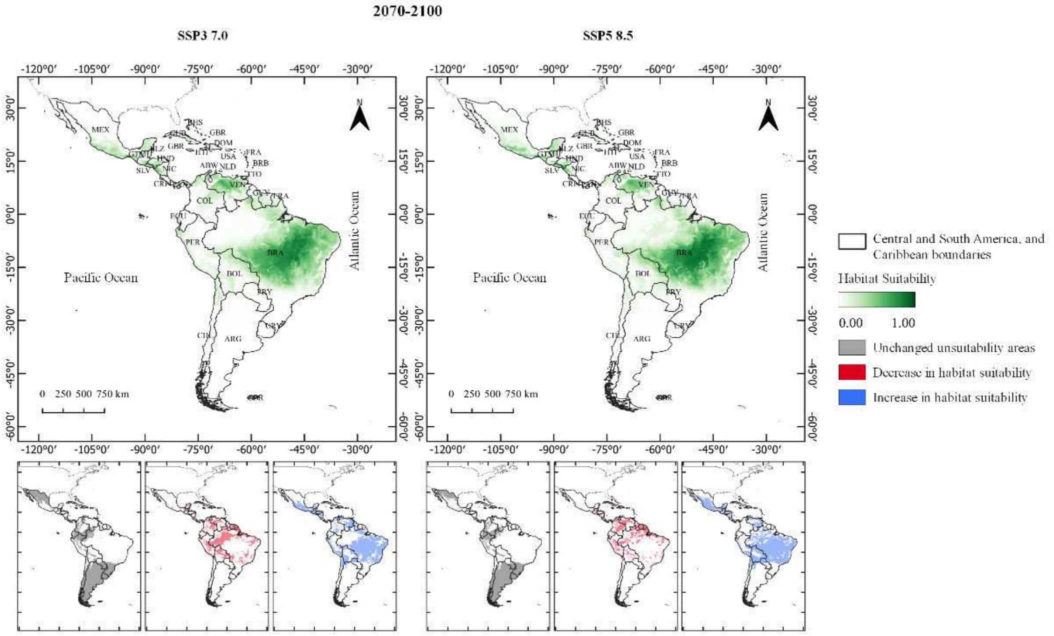


b) *A. eichleri*



2041-2070

SSP3 7.0 **SSP5 8.5**



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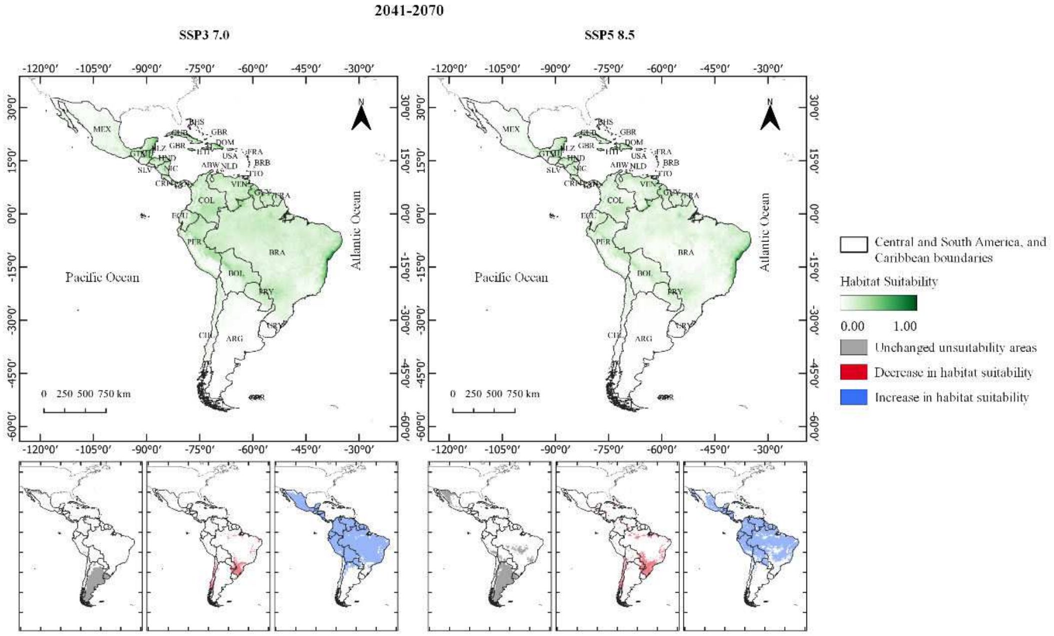
SSP3 7.0 **SSP5 8.5**

c) *A. funifera*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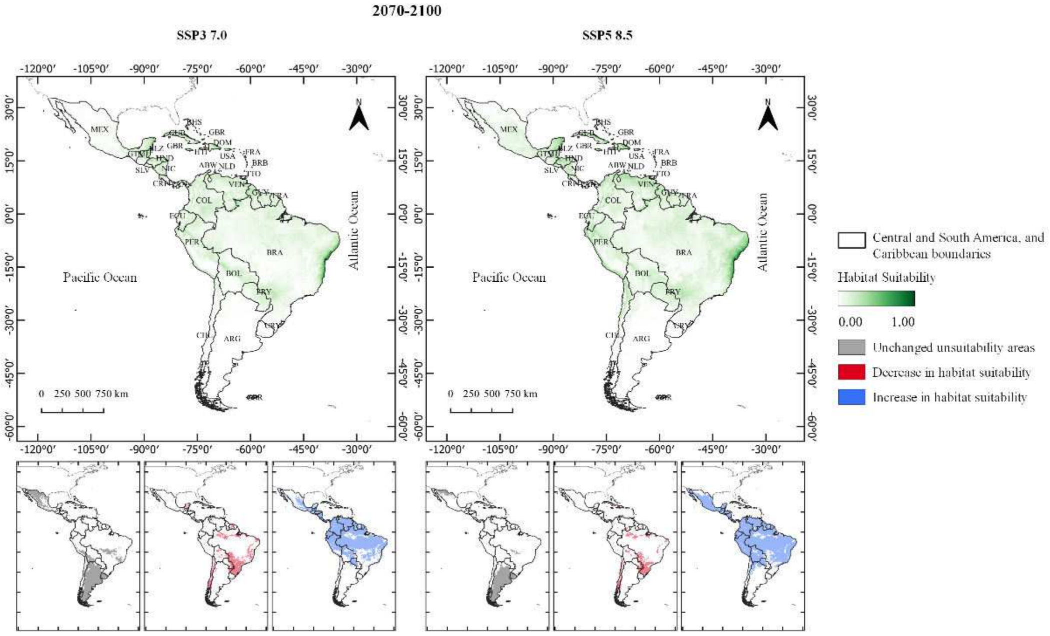
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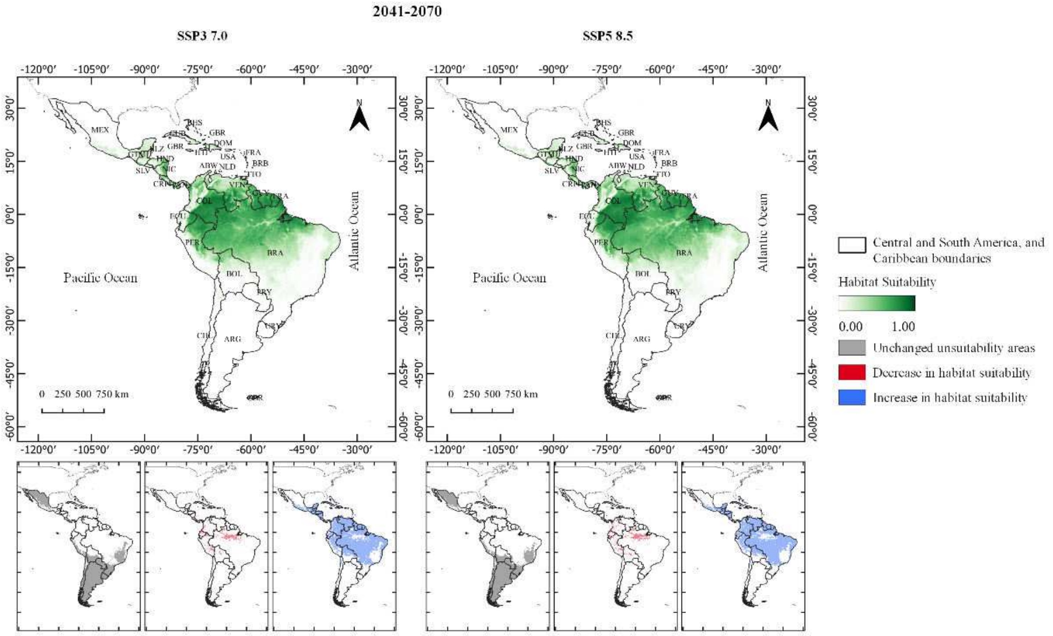
d) *A. maripa*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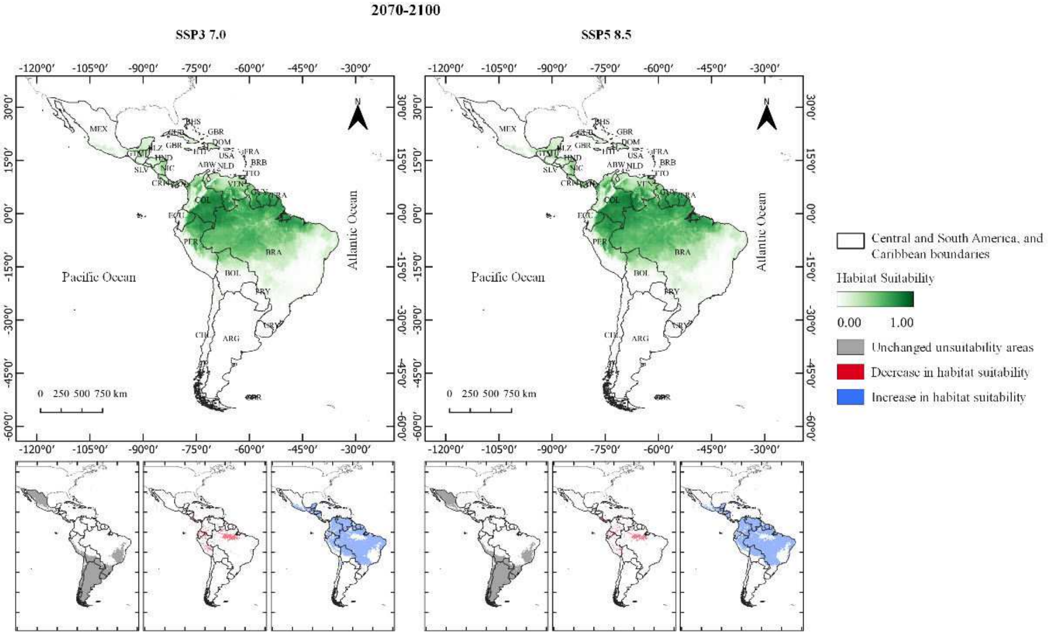
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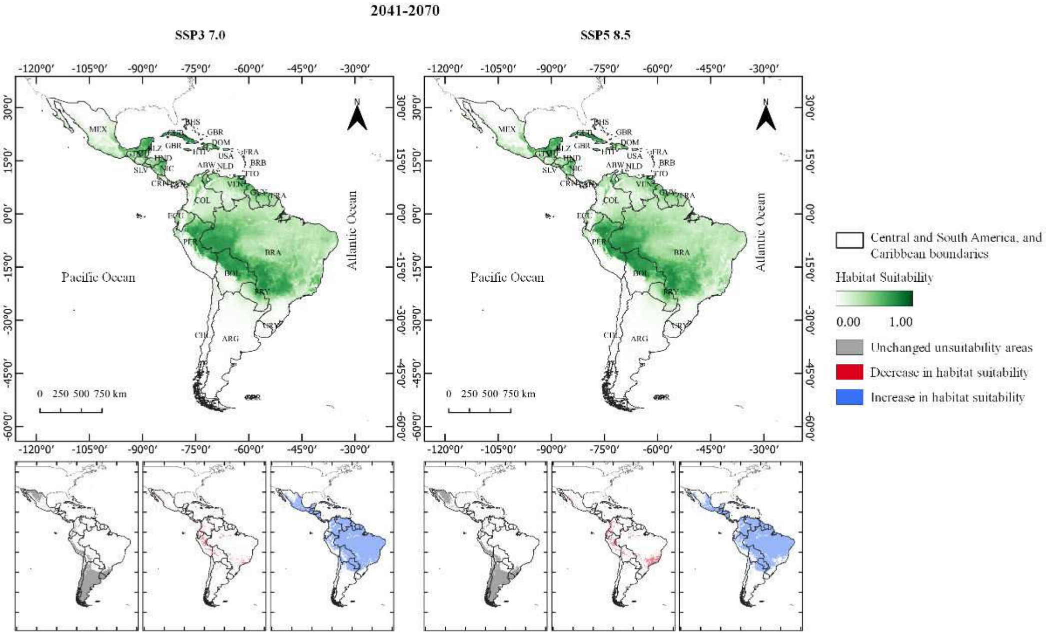
e) *A. phalerata*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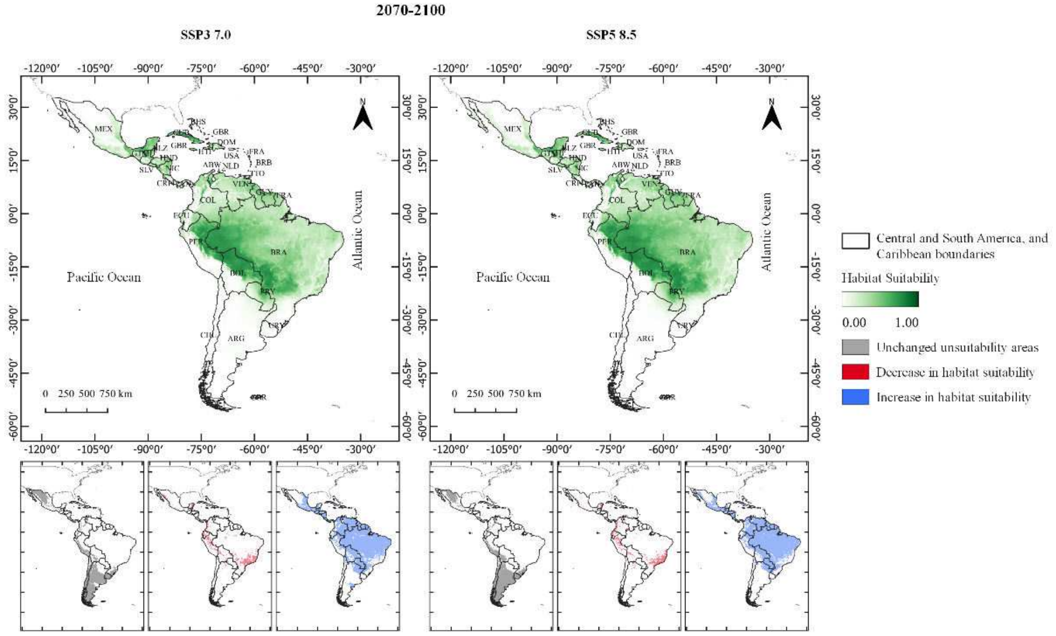
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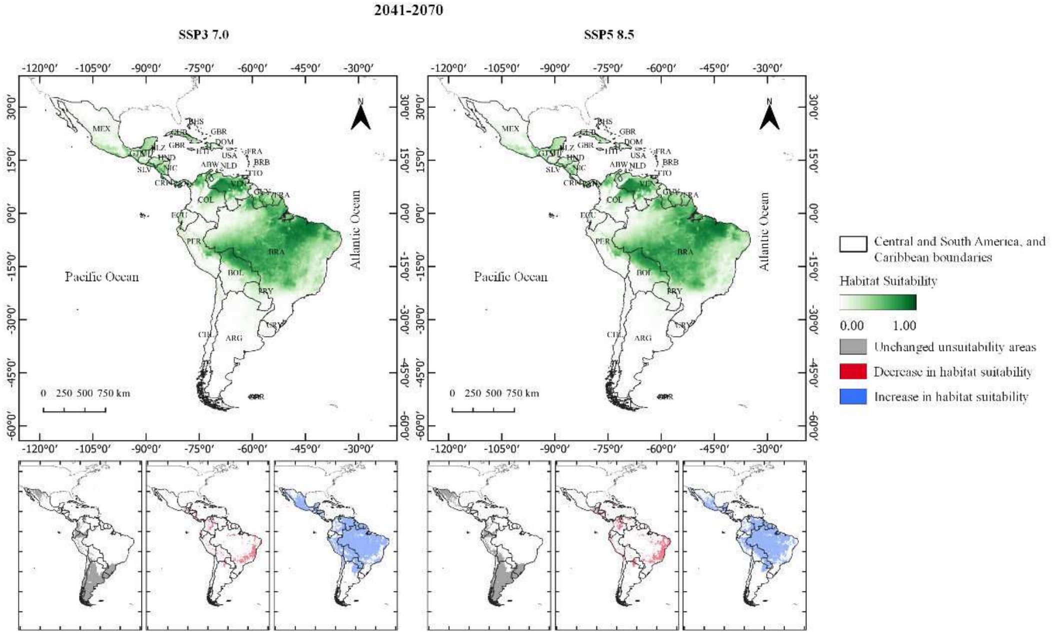
f) *A. speciosa*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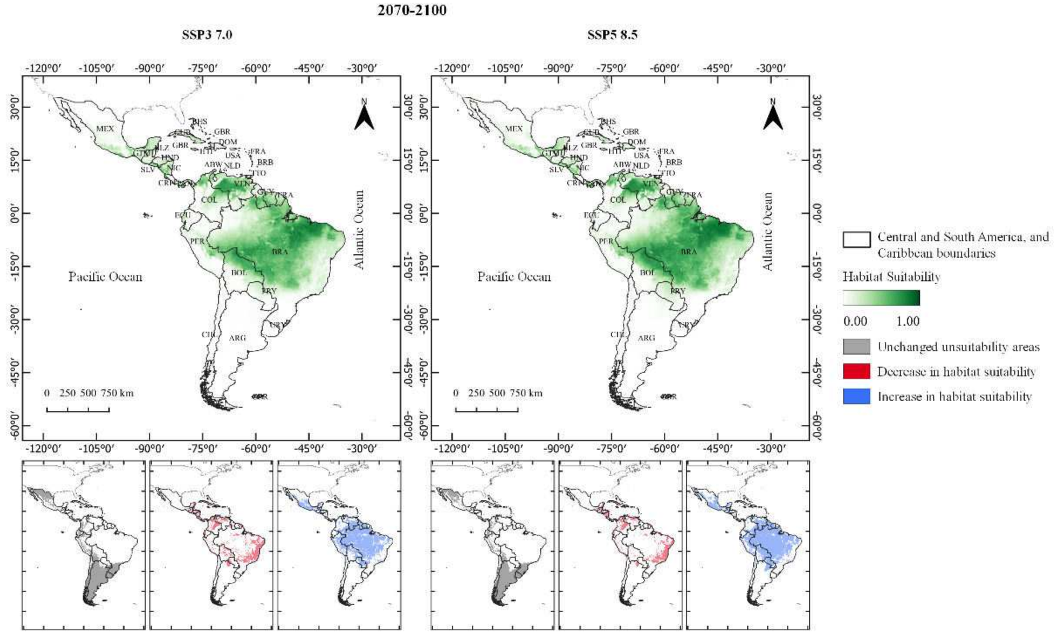
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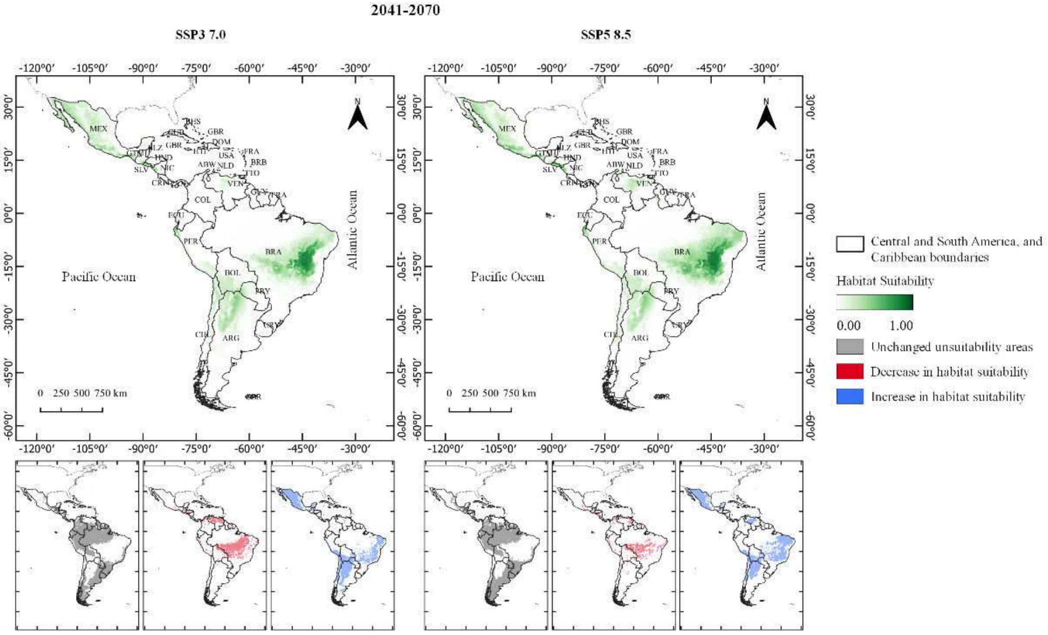
g) *A. vitrivir*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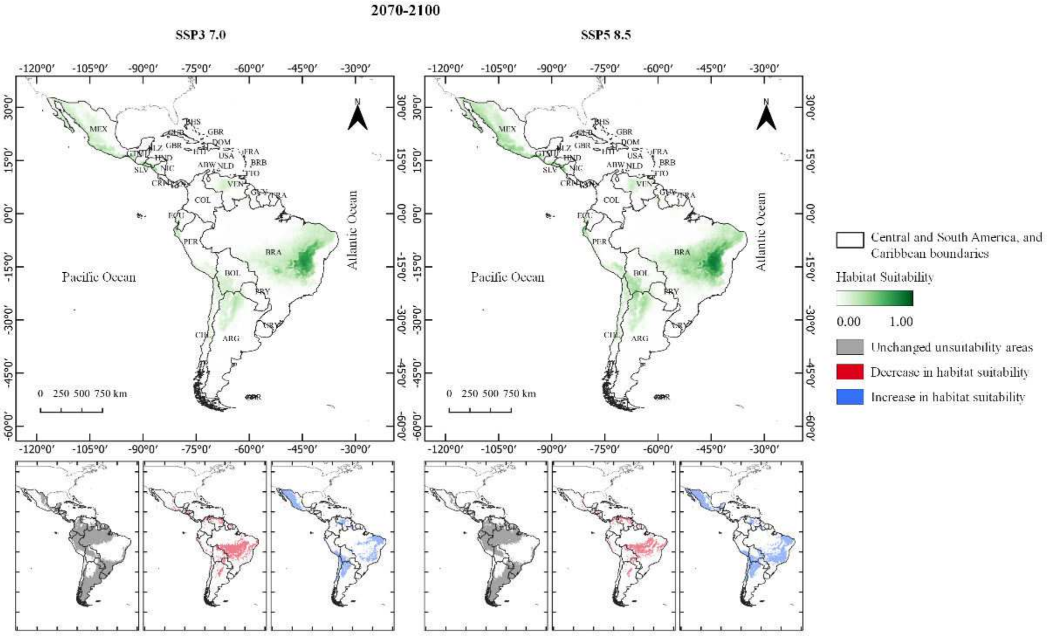
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h) Babassu Complex overall

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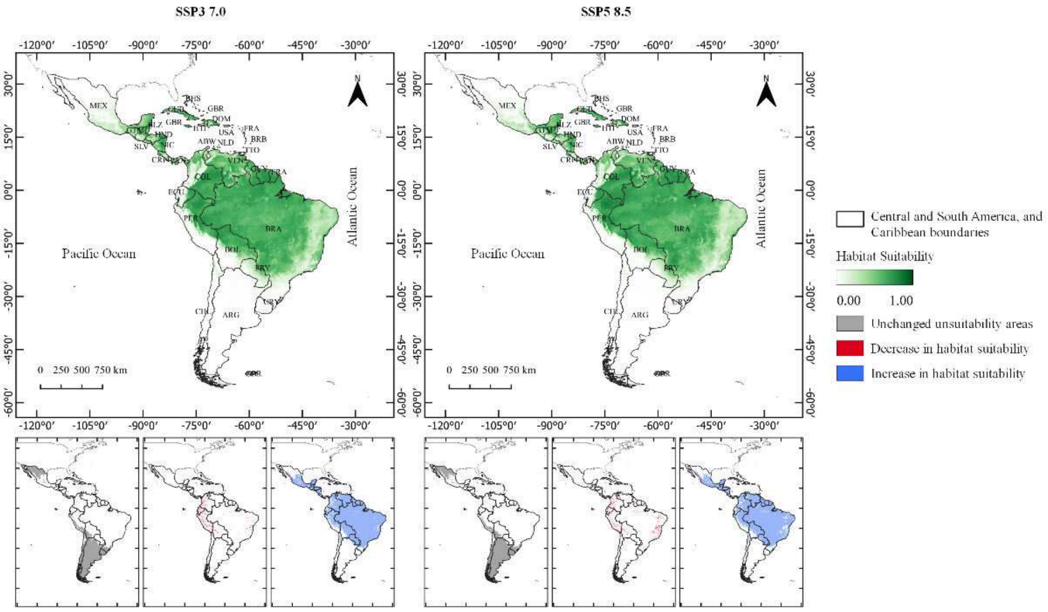

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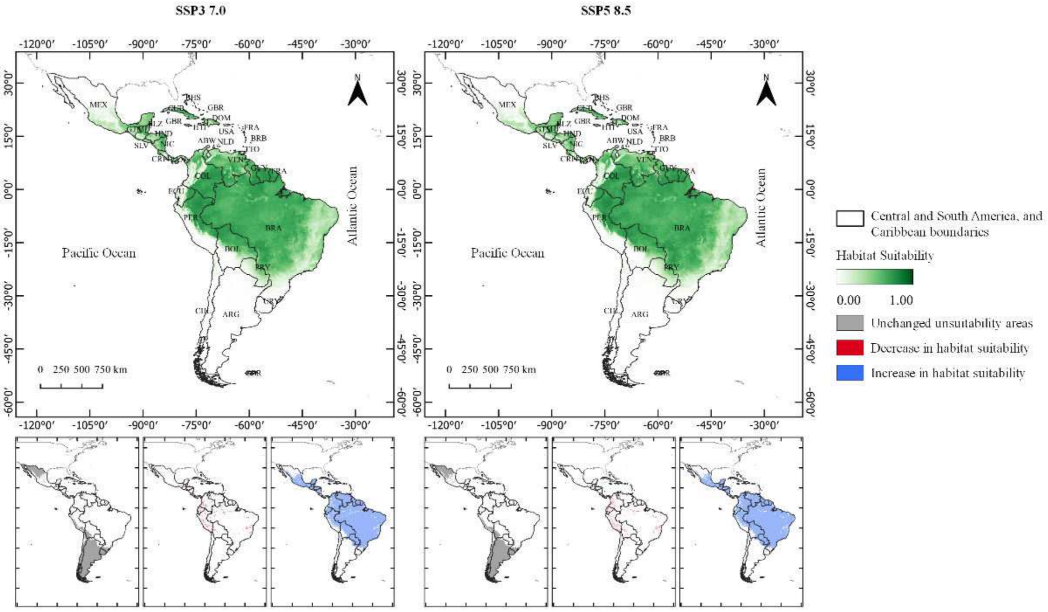

Figure S1.4. Ensemble of future projections habitat suitability and changes under SSP3 7.0 and SSP5 8.5 Scenarios (2041-2070 and 2070-2100) for a) *A. barreirensis*, b) *A. eichleri*, c) *A. funifera*, d) *A. maripa*, e) *A. phalerata*, f) *A. speciosa*, g) *A. vitrivir*, and h) the Babassu Complex overall, in Neotropical region.

DISCUSSÃO INTEGRADORA

O principal eixo integrador desta tese é a noção de incerteza no contexto da biogeografia da conservação. Diferentemente de abordagens que tomam ecossistemas ou espécies como objetos isolados, os capítulos aqui integrados exploram como incertezas informacionais, espaciais e ecológicas moldam a interpretação da distribuição das palmeiras do Complexo Babaçu (*Attalea* spp.) e, por consequência, a compreensão dos sistemas ecológicos aos quais essas espécies estão associadas.

Do ponto de vista conceitual, esta tese contribui ao demonstrar que a incerteza deve ser incorporada como componente analítico central da biogeografia, e não tratada como ruído a ser eliminado em estudos da biogeografia da conservação e planejamento sob incerteza (FERRIER, 2002; MARMION et al., 2009). A articulação entre síntese cartográfica e a modelagem de distribuição de espécies deste trabalho mostra que diferentes escalas de estudo podem revelar diferentes expressões de um mesmo processo biogeográfico.

Ao articular padrões em nível de ecossistema (Mata dos Cocais) e em nível de espécie (Complexo Babaçu), este trabalho demonstra que diferentes escalas analíticas são complementares. As delimitações espaciais ganham maior legitimidade ecológica quando sustentadas por padrões biogeográficos das espécies (KENT et al., 2006; MARTINS et al., 2022), enquanto as projeções de distribuição tornam-se mais interpretáveis quando inseridas em um contexto paisagístico e histórico mais amplo (FOSTER, 2000).

Nesse contexto, a Mata dos Cocais representa um recorte empírico privilegiado para discutir a biogeografia do babaçu em sistemas de transição, funcionando como interface entre padrões ecológicos, históricos e socioespaciais. Dessa forma, os capítulos compartilham um problema comum: como interpretar padrões biogeográficos quando os objetos de análise são marcados por fronteiras difusas, respostas ecológicas heterogêneas e lacunas de informação? Problema este que impacta de várias formas a criação e aplicação de políticas públicas (FERRIER, 2002; ZIZKA et al., 2020).

No Capítulo 1, esse problema se expressa, especificamente, na multiplicidade de delimitações da Mata dos Cocais, no qual evidencia que a representação espacial de sistemas transicionais e seu uso técnico-científico dependem fortemente dos critérios adotados em seus processos de construção e da disponibilidade de informações que garantam sua reprodutibilidade (BRUNSDON; COMBER, 2021; GONÇALVES, 2021).

A síntese cartográfica apresentada transforma a incerteza em um elemento analítico, o que fornece uma base para o planejamento territorial e a conservação (FERRIER, 2002; ZIZKA et al., 2020). Abordagem esta que dialoga com perspectivas da biogeografia que reconhecem fronteiras ecológicas como zonas gradativas e probabilísticas, especialmente em ecossistemas de transição (KENT et al., 1997; LOMOLINO; RIDDLE; WHITTAKER, 2016).

No Capítulo 2, a incerteza emerge, principalmente, na forma de respostas contrastantes entre as espécies do Complexo Babaçu, em relação a variáveis climáticas do cenário presente e considerando diferentes modelos globais de previsão de mudanças climática em cenários futuros, e dos múltiplos algoritmos utilizados e erros estatísticos associados à modelagem As projeções apresentadas evidenciam, que a biogeografia do babaçu é altamente dinâmica no tempo, em consonância com abordagens que reconhecem a natureza não estacionária das distribuições de espécies sob mudanças climáticas (MARMION et al., 2009; VALAVI et al., 2022). Espécies como *Attalea speciosa*, *A. maripa* e *A. phalerata* apresentaram nichos climáticos mais amplos e projeções de expansão das áreas de alta adequabilidade ambiental, enquanto *A. funifera* e *A. vitrivir* exibiram distribuições mais restritas e possíveis reduções sob cenários futuros.

A biogeografia dessas espécies reflete padrões comuns a palmeiras tropicais, como ampla distribuição, elevada plasticidade ecológica e respostas diferenciadas a gradientes climáticos (BLACH-OVERGAARD et al., 2010; EISERHARDT et al., 2011), tornando-as particularmente informativas para a análise de paisagens de transição marcadas por elevada incerteza. Esses resultados indicam que, apesar das semelhanças morfológicas e funcionais, o Complexo Babaçu não deve ser tratado como uma unidade ecológica homogênea. Dessa forma, a heterogeneidade interespecífica observada pode ajudar a explicar por que as diferentes espécies do Complexo ocorrem em diferentes contextos paisagísticos.

Adicionalmente, as projeções em *ensemble* sugerem que as mudanças climáticas podem ampliar a adequabilidade ambiental do Complexo Babaçu em porções da interface Amazônia–Cerrado, ao mesmo tempo em que intensificam assimetrias espaciais de vulnerabilidade. Tal configuração tem implicações diretas para estratégias de conservação e manejo, uma vez que os efeitos das mudanças climáticas não se manifestarão de forma uniforme sobre as espécies nem sobre o território. Nesse contexto, a Mata dos Cocais emerge como um sistema de elevada relevância adaptativa. Sua natureza ecotonal pode conferir maior resiliência frente às mudanças climáticas, especialmente para espécies com elevada tolerância ambiental, como visto para parte do Complexo Babaçu, o que reforça a necessidade de estudos biogeográficos na região (MALANSON; RESLER; TOMBACK, 2017; REHM et al., 2015; SCHNEIDER et al., 2016).

A integração entre a síntese cartográfica e a modelagem de distribuição de espécies representa, ainda, um avanço metodológico relevante para estudos em ecossistemas mal delimitados. A partir da integração dos resultados dos capítulos, é possível observar que as dimensões da incerteza não são paralelas, mas interdependentes, interpretação que dá maior profundidade ecológica aos achados deste trabalho. Quando esses resultados são confrontados, torna-se evidente que a Mata dos Cocais não pode ser entendida como uma unidade socioecológica independente da biogeografia do babaçu.

Nesse cenário, a região mostra-se ser potencialmente uma expressão espacial da biogeografia do babaçu em uma zona de transição, moldada tanto por gradientes ambientais quanto por processos históricos de uso da terra. A congruência espacial observada entre áreas de alta adequabilidade ambiental e os mapas para a região, destaca o papel das palmeiras de babaçu enquanto elementos estruturantes e indicadores biogeográficos da identidade ecológica regionais (BAKER; COUVREUR, 2013; DRANSFIELD et al., 2008; EISERHARDT et al., 2011).

A dimensão sociológica é indissociável da biogeografia do babaçu. Seus recursos constituem elemento central de subsistência, identidade cultural e organização territorial, sustenta modos de vida, identidades culturais e a segurança alimentar de comunidades tradicionais, especialmente as quebradeiras de coco (PORRO, 2019; PORRO; PORRO, 2015). A incerteza, assim, não é apenas ecológica ou cartográfica, mas também social, refletindo disputas de uso da terra e diferentes formas de apropriação da paisagem, com implicações diretas sobre sistemas produtivos tradicionais e estratégias de manejo sustentável para o extrativismo do babaçu. Diante disso, estratégias de conservação que desconsiderem essa dimensão correm o risco de aprofundar desigualdades socioambientais.

A redistribuição espacial da adequabilidade ambiental projetada no Capítulo 2, especificamente, destaca potenciais impactos sociais que podem decorrer da alteração do acesso aos recursos e da dinâmica territorial dessas populações (PORRO, 2019;

RESSIORE; LIMA; TURNHOUT, 2024). A provável sobreposição entre áreas futuras de alta adequabilidade ambiental e regiões sob intensa expansão agropecuária pode evidenciar um cenário de conflito potencial. Sem planejamento integrado, áreas que poderiam atuar como refúgios climáticos podem ser simultaneamente submetidas a pressões antrópicas crescentes, comprometendo sua função ecológica e social (BELLARD et al., 2012; BRODIE et al., 2022).

Em conjunto, os resultados desta tese indicam que a Mata dos Cocais e o Complexo Babaçu só podem ser plenamente compreendidos a partir de uma abordagem integrada, que considere simultaneamente incertezas espaciais, respostas ecológicas específicas e a dimensão humana da paisagem. O Complexo Babaçu emerge como o verdadeiro eixo integrador entre os capítulos, conectando padrões de distribuição, respostas climáticas e dimensões socioecológicas. O uso de múltiplos algoritmos e de projeções em *ensemble*, reduziu a dependência de interpretações baseadas em um único modelo e permitiu identificar áreas de maior convergência e incerteza, abordagem especialmente valiosa em regiões com lacunas de dados (MARMION et al., 2009; VALAVI et al., 2022).

Ao posicionar a incerteza como elemento estruturante da análise, e não apenas uma limitação metodológica, este estudo oferece uma contribuição original para a biogeografia da conservação de palmeiras tropicais e para uma compreensão mais realista e aplicada dos ecossistemas de transição tropicais. Além disso, reforça a necessidade de abordagens flexíveis, processuais e integradas para interpretar e manejar sistemas ecológicos complexos, orientar políticas públicas e promover a resiliência ecológica e social em cenários de mudanças globais.

CONCLUSÕES GERAIS

Este trabalho buscou compreender, de forma integrada, os desafios conceituais e espaciais relacionados à Mata dos Cocais e os potenciais efeitos das mudanças climáticas sobre o Complexo Babaçu (*Attalea* spp.). Embora os dois capítulos apresentem enfoques e métodos distintos, ambos convergem epistemologicamente sobre a mesma problemática: a biogeografia da conservação em face da incerteza.

O trabalho dedicado à Mata dos Cocais documenta a variabilidade das delimitações existentes e demonstra que essa variabilidade tem implicações práticas e normativas. A identificação de uma área de consenso, uma zona núcleo recorrente entre diferentes mapas, não elimina a incerteza, mas oferece um ponto de partida operacional para intervenções territoriais. Ao explicitar os critérios divergentes entre fontes e ao hierarquizar evidências cartográficas, o capítulo fornece uma base mais sólida para decisões espaciais que, até então, apoiavam-se em noções conflitantes sobre o que constitui a própria extensão dessa região.

O conjunto de análises bioclimáticas para as espécies do Complexo Babaçu, por sua vez, mostra que previsões sobre adequabilidade ambiental são sensíveis tanto às escolhas metodológicas quanto às lacunas de dados biológicos. Existe uma grande lacuna de conhecimento a ser explorada acerca dos estudos ecológicos sobre as espécies de babaçu, suas áreas de distribuição e os nichos que ocupam. As projeções sinalizam tendências de deslocamento e de alteração na adequabilidade climática de espécies distintas, mas também evidenciam variações entre algoritmos e entre cenários climáticos. Assim, ainda que os modelos ofereçam cenários plausíveis, eles devem ser interpretados como ferramentas probabilísticas condicionadas às incertezas inerentes de amostragem, de resolução ambiental e de projeções climáticas, e não como previsões determinísticas.

Ao tratar separadamente a incerteza cartográfica e a incerteza preditiva, esta tese demonstra que essas dimensões se reforçam mutuamente: delimitações espaciais pouco consensuais dificultam a validação empírica e a contextualização das projeções de adequabilidade; inversamente, projeções climáticas com grande variabilidade aumentam a complexidade de definir áreas prioritárias quando a própria extensão do ecótono é incerta. Reconhecer essa reciprocidade é, a meu ver, a contribuição conceitual mais relevante do trabalho, a de que a incerteza é tanto objeto de estudo quanto condicionante da ação no âmbito da biogeografia da conservação. Em conjunto, as evidências produzidas mostram que a ausência, a dispersão e a qualidade heterogênea de informações espaciais e ecológicas não são meras dificuldades técnicas, constituem fatores estruturantes que moldam interpretações, decisões de manejo e prioridades conservacionistas.

Durante o desenvolvimento do trabalho foram observadas algumas limitações do estudo, explicitadas ao longo do texto. Dentre estas, destacam-se: vieses e lacunas nos dados de ocorrência das espécies do Complexo Babaçu e na cartografia disponível sobre a Mata dos Cocais; a dependência de variáveis ambientais de resolução contínua que nem sempre capturam micro-habitat ou heterogeneidade local; os modelos pressupõem dispersão ilimitada, ignorando barreiras geográficas (por exemplo, desmatamento, cadeias de montanhas) que podem limitar as mudanças de amplitude de adequabilidade; e as incertezas inerentes às projeções climáticas regionais. Essas limitações não comprometem o valor dos resultados, mas condicionam sua aplicação, sobretudo em contextos de tomada de decisão onde custos sociais e ecológicos são elevados.

Além das implicações espaciais e metodológicas, esta tese evidencia também os aspectos ecológicos fundamentais das palmeiras de babaçu, cuja ampla plasticidade ecológica pode explicar em grande parte sua persistência em ecossistemas de transição. A análise das respostas diferenciadas das espécies do Complexo Babaçu aos gradientes ambientais sugere que variações em traços funcionais, como tolerância hídrica, fenologia reprodutiva e dispersão de sementes, possivelmente exercem papel decisivo na configuração atual e futura das distribuições potenciais de suas espécies. Dessa forma, os resultados reforçam que compreender a ecologia das palmeiras de babaçu é condição essencial para interpretar sua biogeografia e projetar estratégias de conservação que considerem tanto as dimensões climáticas quanto os mecanismos ecológicos subjacentes à ocupação dessas paisagens.

A integração de elementos ecológicos, geográficos e climáticos sob a perspectiva da biogeografia, se mostrou promissora, principalmente considerando sua aplicabilidade para à conservação ambiental, à restauração/recuperação de ambientes antropizados e à previsão dos impactos das mudanças climáticas sobre as espécies em cenários de incertezas ambientais e informacionais. Os mapas e modelos aqui produzidos são instrumentos valiosos, mas seu papel efetivo depende do seu uso enquanto ferramenta dinâmica de diálogo entre ciência, gestão e sociedade.

Assim, a partir dos resultados e das limitações identificadas, proponho quatro linhas prioritárias de desenvolvimento aplicável e científico. Primeiro, buscar o aprimoramento da base cartográfica da Mata dos Cocais por meio de integração multiescalar, envolvendo, por exemplo, sensoriamento remoto de alta resolução, validação de campo e o uso de conhecimentos locais e tradicionais para reduzir ambiguidades formais. Segundo, o fortalecimento da base ecológica das modelagens com a inserção de dados de fenologia, demografia, fisiologia hídrica e genética das espécies de babaçu, de modo a aumentar a plausibilidade ecológica das projeções. Terceiro, a incorporação de variáveis antropogênicas (uso do solo, infraestrutura, regimes de fogo, dinâmicas socioeconômicas) em modelos integrados que combinem cenários climáticos e de uso da terra. Quarto, a promoção de estratégias de manejo adaptativo e de gestão participativa com comunidades locais, de modo que ações de conservação e o uso sustentável sejam informados por evidências e aceitáveis socialmente.

A preservação da Mata dos Cocais e a sustentabilidade dos babaçuais, portanto, dependerão não apenas de avanços metodológicos, mas sobretudo da capacidade de traduzir incerteza em estratégias de ação e decisões adaptativas, cientificamente embasadas e socialmente legitimadas. Ao revelar como incertezas cartográficas e preditivas podem limitar o planejamento territorial e a conservação de espécies e, de forma mais ampla, ecossistemas de transição, este trabalho reforça a importância da biogeografia da conservação como campo estratégico para compreender, projetar e intervir em paisagens socioecológicas complexas, especialmente em regiões tropicais sujeitas à múltiplas pressões ambientais.

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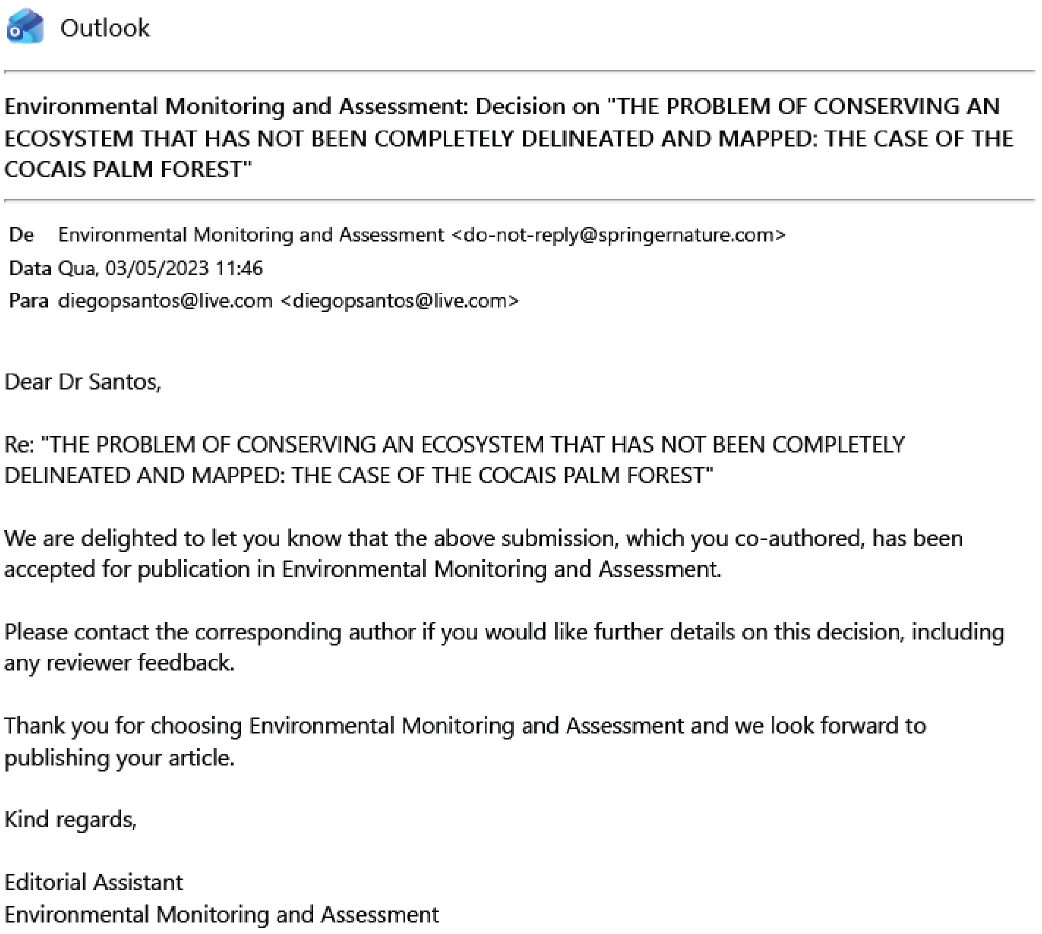
ANEXOS

ANEXO A – COMPROVANTE DE ACEITE DO ARTIGO "*THE PROBLEM OF CONSERVING AN ECOSYSTEM THAT HAS NOT BEEN COMPLETELY DELINEATED AND MAPPED: the case of the cocais palm forest*", SUBMETIDO E PUBLICADO NA REVISTA *ENVIRONMENTAL, MONITORING AND ASSESSMENT.*



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De Environmental Monitoring and Assessment <do-not-reply@springernature.com>
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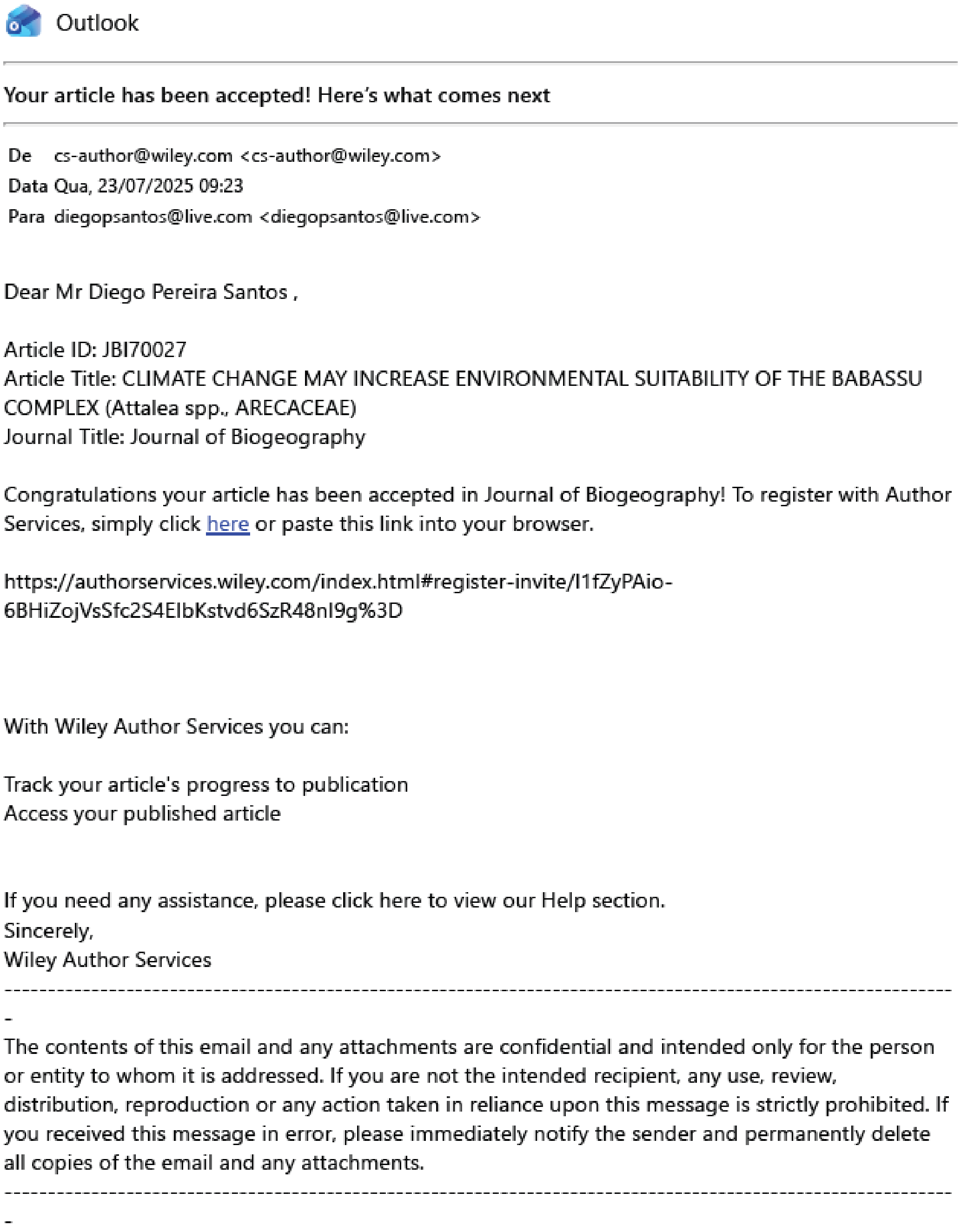
ANEXO B – COMPROVANTE DE ACEITE DO ARTIGO “*CLIMATE CHANGE MAY INCREASE ENVIRONMENTAL SUITABILITY OF THE BABASSU COMPLEX* (*Attalea* spp., ARECACEAE)”, SUBMETIDO E PUBLICADO NA REVISTA *JOURNAL OF BIOGEOGRAPHY*.



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