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JÚLIA ANGELI DA SILVA

IMPACTOS DAS MUDANÇAS CLIMÁTICAS NA DISTRIBUIÇÃO DE PALMEIRAS DA MATA ATLÂNTICA: A INFLUÊNCIA DOS TRAÇOS FUNCIONAIS DAS ESPÉCIES

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Orientadora: Dra. Eliana Cazetta
Co-orientadores: Dra. Daniela Custódio Talora e
Dr. Neander Marcel Heming

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Dra. Eliana Cazetta
Universidade Estadual de Santa Cruz
(Orientadora)

Dra. Rita de Cássia Quitete Portela
Universidade Federal do Rio de Janeiro

Dra. Vanessa Leite Rezende
Universidade Federal de Lavras

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IMPACTOS DAS MUDANÇAS CLIMÁTICAS NA DISTRIBUIÇÃO DE PALMEIRAS DA MATA ATLÂNTICA: A INFLUÊNCIA DOS TRAÇOS FUNCIONAIS DAS ESPÉCIES

RESUMO

Devido às intensas mudanças ambientais induzidas pelas atividades humanas, como as mudanças climáticas, compreender a distribuição geográfica das espécies, os efeitos dessas mudanças nos padrões de distribuição e riqueza, e identificar os traços relacionados os à distribuição e às mudanças climáticas é crucial para garantir sua conservação e manejo eficaz. Neste trabalho, utilizamos como modelo a família Arecaceae (palmeiras), que desempenha um papel fundamental na estrutura e funcionamento das florestas. Utilizando modelos de nicho ecológico, estimamos as áreas climaticamente adequadas para as palmeiras no cenário climático atual e nos cenários futuros. Combinando esses modelos e traços funcionais de 63 espécies de palmeiras da Mata Atlântica brasileira, realizamos regressões de mínimos quadrados generalizada filogenética para examinar a relação entre traços funcionais e o tamanho da área de distribuição geográfica, bem como entre esses traços e as mudanças de área nos cenários futuros de mudanças climáticas. Nossos resultados revelam uma variação no tamanho da área de distribuição entre as espécies de palmeiras, com algumas apresentando distribuições altamente restritas, enquanto outras ocupam vastas áreas do bioma. A riqueza atual de espécies é maior ao longo da costa nordeste e em partes da região sudeste do Brasil, onde espera-se uma redução substancial da riqueza nos cenários climáticos futuros, embora a maioria do bioma deva manter altos níveis de diversidade alfa. Além disso, nossas projeções indicam que mais de 61% das espécies de palmeiras enfrentarão uma diminuição nas suas áreas climaticamente adequadas em todos os cenários futuros. Identificamos que as palmeiras com caules mais altos e frutos maiores tendem a ocupar áreas geográficas mais amplas. Enquanto que espécies com distribuições restritas e caules mais altos são particularmente vulneráveis às perdas de áreas climaticamente adequadas nos cenários climáticos futuros. Nossos resultados destacam regiões de excepcional riqueza de palmeiras na Mata Atlântica, que também serão as mais impactadas pela perda de espécies no futuro. Além disso, enfatizamos as espécies com distribuições restritas e ressaltamos a importância dos traços funcionais na definição das distribuições das espécies e na avaliação da vulnerabilidade às mudanças climáticas, com base nas projeções futuras. Essas informações são essenciais para a conservação da biodiversidade em uma das florestas tropicais mais ameaçadas do mundo.

Palavras-chave: Distribuição geográfica, aquecimento global, Arecaceae, modelagem de nicho ecológico, diversidade alfa, traços funcionais, conservação.

IMPACTS OF CLIMATE CHANGE ON THE DISTRIBUTION OF ATLANTIC FOREST PALMS: THE INFLUENCE OF SPECIES FUNCTIONAL TRAITS

ABSTRACT

Due to the intense environmental changes induced by human activities, such as climate change, understanding the geographic distribution of species, the effects of these changes on distribution patterns and richness, and identifying traits related to distribution and climate change is crucial for ensuring their conservation and effective management. In this study, we use the Arecaceae family (palms) as a model, which plays a key role in forest structure and functioning. Using ecological niche models, we estimate the climatically suitable areas for palms in the current and future climatic scenarios. By combining these models and functional traits of 63 palm species from the Brazilian Atlantic Forest, we perform phylogenetic generalized least squares regressions to examine the relationship between functional traits and geographic distribution area size, as well as between these traits and area changes in future climate change scenarios. Our results reveal variation in the distribution area size among palm species, with some exhibiting highly restricted distributions, while others occupy vast areas of the biome. The current species richness is higher along the northeastern coast and parts of the southeastern region of Brazil, where a substantial decrease in richness is expected under future climate scenarios, although most of the biome is projected to maintain high levels of alpha diversity. Furthermore, our projections indicate that over 61% of palm species will face a decrease in their climatically suitable areas under all future scenarios. We identify that palm with taller stems and larger fruits tend to occupy broader geographic ranges, while species with restricted distributions and taller stems are particularly vulnerable to the loss of climatically suitable areas in future climate scenarios. Our results highlight regions of exceptional palm richness in the Atlantic Forest, which will also be the most impacted by species loss in the future. Additionally, they emphasize species with restricted distributions and highlight the importance of functional traits in determining species distributions and assessing vulnerability to climate change based on future projections. These insights are therefore essential for biodiversity conservation in one of the most threatened tropical forests in the world.

Keywords: Geographic distribution, global warming, Arecaceae, ecological niche modeling, alpha diversity, functional traits, conservation.

SUMÁRIO

Introdução geral

As mudanças climáticas são amplamente reconhecidas como uma das maiores ameaças à biodiversidade (Parmesan, 2006), já que as espécies provavelmente não conseguirão se adaptar às rápidas mudanças nos padrões de temperatura e precipitação (Román-Palácios e Wiens, 2020). Projeções indicam um contínuo aumento da temperatura da superfície terrestre nas próximas décadas (IPCC, 2023). Como resultado, muitas espécies podem enfrentar mudanças em suas áreas de distribuição, seja por expansão, retração ou realocação, em busca de condições climáticas mais favoráveis (Bellard et al., 2012; Lenoir e Svenning, 2015), comprometendo o funcionamento dos ecossistemas (Nunez et al., 2019). Além disso, os impactos não se limitam a mudanças diretas, ou seja, algumas espécies podem ser indiretamente afetadas pela perda ou deslocamento das espécies as quais interagem (Thomas, 2010).

Em um contexto de intensas mudanças ambientais induzidas pelas atividades humanas, como o aquecimento global, compreender a distribuição geográfica das espécies é crucial para assegurar sua conservação e manejo eficaz (Mace, 2004; Mutke e Barthlott, 2005). Fatores como clima, solo, disponibilidade de luz, distúrbios, interações ecológicas, barreiras geográficas, amplitude do nicho, idade e capacidade de dispersão influenciam o tamanho da área de distribuição geográfica das espécies (Alzate e Onstein, 2022; Mod et al., 2016; Sheth et al., 2020). Espécies com áreas de distribuição restritas são particularmente vulneráveis à extinção, pois enfrentam maior risco de perda de habitat e podem ser menos capazes de se adaptar a mudanças ambientais (Gaston e Fuller, 2009; Purvis et al., 2000). Muitas dessas espécies em declínio já apresentam uma redução significativa em suas áreas de distribuição, o que torna o tamanho da área um dos indicadores de risco de extinção (Leão et al., 2020). Portanto, entender as distribuições e padrões espaciais das espécies é fundamental para o desenvolvimento de estratégias de manejo que possam mitigar as ameaças atuais e futuras, otimizando os esforços de conservação (Scheele et al., 2018; Waldron et al., 2017).

As plantas estão entre os grupos mais vulneráveis às mudanças climáticas (Walther, 2003), com estimativas sugerindo que entre 23% e 31% das espécies podem enfrentar extinção devido ao aquecimento global (Wiens e Zelinka, 2024). Além de impactar a biodiversidade global, essas mudanças também podem alterar significativamente a distribuição geográfica das plantas (Parmesan, 2006), forçando-as a migrar em busca de áreas com condições ambientais mais favoráveis e assim expandir ou contrair suas áreas de distribuição no futuro (Garcia et al., 2014; Kelly e Goulden, 2008). Portanto, estudos que investiguem como as mudanças climáticas influenciam a distribuição das plantas são essenciais para prever padrões futuros de biodiversidade e auxiliar na formulação de políticas públicas que promovam a conservação da biodiversidade.

A família das palmeiras (Arecaceae) está sendo significativamente impactada pelas mudanças climáticas, enfrentando tanto a expansão quanto a redução de suas áreas de distribuição, além de potencialmente remodelar as interações ecológicas entre as espécies (Blach-Overgaard et al., 2015; Eiserhardt et al., 2011; Sales et al., 2021; Vaz e Nabout, 2016). As palmeiras estão predominantemente distribuídas nos Neotrópicos, onde desempenham um papel fundamental na estrutura e funcionamento das florestas (Galetti e Aleixo, 1998; Henderson, 2002; Muscarella et al., 2020), incluindo a Mata Atlântica, um dos biomas mais ameaçados pelas mudanças climáticas (Bellard et al., 2014), em que a vegetação florestal atualmente ocupa apenas 22,9% de sua área original (Vancine et al., 2024). Além disso, as palmeiras são essenciais para os animais frugívoros tropicais, pois fornecem uma alta abundância de frutos carnosos e sementes (Galetti et al., 2013; Zona e Henderson, 1989).

A distribuição geográfica das espécies e sua vulnerabilidade às mudanças climáticas estão intimamente relacionadas aos traços funcionais das espécies, que desempenham um papel crucial na capacidade de persistência das espécies (Nathan, 2006; Pacifici et al., 2017). Por exemplo, palmeiras com distribuições geográficas restritas e aquelas associadas ao interior de florestas de dossel fechado tendem a perder mais áreas adequadas no futuro devido à sua baixa tolerância a condições sazonais e secas, características esperadas nos cenários futuros de mudanças climáticas (Blach-Overgaard et al., 2015; Lee et al., 2015). Espécies com caules curtos, que minimizam a perda de água e demonstram maior resiliência ao estresse hídrico, juntamente com aquelas que produzem frutos maiores, que favorecem o estabelecimento em condições de altas temperaturas e aumentam o sucesso reprodutivo, têm o potencial de expandir suas áreas adequadas em cenários climáticos futuros (Cássia-Silva et al., 2020; Göldel et al., 2015; Westoby et al., 1996). Esses traços podem tanto facilitar quanto restringir a dispersão de longa distância, influenciando diretamente suas áreas de distribuição (Nathan, 2006). A especialização no habitat torna as espécies do interior da floresta mais vulneráveis à destruição de seu habitat, resultando em distribuições mais restritas. Em contraste, espécies encontradas em áreas abertas, por serem mais generalistas, tendem a apresentar distribuições mais amplas, devido à maior flexibilidade diante de diferentes condições ambientais (Petrocelli et al., 2024). Além disso, espécies com caules mais grossos, maior altura e sementes maiores — geralmente associadas a frutos maiores — possuem maior capacidade competitiva e tendem a ser dispersas por frugívoros de maior porte, permitindo distâncias de dispersão mais longas e a colonização de novos ambientes, o que contribui para distribuições mais amplas (Bemmels et al., 2018;

Bucharova e Van Kleunen, 2009; Jenkins et al., 2007; Lavergne et al., 2004; Thomson et al., 2011). Assim, identificar as características que moldam a área de distribuição das espécies e investigar como esses traços estão associados a perda e ganho de área nos cenários climáticos futuros é crucial para avaliar os impactos climáticos e implementar estratégias de conservação fundamentadas nessas características.

Diante deste contexto, esta dissertação tem como objetivo principal avaliar a distribuição atual e futura das palmeiras da Mata Atlântica. A dissertação está dividida em dois capítulos, com os seguintes objetivos específicos: 1. avaliar os padrões de distribuição e a riqueza de espécies de palmeiras da Mata Atlântica no cenário climático atual e identificar os traços funcionais associados à área de distribuição destas espécies; 2. avaliar como as mudanças climáticas vão influenciar a riqueza de espécies e os padrões de distribuição das palmeiras, bem como quais traços estão associados com os maiores ganhos e perdas de áreas adequadas nos cenários climáticos futuros.

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CHAPTER 1

Angeli, J., Talora, D. C, Heming, N. H., **Cazetta, E.** FUNCTIONAL TRAITS SHAPING THE POTENTIAL DISTRIBUTION OF PALM SPECIES IN THE ATLANTIC FOREST.

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Functional traits shaping the potential distribution of palm species in the Atlantic Forest

Júlia Angeli [1 2 3], Daniela Custódio Talora[1 3], Neander Marcel Heming[1 3], Eliana Cazetta[1 2 3]

[1]Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Departamento de Ciências Biológicas, Universidade Estadual de Santa Cruz, Ilhéus, BA 45662-900, Brazil

[2]Ecological Interactions of Tropical Plants Lab

[3]Applied Ecology and Conservation Lab

[*] Corresponding author: Júlia Angeli (juliaangeli34@gmail.com)

ABSTRACT

The geographic range size of species is shaped by several environmental and biological factors with functional traits playing a critical role by influencing long-distance dispersal. In plants, traits related to fruit and stem size can affect range size, as larger fruits and taller stems enhance dispersal capacity. In this study, we focus on Arecaceae (palms), which plays a key role in forest structure. This study evaluates the current potential distribution of palm species in the Atlantic Forest, identifying regions with the highest species richness and the functional traits linked to species' range size. We first compiled data on functional traits—stem height, stem diameter, fruit length, fruit width, and habitat—for 63 palm species. We then integrated environmental variables with known species occurrences to estimate climatically suitable areas using ecological niche models. Finally, we performed phylogenetic generalized least squares regression to examine the relationship between functional traits and geographical range size. Our results reveal significant variation in range size among species, with some exhibiting highly restricted potential distributions, while others occupy vast areas of the biome. Species richness is highest along the northeastern coast and parts of the southeastern region of Brazil. Palms with taller stems and larger fruits tend to occupy broader geographic ranges. These findings highlight regions of exceptional palm richness, emphasize species with restricted distributions, and underscore the importance of functional traits in shaping species distributions. They also provide crucial insights for biodiversity conservation in one of the world's most threatened tropical forests.

Key-words: Arecaceae; species distribution; geographic range size; ecological niche models; richness; fruit size; stem height

1. Introduction

The geographical distribution of species is shaped by a variety of environmental and biological conditions. For plants, these distributions are influenced by variables such as climate, soil properties, light availability, disturbances, and ecological interactions, which can vary across different spatial scales (Mod et al., 2016). Species with restricted distributions are typically confined to narrower ranges of environmental conditions (Baltzer et al., 2007), making them more vulnerable to environmental changes. In contrast, species with wide geographical distributions tend to exhibit greater tolerance to environmental factors, allowing them to thrive in a broader range of habitats (Baltzer et al., 2007). Thus, understanding species distribution is crucial for effective conservation and management (Mutke and Barthlott, 2005), as restricted distributions often indicate a threatened status (IUCN, 2022).

The geographical range of species can be also influenced by their functional traits, which can either promote or limit long-distance dispersal (Nathan, 2006). For instance, large seeds, often associated with larger fruits, tend to be dispersed by larger frugivores, allowing for longer dispersal distances (Jenkins et al., 2007) and, consequently, wider distribution areas. Similarly, species with larger stem diameters and greater height have a higher competitive ability, enabling them to colonize new environments, resulting in wider distributions (Bemmels et al., 2018; Bucharova and Van Kleunen, 2009; Lavergne et al., 2004; Thomson et al., 2011). Therefore, traits such as fruit size and stem height play a key role in determining species' geographic range.

Understanding these patterns, however, is often challenged by the limitations and scarcity of species presence data. In this context, ecological niche modeling (ENM) stands out as a valuable tool for predicting suitable habitats, especially in under-sampled regions or for species with limited occurrence records (Ishihama, 2019). Environmental predictor-based models generate projections of potential habitats, providing an approximation of the species' fundamental niche (Guisan and Zimmermann, 2000). By enhancing our understanding of species' spatial distribution, ENM not only contributes to biodiversity conservation in a constantly changing world but also guides research, monitoring strategies, and the development of effective conservation policies.

In this study, we used the Arecaceae family as a model to understand how plant traits, particularly those related to dispersal, influence the geographical range size of species. The Arecaceae family plays a key role in forest structure (Galetti and Aleixo, 1998) and are among the most abundant tree group in tropical and subtropical ecosystems (Dransfield et al., 2008; Muscarella et al., 2020; Uhl and Dransfield, 1987). Additionally, palms exhibit significant geographical variation in species richness and life forms, acting as essential resources for frugivores (Zona and Henderson, 1989; Henderson, 2002; Muñoz et al., 2019). They provide a high abundance of fleshy fruits (Zona and Henderson, 1989; Galetti et al., 2013), whose seeds are dispersed by several animals, including birds, bats, non-flying mammals, reptiles, insects, and even fish (Zona and Henderson, 1989). This reliance on frugivores for seed dispersal significantly affects both the effectiveness and distance of dispersal, influencing their geographic range size (Estrada et al., 2015; Nathan, 2006; Petrocelli et al., 2024). Furthermore, the Arecaceae family is recognized as one of the most economically important plant families and has been extensively exploited by humans in tropical regions (Scariot, 1999).

In this study, we used ecological niche models to estimate the potential distribution of palm species in the Atlantic Forest under the current climate scenario, identifying regions with the highest species richness. Moreover, our objective was to identify the functional palm traits that are associated with the potential distribution of both restricted and widely distributed species. Currently, the Atlantic Forest's Forest vegetation covers only 22.9% of its original area, with 97% of the fragments being small (<50 ha), and only 10% of the vegetation is protected within protected areas and indigenous territories (Vancine et al., 2024). The distribution of these forest remnants is heterogeneous throughout the biome. Since the Arecaceae family is widely distributed in both intact and fragmented tropical forest areas (Uhl and Dransfield, 1987), we expected that palm species exhibit heterogeneous distribution patterns, with some species covering the entire extent of the biome while others have more restricted ranges. We expect that species with larger fruits, taller stems, and greater stem diameters will have larger potential distribution areas compared to species with smaller fruits, shorter stems, and smaller stem diameters. Furthermore, we hypothesize that species inhabiting open vegetation will have larger range sizes than those restricted to closed forests and with taller stems. Open-area species are often more generalist and tolerant to diverse climatic conditions, whereas forest-interior species tend to be habitat specialists, making them more vulnerable to deforestation and resulting in restricted distributions (Petrocelli et al., 2024).

2. Methods

2.1. Study Area

Our study area is the Brazilian Atlantic Forest (Figure 1), a biodiversity hotspot (Myers et al., 2000) and one of the most threatened biomes globally (Bellard et al., 2014). The biome is characterized by high environmental heterogeneity, topographic variability, and a high level of endemism (Peres et al., 2020), with over 18,000 identified plant species (Flora e Funga do

Brasil, 2024). However, human activities have intensely transformed the region since the 16th century, causing significant deforestation and fragmentation, which have significantly impacted biodiversity (Joly et al., 2014).

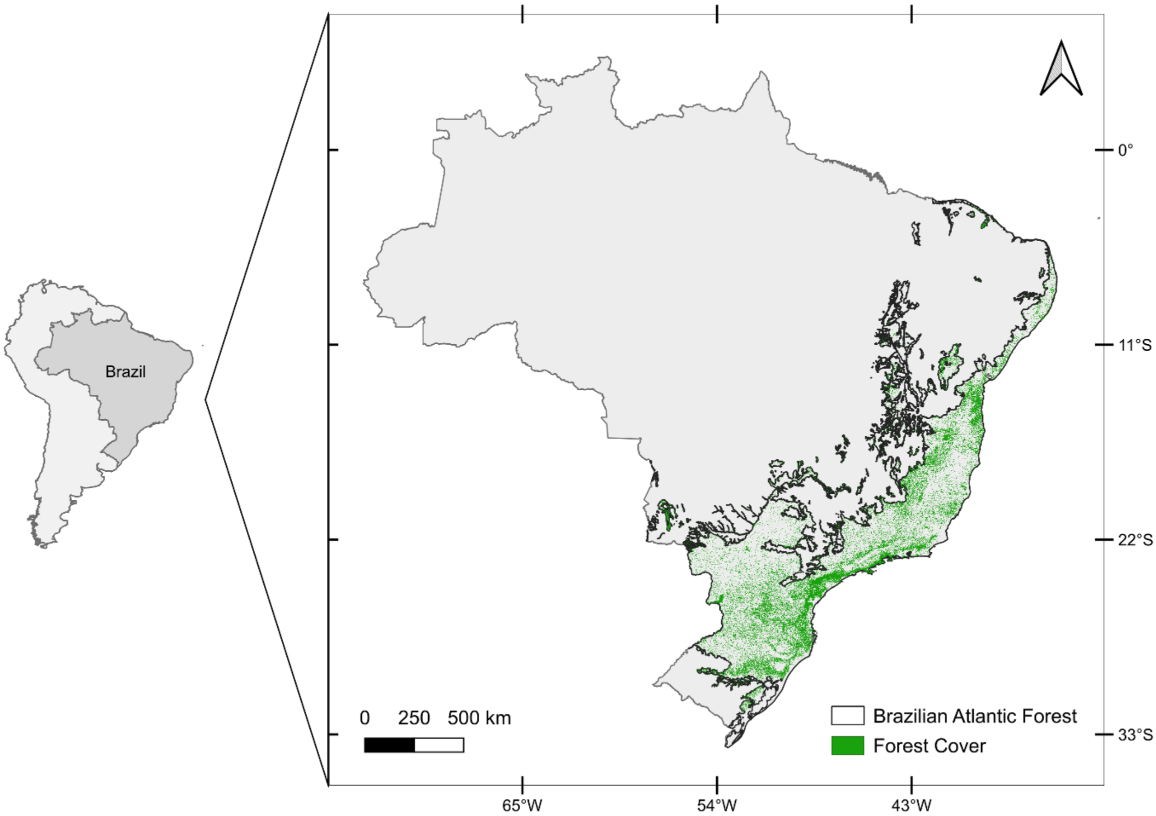

Figure 1: Map of the Brazilian Atlantic Forest, showing forest cover in green.

2.2 Occurrence Points

We defined a list of 88 Atlantic Forest palm species, incorporating both native and exotic species (including four exotic species), based on Cerqueira et al. (2023) and Bello et al. (2017) (Table S1). These references comprise a compilation of species from the biome, including a systematic review of all native palm species in the Atlantic Forest, as well as a survey of plant species and ecological interactions in the Atlantic Forest, respectively. Species occurrence records were retrieved from databases such as Global Biodiversity Information Facility, SpeciesLink, Integrated Digitized Biocollections, and iNaturalist. The nomenclature and synonyms used follow the *Flora Brasileira: Arecaceae (Palmeiras)* (Lorenzi et al., 2010) and Cerqueira et al. (2023). After obtaining the data, we reviewed the records to identify inconsistencies, removing duplicates, incomplete, and improbable coordinates using the *scrubr* package (Chamberlain, 2021) in R (R Core Team, 2024). To reduce spatial autocorrelation and potential geographic biases, we applied the *spThin* optimization algorithm (Aiello-Lammens et al., 2015), which removes occurrence records less than 10 km apart, improving ecological niche model performance (Boria et al., 2014). After the data cleaning, *Attalea seabrensis* and *Phoenix sylvestris* were removed from the analyses due to lack of records within the Atlantic Forest boundaries. Additionally, species with fewer than five occurrence records were excluded, resulting in 63 species for ecological niche modeling (Table S1).

2.3 Species Traits

For each palm species, we used traits commonly associated with species distribution, competitive ability, and dispersal capacity: stem height, stem diameter, fruit length, and fruit width (Goldel et al., 2015; Cornelissen et al., 2003; Westoby, 1998). We also classified each species based on its habitat preference as either open-area or forest-interior, following Benchimol et al. (2016). Additional information was obtained from *Flora Brasileira: Arecaceae* (Lorenzi et al., 2010). Species classified as "forest-interior" are those predominantly found in dense-canopy forests, while "open-area" species mainly occur in open environments or less dense-canopy forests. Although some species may occur in both habitat types, we classified them based on their primary habitat preference.

Stem and fruit traits were obtained from the global functional trait database for palms, PalmTraits 1.0 (Kissling et al., 2019). For acaulescent species, we assigned values of zero, and for species, such as *Attalea humilis,* that occur both in acaulescent and stem solitary growth form, we assigned the maximum stem height. For some species, additional information was gathered through further research in *Flora Brasileira: Arecaceae (Palmeiras)* (Lorenzi et al., 2010), the *Flora e Funga do Brasil* project (Arecaceae in Flora e Funga do Brasil, 2024), and other literature sources (Table S2). To fill in missing data for four species (*Acrocomia intumescens, Allagoptera brevicalyx, Attalea apoda,* and *Geonoma rodeiensis*), we used the average maximum stem diameter values from the respective genera in our species list. The same approach was applied to estimate the average fruit width of *Geonoma rodeiensis*. For the only species in our list from the genus *Trithrinax*, the average fruit length was missing; in this case, we used the average of the genus *Trithrinax* species available in PalmTraits 1.0 (Kissling et al., 2019).

Table 1: Functional traits of 63 palm species from the Atlantic Forest. For continuous traits we present mean, maximum, and minimum values.

Traits	**Type**	**Mean (max, min)**

Habitat	Categorical (Open-area, Forest-interior)	
Maximum stem height	Continuous	10.26 m (0 e 40)
Maximum stem diameter	Continuous	19.55 cm (0 e 66)
Mean fruit length	Continuous	2.96 cm (0.6 e 12.5)
Mean fruit width	Continuous	2.12 cm (0.55 e 6)

2.4 Bioclimatic Variables

Bioclimatic variables were obtained from the *WorldClim v2.1* platform (Fick & Hijmans, 2017), with a spatial resolution of 2.5° (~4.5 km²) for the current climate scenario (1970-2000) (Table 2). We used a correlation matrix using Pearson correlation coefficients and the *select_vars* function from the R package *ENMwizard* (Heming et al., 2019) to select bioclimatic variables with correlations below 75%, in order to reduce collinearity issues. Selected climatic variables for each species are listed in Table S1.

Table 2: Bioclimatic variables derived from temperature and precipitation data obtained from WorldClim v2.1 (Fick and Hijmans, 2017).

Variable	**Description**
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month

BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

2.5 Ecological Niche Models (ENMs)

We estimated the climatically suitable areas for the 63 palm species using ENMs, which allow us to estimate the relationship between environmental variables and the known occurrences of the species. We used the *MaxEnt* algorithm (version 3.4.1, Phillips et al. 2017) through the *ENMwizard* package (Heming et al., 2019) to model the potential distribution of the species. *MaxEnt* is recognized for its good performance and accuracy, even when applied to small samples (Hernandez et al., 2006). The calibration area was created with a 1.5° buffer around the minimum convex polygon (MCP) of all occurrences. The models were fitted using options for Feature classes (FC) and Regularization multipliers (RMs), including all combinations of the following classes: linear (L), product (P), and quadratic (Q), along with RM values (ranging from 0.5 to 5, with increments of 0.5), resulting in 70 models per species.

To validate and assess the predictive capacity of the models, we applied two methods of geographical partitioning on the occurrence records: block or jackknife, using the "ENMevaluate_b" function from the *ENMwizard* package (Heming et al., 2019). The jackknife partitioning method was used for species with fewer than 15 occurrence records (Shcheglovitova and Anderson, 2013). This method involves removing one point from the dataset at a time and building a new model without the removed point (Pearson et al., 2007). In contrast, the block method divides the occurrence points into four spatially independent blocks, performing four iterations in which one block is used to evaluate the model while the others are used for calibration (Roberts et al., 2017).

We constructed a consensus model for each species from the top 10% of MaxEnt models based on the criteria of the lowest omission rate (OR) and highest mean area under the curve (AUC) (Boria et al., 2017). The performance metrics of the model (AUC and OR) were calculated using the *ENMeval* package (Muscarella et al., 2014). The potential continuous distributions of each species were then converted into a binary vector (climatically suitable and unsuitable areas) by applying a threshold that excludes 10% of the occurrence points with the lowest environmental suitability values (Barros et al., 2012; Liu et al., 2005). We projected the models only in the study area and constructed maps of potential distribution in the current scenario with the occurrence points of each species in the Atlantic Forest biome (Figure S1). Finally, to identify species with restricted and wide distributions, we calculated the climatically suitable area for each species using the terra package (Hijmans et al., 2022) and organized all species in ascending order of their distribution areas (Figure S1).

2.6 Removal of Overprediction

The ENMs project areas as climatically suitable even when they are inaccessible, leading to an overestimation. To correct this, we generated a minimum convex polygon around all filtered occurrence records for the study area and used this polygon to adjust the binary models. As a result, the resulting maps were plotted without overprediction, excluding potentially inaccessible areas (Soberon and Peterson, 2005). We did not apply buffers to these maps, as the low dispersal capacity of palms would not affect the pixel size in the map of each species (Blach-Overgaard et al., 2010; Carrete et al., 2022; Tella et al., 2020).

2.7 Data Analysis

We calculated alpha diversity (species richness) by summing binary maps of the species for the current climate scenario using the “rast.sr” function from the R package *phyloraster* (Alves-Ferreira et al., 2024). To evaluate the influence of functional traits on the distribution area, we applied Phylogenetic Generalized Least Squares (PGLS) regression models, incorporating the species phylogeny to account for phylogenetic autocorrelation, as phylogenetically closer species tend to share a common evolutionary history and, therefore, exhibit similar traits (Ibanez et al., 2016; Losos, 2008). The phylogeny used was based on the maximum credibility tree calculated by the “maxCladeCred” function from the R package *phangorn* (Schliep, 2011), derived from the 1000 constraint trees of palm phylogeny at the species level from Faurby et al. (2017). We trimmed the tree to include only the 63 species in our study and added missing species using the “phylo.maker” function from the R package *V.PhyloMaker2* (Jin and Quian, 2022). The resulting tree is available in Newick format and can be viewed in Figure S2.

We evaluated the collinearity among predictor variables (Habitat, maximum stem length, maximum stem diameter, average fruit length, and average fruit width) using the "vif.cor" function from the R package *usdm* (Naimi et al., 2014) with a threshold of 0.5. We opted to retain the average fruit width variable, as it has greater biological relevance compared to fruit length; frugivore consumption selection is limited by fruit width, not length. Thus, the remaining variables for the PGLS analyses were: Habitat, maximum stem length, and average fruit width.

We assessed which additive effects among predictor variables explained the potential geographical distribution area of palm species by constructing a global model including all predictor variables using the function “pgls” from the R package *caper* (Orme et al., 2023). We used the “dredge” function from the R package *MuMIn* (Barton, 2024), which built 8 models with different combinations of predictor variables (Table S3). The models were evaluated based on the Akaike Information Criterion (AIC), and we selected the best models based on the lowest AIC and ΔAIC <2 compared to the next best model. We checked the constant variance and normality of the model residuals through visual inspection and normality testing. All analyses were performed in R (R Core Team, 2024).

3. Results

3.1 Ecological and functional overview of palm species

Of the 63 palm species analyzed, 28 were classified as forest-interior species, and 35 as open-area species. These species were distributed across 15 genera within the palm family. Regarding fruit size, 47 species (approximately 75%) produce small fruits (length < 4 cm), while the remaining 16 species (about 25%) produce large fruits (length ≥ 4 cm) (Kissling et al., 2019; Onstein et al., 2017). The average fruit length was 2.96 cm (±2.30 cm), ranging from 0.6 to 12.5 cm, while the average fruit width was 2.12 cm (±1.28 cm), with a range of 0.55 to 6 cm. Regarding the stem, the average height was 10.26 m (±9.55 m), with a range from 0 to 40 m, and the average diameter was 19.55 cm (±17.01 cm), varying from 0 to 66 cm.

3.2 General ENM Patterns

The ecological niche models were well fitted for most species, with mean Area Under the Curve (AUC) values ranging from 0.7 to 0.98. Models for 14 species showed moderate fits, with AUC values between 0.5 to 0.66. The average AUC value was 0.86, while the average Omission Rate (OR) was 0.18, ranging from 0 to 0.5.

3.3 Richness Pattern

Palm species richness varied from 0 to 34 species, with highest values observed along the northeastern coast and parts of the southeastern region of Brazil (Figure 2). We also observed intermediate species richness across most of the Atlantic Forest, in contrast to the interior regions of the biome near the Caatinga, which showed no species richness (n=0; Figure 2).

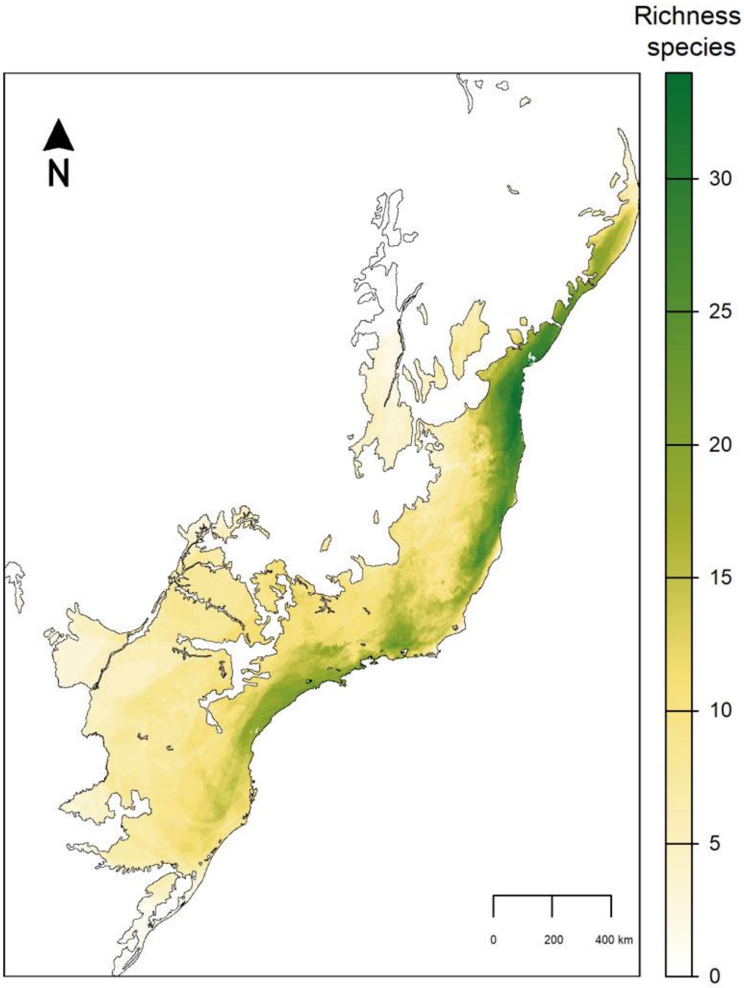

Figure 2: Map illustrating palm species richness across the Atlantic Forest. The green coloration indicates regions with higher species richness, transitioning to lighter shades of yellow in areas with fewer species. White regions represent areas where no palm species are present.

3.4 Distribution Patterns

The maps of potential distribution areas show distinct patterns among palm species (Figure S1). Species such as *Syagrus insignis*, *Attalea apoda*, and *Butia yatay* exhibited the smallest potential distribution areas, with 4,932 km², 7,791 km², and 8,204 km², respectively (Figures 3a-c). In contrast, *Roystonea oleracea*, *Euterpe edulis*, and *Syagrus romanzoffiana* presented the largest potential distribution areas, covering most of the biome, with 703,338 km², 1,033,146 km², and 1,241,571 km², respectively (Figures 3d-f). Notably, half of the palm species had potential distribution areas below 100,000 km² (Figure S1).

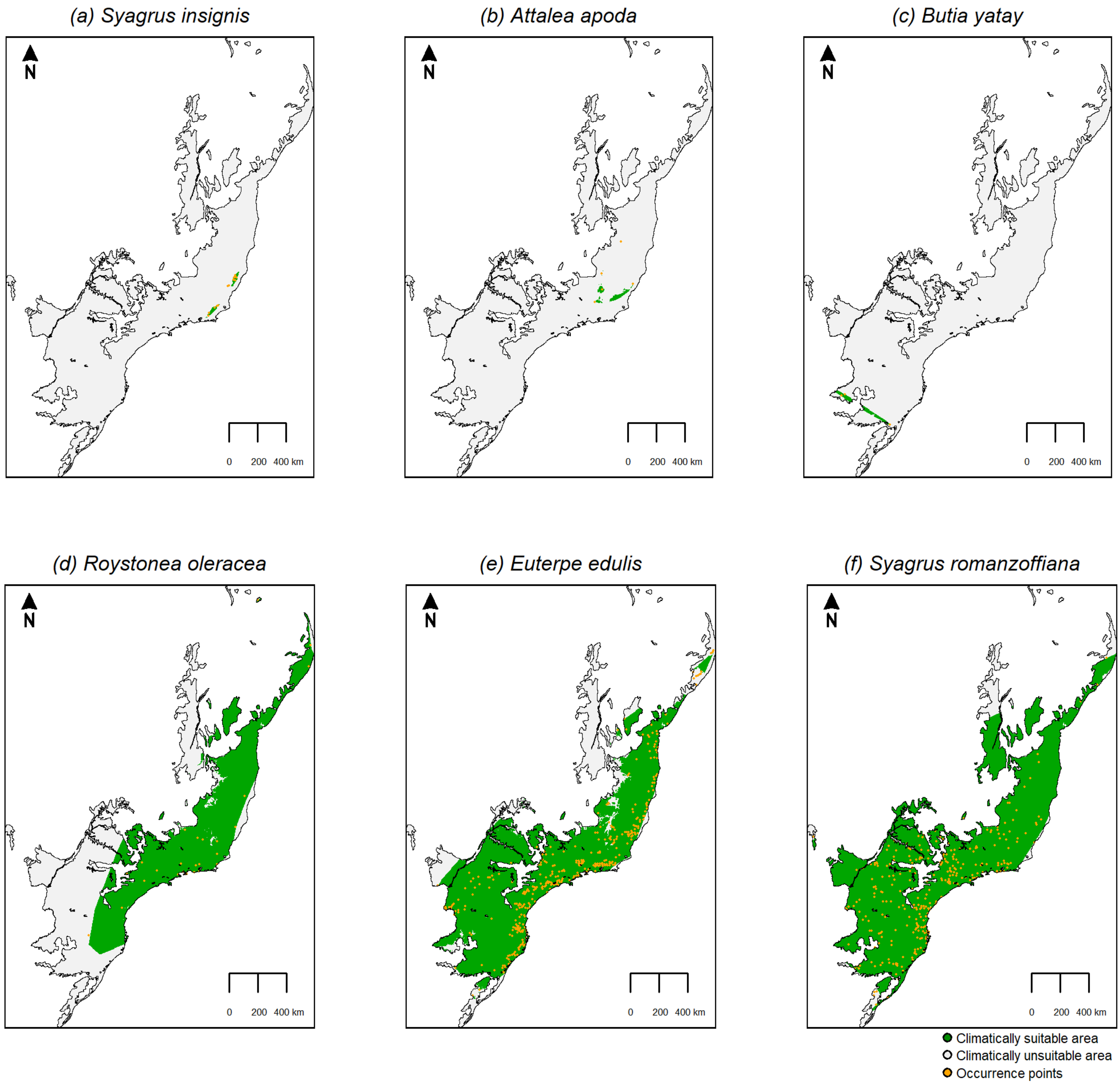

Figure 3: Current potential distribution maps for the three most range-restricted species and the three most widely distributed species, along with their occurrence points in the Brazilian Atlantic Forest. The green area indicates the climatically suitable area in the current climate scenario for the palm species, the white area indicates the climatically unsuitable area, and the orange points indicate the cleaned occurrence points.

3.5 PGLS Analysis

The PGLS analysis indicated that maximum stem height and average fruit width are the most important variables explaining the potential distribution of Atlantic Forest palms. The model with the lowest AICc included only maximum stem height (weight = 0.278), which showed a significant effect (SE = 0.25; t-value = 2.35; F-value = 5.53; p-value = 0.0219; Adj

R^2 = 0.068) (Figure 4). A second model, with the lowest AIC and ΔAIC < 2, included only average fruit width (weight = 0.243), also demonstrating a significant effect (SE = 0.59; t-value = 2.29; F-value = 5.24; p-value = 0.0254; Adj R^2 = 0.064) (Figure 4). Thus, these findings indicate that species with greater maximum stem height and larger average fruit width tend to occupy larger potential distribution areas than species with smaller stem heights and fruits.

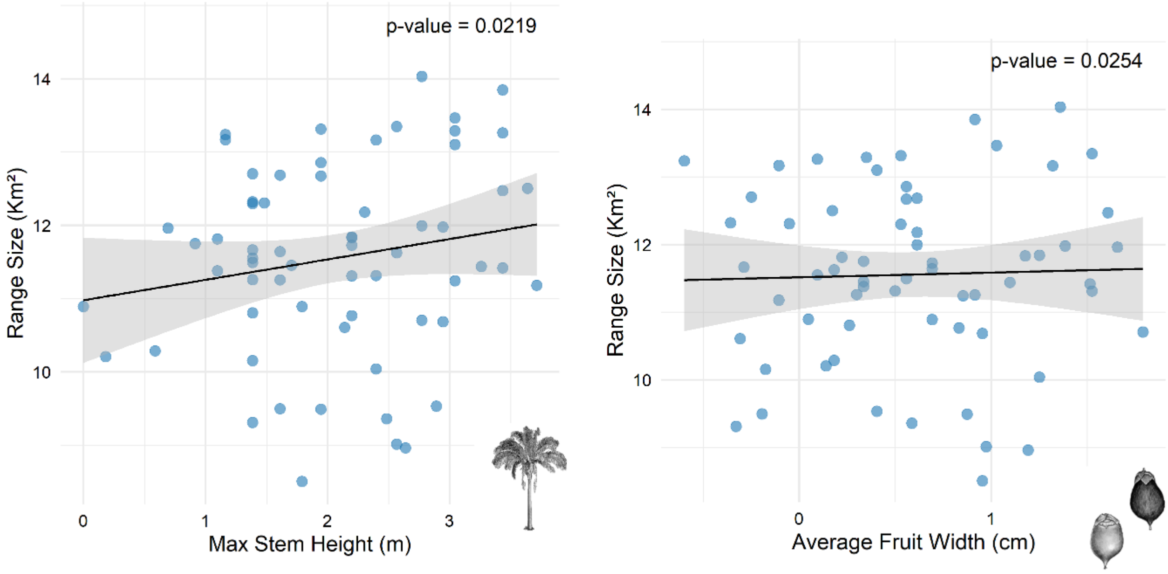

Figure 4: Effect of maximum stem height and average fruit width on the potential distribution area of Atlantic Forest palms. Each point represents one of the 63 palm species in the Atlantic Forest. The regression lines (in black) were inferred using phylogenetic generalized least squares (PGLS) models, and the shaded areas indicate the standard error around the estimates. All variables (range size, max stem height, and average fruit width) were log-transformed. The fruit and palm illustrations used in the graphs were sourced from Elias et al., 2018.

4. Discussion

Our study reveals a significant variation in the potential distribution of palm species in the Atlantic Forest, highlighting distinct patterns among them. We observed that species traits, such as larger stems and fruits, are associated with broader distribution areas, while smaller stems and fruits are linked to more restricted ranges. This variation reflects the multifaceted factors shaping species distributions and underscores the importance of integrating trait-based approaches into conservation planning. Considering both widely distributed and restricted species, along with their functional traits, is crucial not only for addressing conservation challenges but also for deepening our understanding of species distributions.

4.1 Richness and Distribution of the palm family in the Atlantic Forest

We identified regions with the highest palm richness, such as the northeastern and southeastern coasts of Brazil, which are known to be among the global centers of plant diversity (Barthlott et al., 2005). In these areas, the richness of palm species exceeds 30, aligning with the continental patterns of palms described by Bjorholm et al. (2005) and the distribution found for woody plants of the Atlantic Forest (Zwiener et al., 2018). The southern part of Bahia, in particular, stands out in our study, exhibiting one of the highest palm diversities. This region is of significant conservation importance due to its high species richness and endemism, particularly among trees (Martini et al., 2007). As the Atlantic Forest is recognized as a biodiversity hotspot (Myers et al., 2000), identifying areas with high palm richness, such as those highlighted in this study, is crucial for prioritizing conservation efforts in regions of exceptional biodiversity.

The findings of our study indicate that areas with higher precipitation and humidity, such as the northeastern and southeastern coasts of Brazil, exhibit greater palm species richness, while drier regions, such as the transition between the Atlantic Forest and the Caatinga, show a drastic reduction in species richness. Climatic variables, mainly those associated with precipitation, play a central role in the distribution and diversity of palms in the Neotropics (Eiserhardt et al., 2011), with more humid areas favoring the development of more diverse plant communities. This trend is consistent with the results of Salm et al. (2007), who observed a gradual decrease in plant diversity as one moves inland and southward within the biome.

Our results reveal distinct distribution patterns among palm species, with some restricted to areas smaller than 10,000 km², while others are found throughout the entire biome. This variability in the distribution patterns of palms in the Atlantic Forest emphasizes the wide diversity in the size of suitable areas for each species. These differences may be attributed to historical constraints and the biogeographical context, including factors such as landscape homogeneity, climate, and the existence of dispersal barriers (Kreft et al., 2006), along with climatic and spatial constraints (Blach-Overgaard et al., 2010). Additionally, these differences may be related to the specific ecological and functional traits, as discussed below, which also contribute to these variations (Cássia-Silva et al., 2022).

We found that some palm species have very restricted potential distribution areas. Spatial limitation can increase species' vulnerability to extinction, as they are more exposed to the impacts of habitat loss and environmental changes (Gaston and Fuller, 2009). Most declining species will experience reduced distribution areas before facing extinction, making range size an important indicator of species threat (Leão et al., 2020). For example, among our most restricted species, *Syagrus insignis*, with a distribution area of only 4,932 km², is considered threatened according to IUCN criteria (IUCN, 2022).

We also found that the species *Attalea apoda, Butia yatay, Geonoma fiscellaria, Syagrus lorenzoniorum, Bactris horridispatha, Geonoma wittigiana*, and *Syagrus ruschiana* have distribution areas ranging from 5,000 km² to 20,000 km². According to IUCN criteria, species within this distribution range are eligible for classification as Vulnerable (VU). However, only *Bactris horridispatha*, with a potential distribution area of 13,229 km² in our projections, is classified as Vulnerable (VU) by the IUCN. This species, found in the coastal forests of Bahia, faces significant threats due to habitat conversion (Loftus, 2013). In contrast, *Syagrus ruschiana*, with 13,792 km² in our projection, is listed under the IUCN's extinction risk status as Least Concern (LC). Considering the potential vulnerability of these species based on our distribution projections and the threats they face, including these species in the IUCN Red List as Vulnerable could help ensure better conservation efforts for them and highlight the need for more detailed assessments of their status in light of environmental pressures.

In contrast, species such as *Roystonea oleracea*, *Euterpe edulis*, and *Syagrus romanzoffiana* exhibit the largest potential distribution areas, all exceeding 700,000 km². This suggests that these species have a greater ecological amplitude or adaptability to a wide variety of environmental conditions within the biome. Specifically, *Euterpe edulis* stood out for its extensive geographical range, supporting the findings of Souza and Prevedello (2019), which highlighted its presence across broad latitudinal and altitudinal ranges.

4.2 Functional traits explaining the potential range size

In this study, we observed a positive relationship between stem height and species range size, supporting our initial expectations. This finding aligns with previous studies demonstrating a positive correlation between plant height and range size, where taller species tend to occupy larger distribution areas compared to shorter ones (Lavergne et al., 2004; Kolb et al., 2006). Furthermore, studies on Amazonian palms corroborate this pattern, emphasizing a positive correlation between species height and distribution ranges (Kristiansen et al., 2009; Ruokolainen et al., 2002). Indeed, taller plants exhibit greater seed dispersal efficiency and higher fruit production, which facilitates their ability to colonize new habitats and expand their geographic distribution (Thomson et al., 2011). Fruits released from greater heights travel longer distances before reaching the ground, increasing the potential dispersal range of seeds (Arellano et al., 2015; Kristiansen et al., 2009). This enhanced dispersal capacity promotes the colonization of new habitats, contributing to the expansion of distribution areas. Additionally, taller species have significant competitive advantages (Sporbert et al., 2021). Access to the upper canopy, where light availability is higher, minimizes restrictions on growth and reproduction (Falster and Westoby, 2003; Svenning, 2002). In other words, the greater height of plants from widely distributed species suggests that these species may have a competitive advantage in terms of space and light compared to species with more restricted distributions (Sporbert et al., 2021). As a result, these species produce more fruits, which, combined with efficient dispersal, increase their chances of establishment and reproductive success in new locations. Conversely, smaller species, limited by lower light availability in the understory, face competitive disadvantages that restrict their colonization and expansion capacity (Svenning, 2002). Moreover, smaller seeds from shorter species often have reduced survival and establishment rates (Moles and Westoby, 2006).

According to our hypothesis regarding the fruit width variable, our results indicate a positive relationship with species' distribution area. Plants with larger fruits, often dependent on large frugivores for seed dispersal (Jordano, 2000), exhibit greater dispersal capacity and, consequently, a more extensive geographic distribution compared to species with smaller fruits (Nathan, 2006; Jenkins et al., 2007). The dispersal distance also directly depends on seed size, as only large animals are capable of dispersing large seeds through endozoochory (de Almeida and Galetti, 2007; Andreazzi et al., 2012; Galetti et al., 2013), significantly expanding the distribution area of plants. Furthermore, seed and fruit size play a crucial role in plant establishment success, as larger seeds contain greater energy reserves, which enhance seedling survival under harsh conditions (Westoby et al., 1996). However, the ongoing defaunation process, particularly the decline of large frugivores (Galetti et al., 2013), may significantly impact these dynamics. As these animals play a crucial role in long-distance seed dispersal, their loss can limit plant recruitment and reduce the ability of species with large seeds to colonize new areas, potentially restricting their distribution range (Petrocelli et al., 2024). This process may help explain some of the inconsistencies reported in the literature regarding the relationship between traits and distribution size. While Guo et al. (2024) found a positive relationship between seed size and global distribution in exotic regions, others, like Murray (2002), reported weak correlations, and studies by Bemmels et al. (2018) and Petrocelli et al. (2024) even observed negative correlations for species with animal-mediated dispersal, likely due to the decline of large frugivores. These inconsistencies suggest that not only individual traits can fully explain distribution patterns; instead, combining multiple traits provides better predictions for ecological strategies and macroecological processes (Winemiller et al., 2015; Marino et al., 2020; Sporbert et al., 2021).

5. Conclusion

In conclusion, our study highlights regions of exceptional palm richness in the Atlantic Forest, emphasizing the importance of prioritizing conservation efforts in areas such as the northeastern and southeastern coasts of Brazil. The observed variability in the distribution patterns of palm species highlights the importance of recognizing species with restricted distribution areas, such as *Syagrus insignis*, *Attalea apoda, Butia yatay*, and others, which is crucial for mitigating the risks of extinction, especially in the face of ongoing habitat loss and environmental change. Finally, the identification of traits associated with the distribution size of palm species in the Atlantic Forest highlights the practical utility of these traits for conservation efforts, emphasizing the importance of prioritizing these traits in conservation strategies. This approach expands the applicability of our findings to other plant groups and generates new insights and concerns regarding the conservation of both species and their functional traits. These findings can be particularly valuable for identifying species with small distribution areas that require priority protection, especially in regions with high fragmentation and biodiversity loss, such as the Atlantic Forest.

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Author contributions:

Júlia Angeli: Conceptualization, Data Curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing. **Daniela Custódio Talora:** Conceptualization, Supervision, Validation, Writing - Review & Editing. **Neander Marcel Heming:** Formal analysis, Methodology, Software, Validation. **Eliana Cazetta:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - Review & Editing.

Conflict of interest

The authors declare no conflicts of interest.

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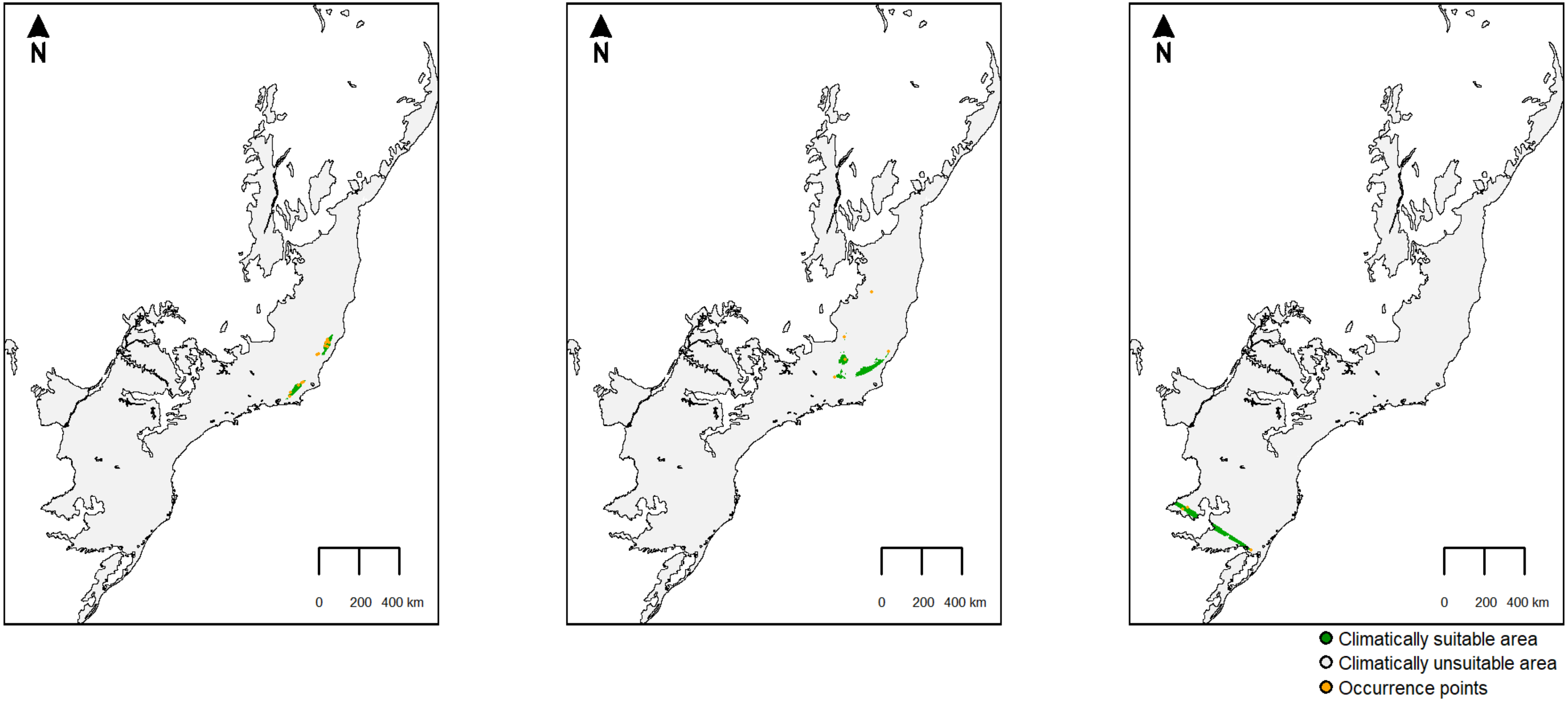
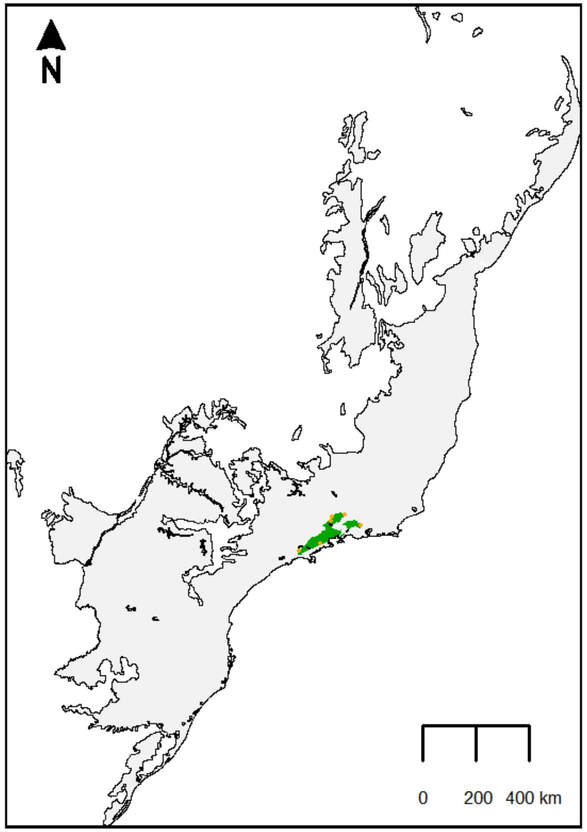
Supplementary material

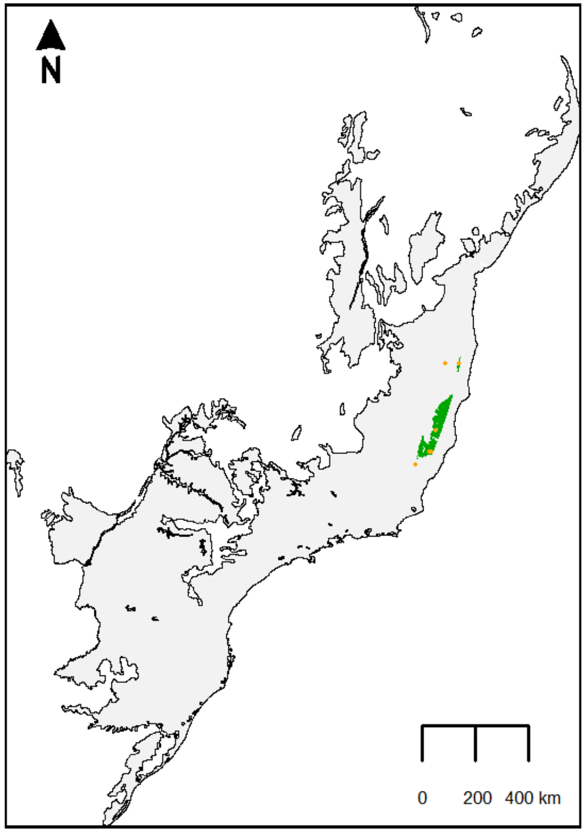
Figure S1: Current potential distribution maps for each species and their occurrence points in Brazilian Atlantic Forest.

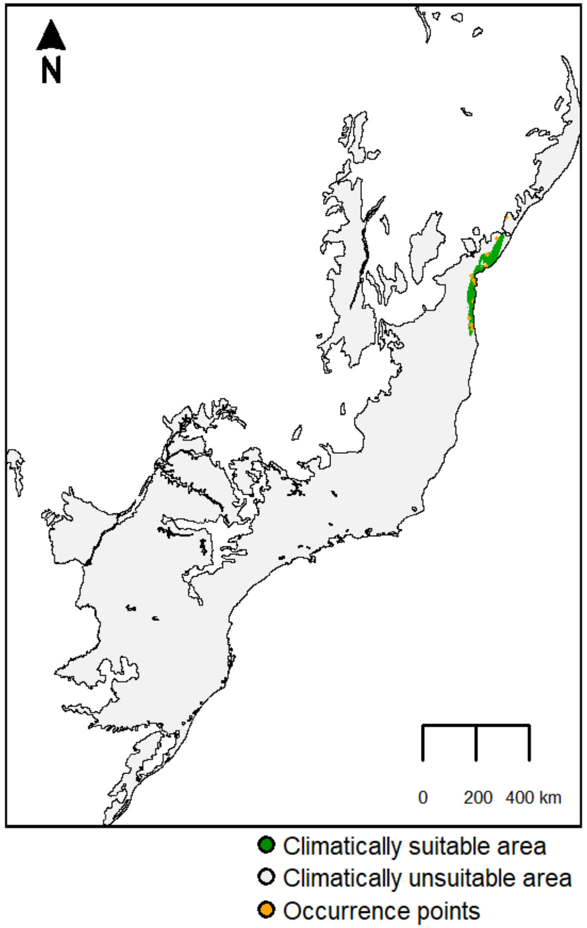
Syagrus insignis	*Attalea apoda*	*Butia yatay*
4932.416209 km²	7791.148884 km²	8203.891659 km²



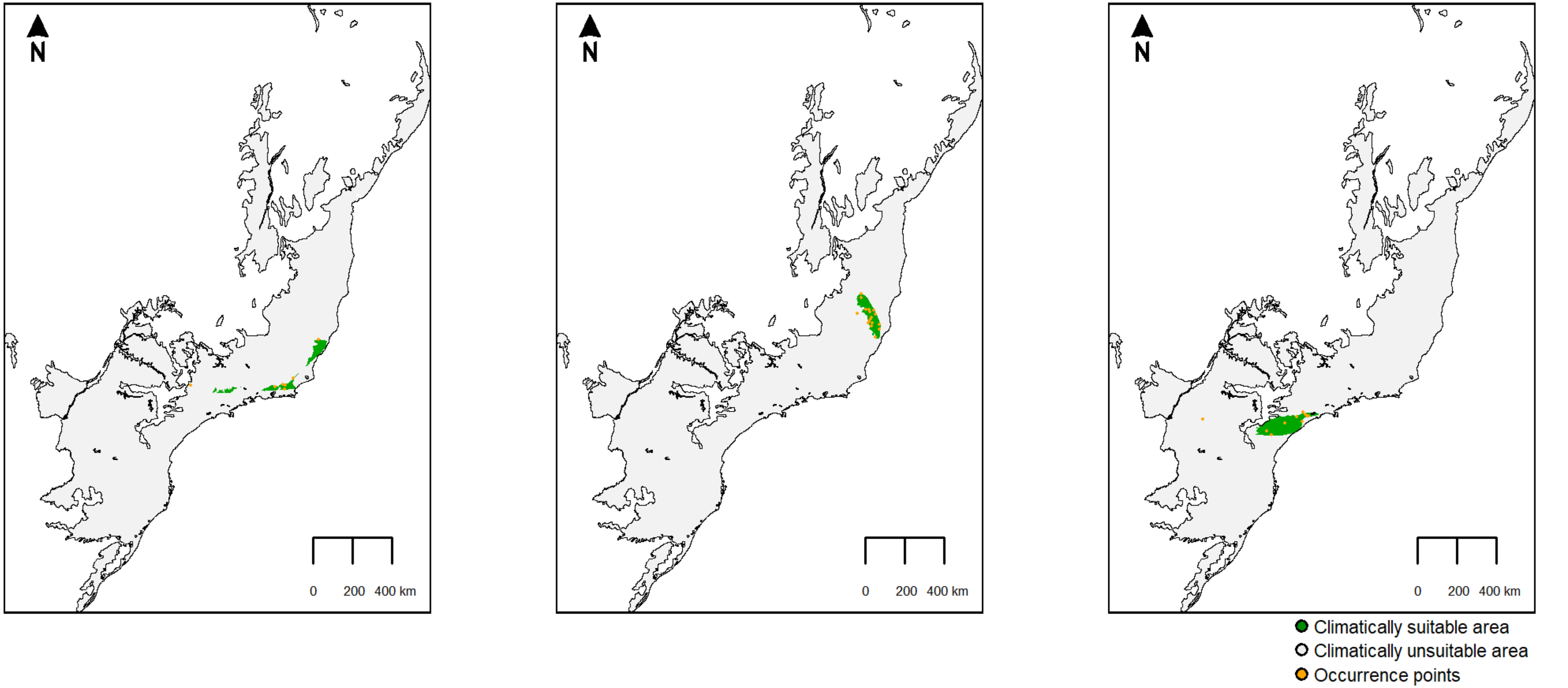
Geonoma fiscellaria	Syagrus lorenzoniorum	Bactris horridispatha
11052.65584 km²	11602.07101 km²	13229.84712 km²



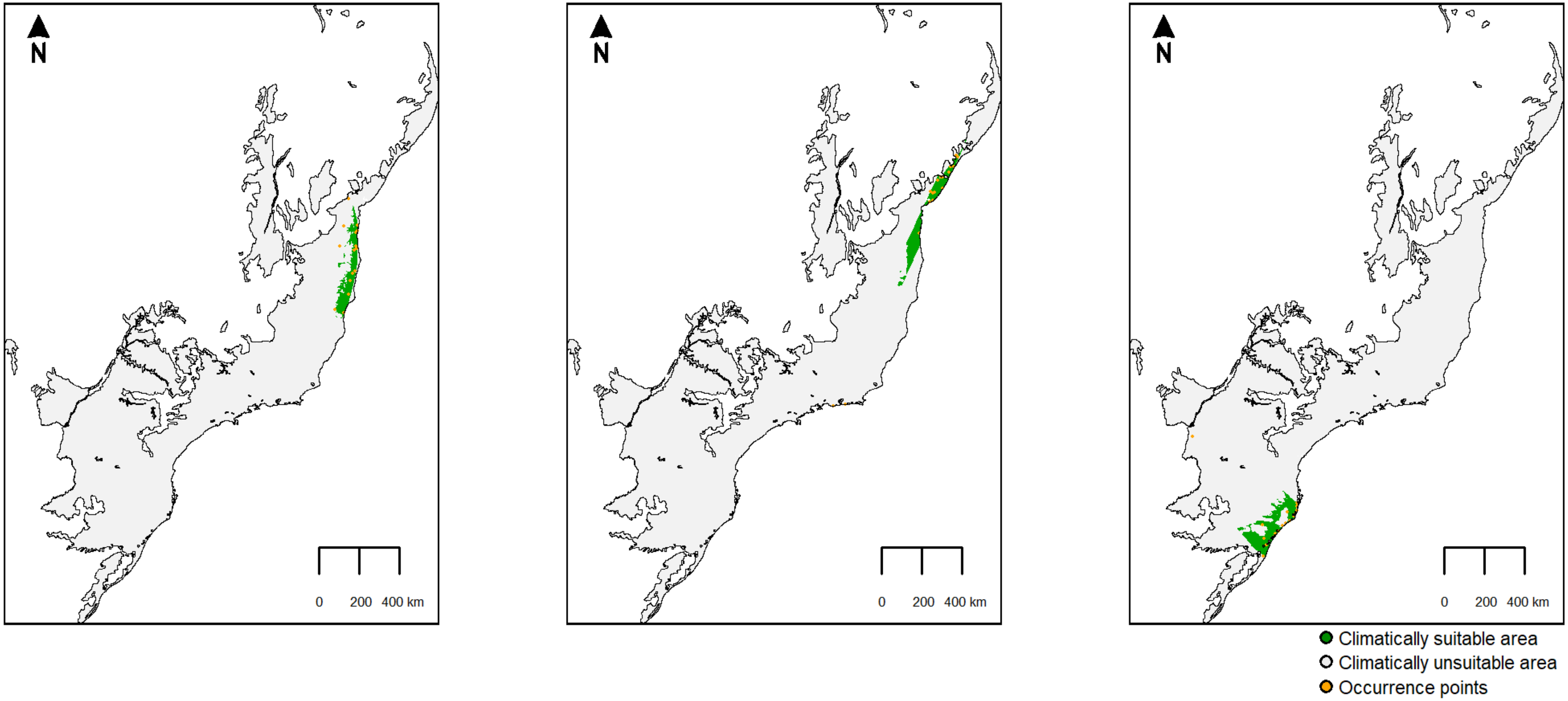




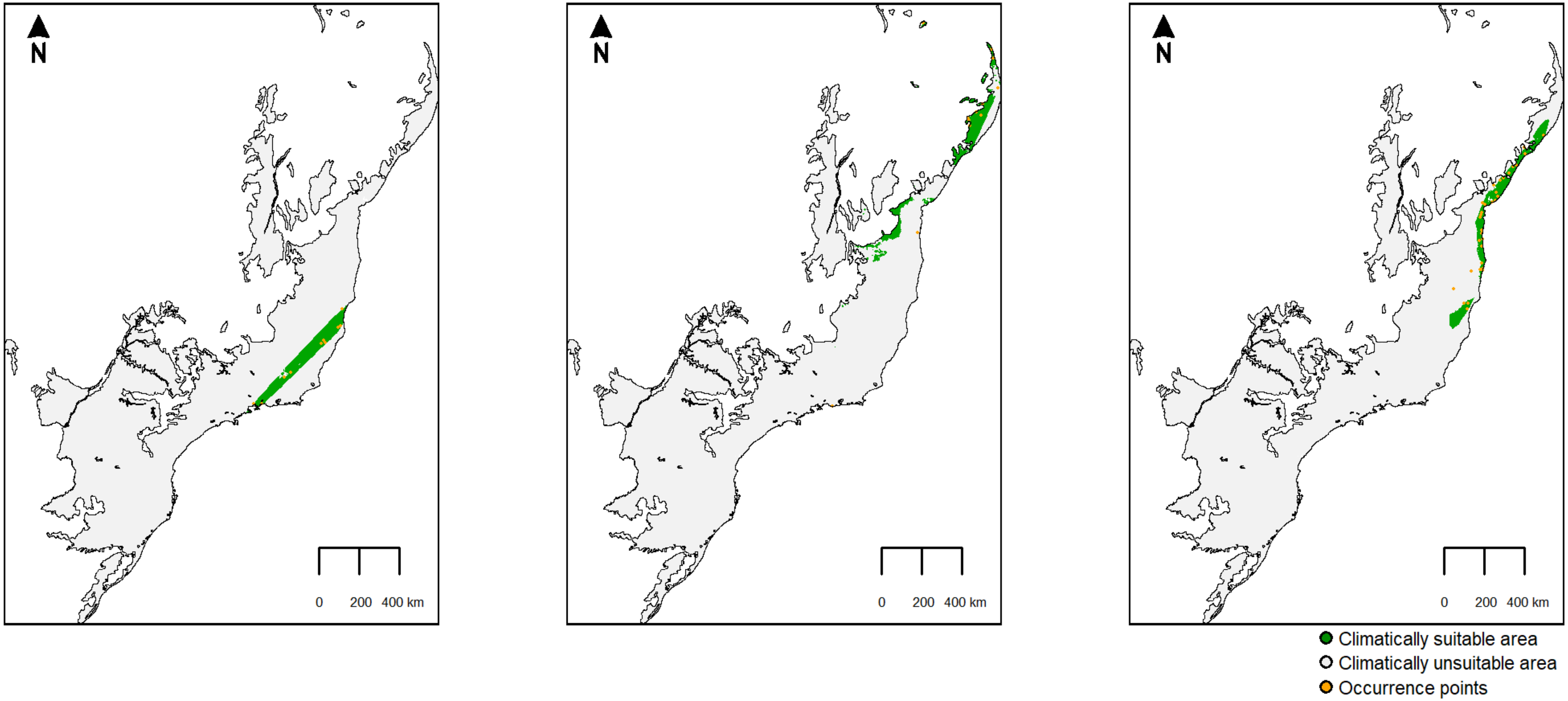
Geonoma wittigiana	*Syagrus ruschiana*	*Syagrus hoehnei*
13313.04498 km²	13792.89321 km²	22909.96415 km²



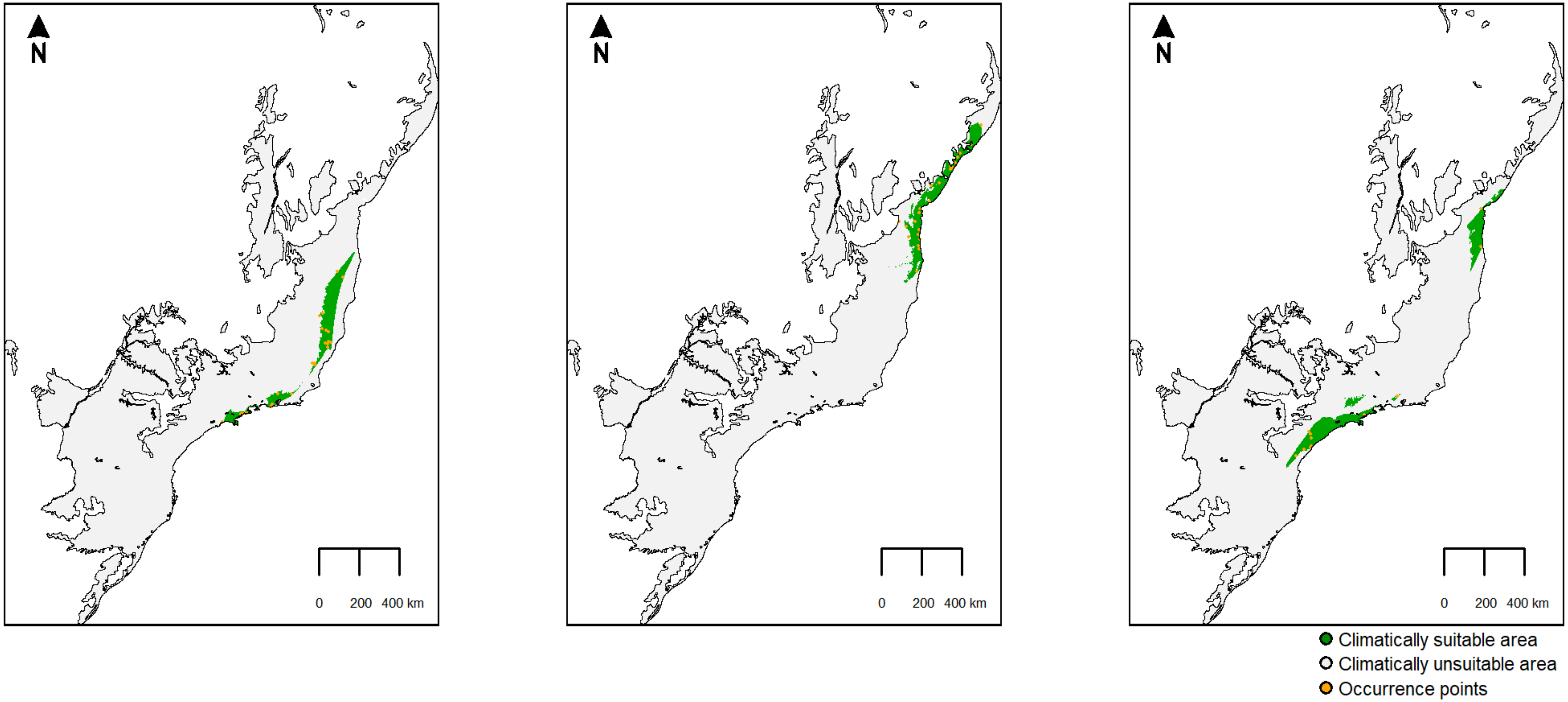
Geonoma rubescens	*Allagoptera brevicalyx*	*Butia catarinensis*
25672.84102 km²	27081.69807 km²	29306.10897 km²



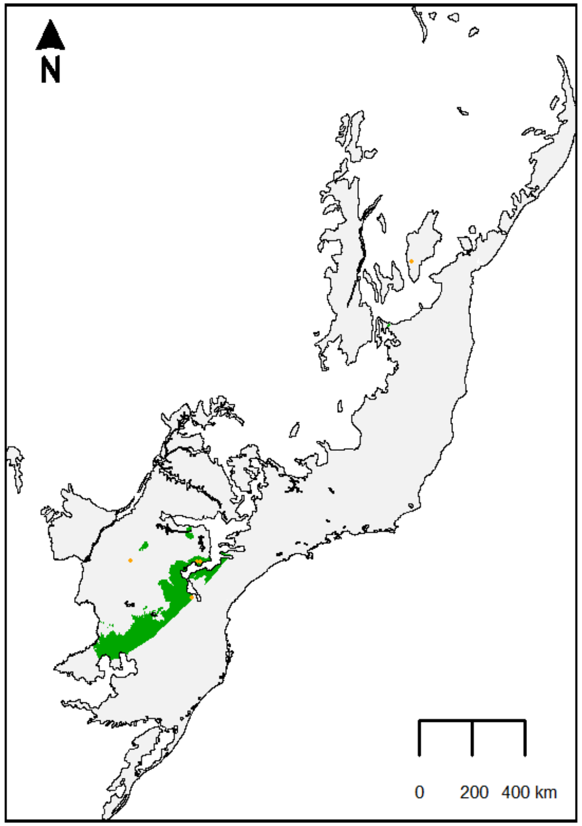
Geonoma rodeiensis	*Syagrus cearensis*	*Attalea funifera*
40392.04 km²	43731.24032 km²	44573.88844 km²

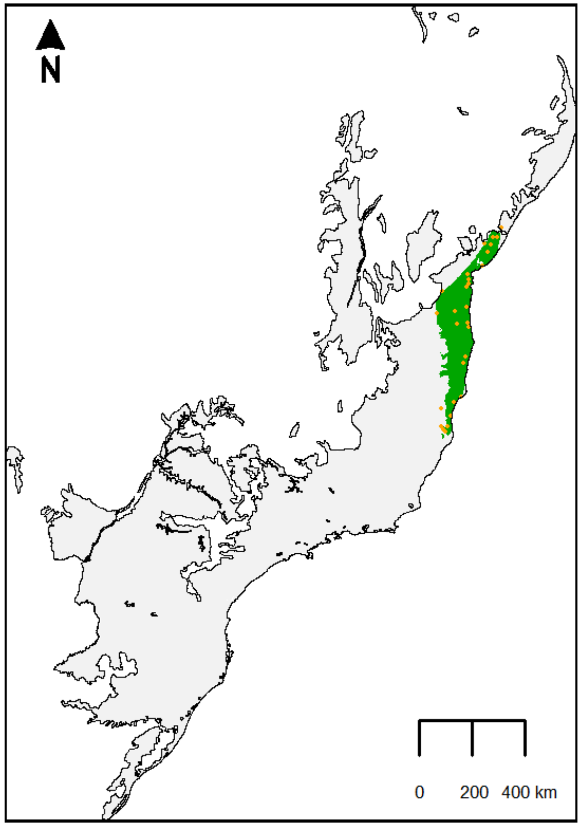


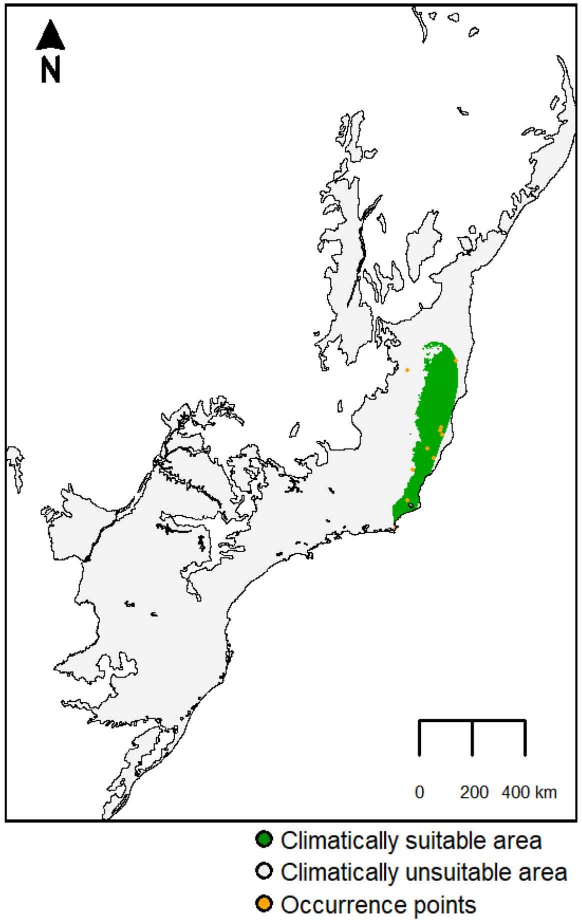
Syagrus pseudococos	*Bactris glassmanii*	*Bactris hatschbachii*
47431.53107 km²	49280.57774 km²	53721.99116 km²



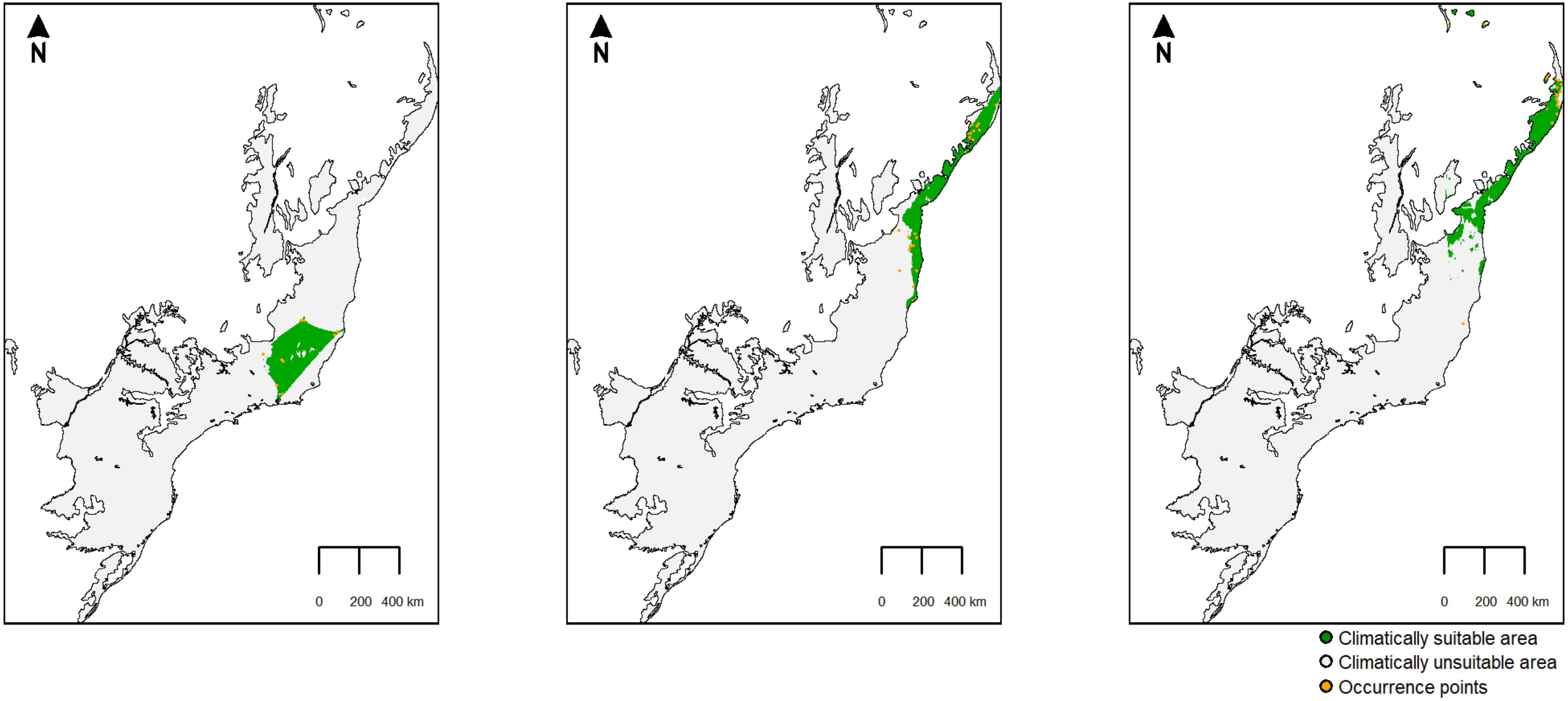
Butia microspadix	*Syagrus botryophora*	*Syagrus picrophylla*
53816.35483 km²	71598.26684 km²	76269.19606 km²



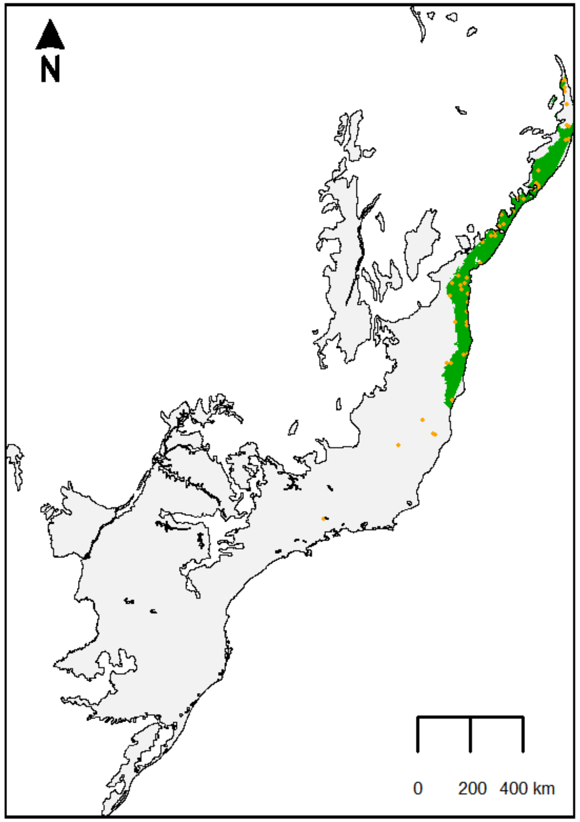


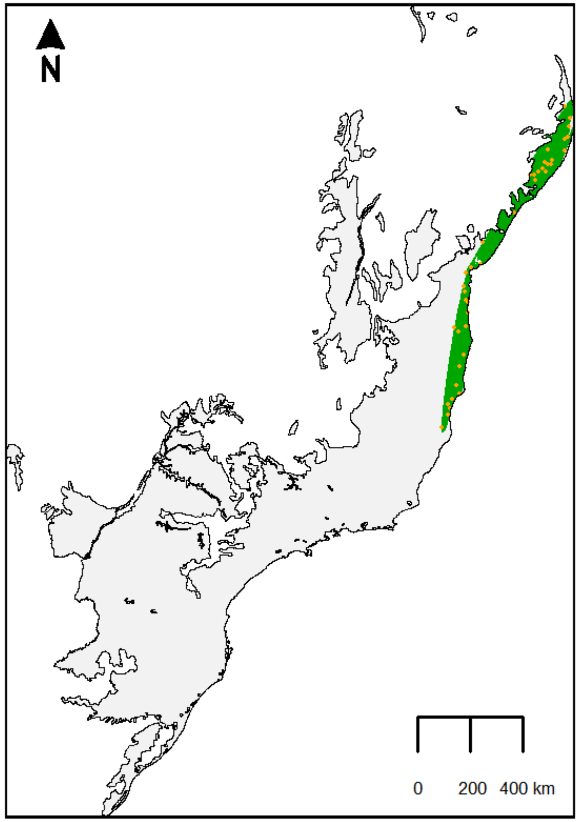


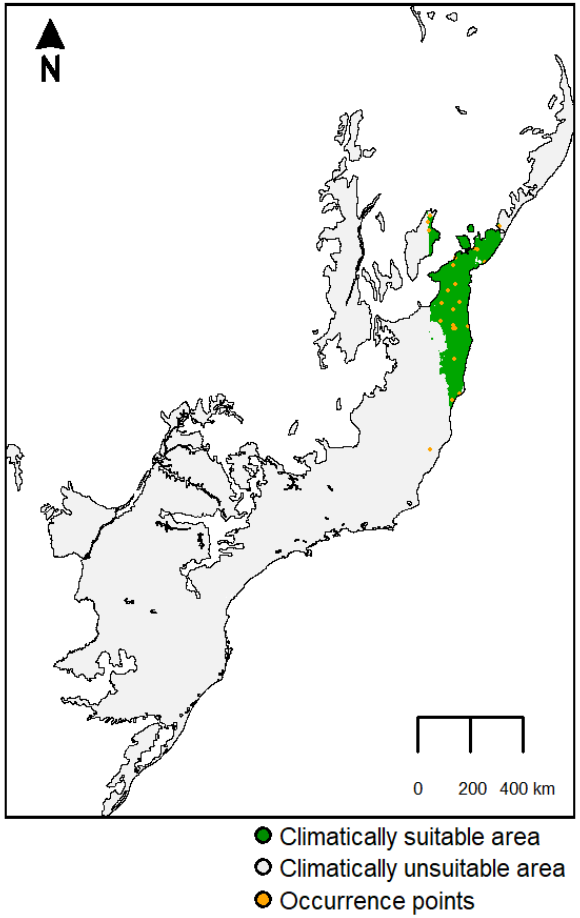
Syagrus macrocarpa	*Bactris pickelii*	*Acrocomia intumescens*
77094.83064 km²	77564.62808 km²	81536.90678 km²



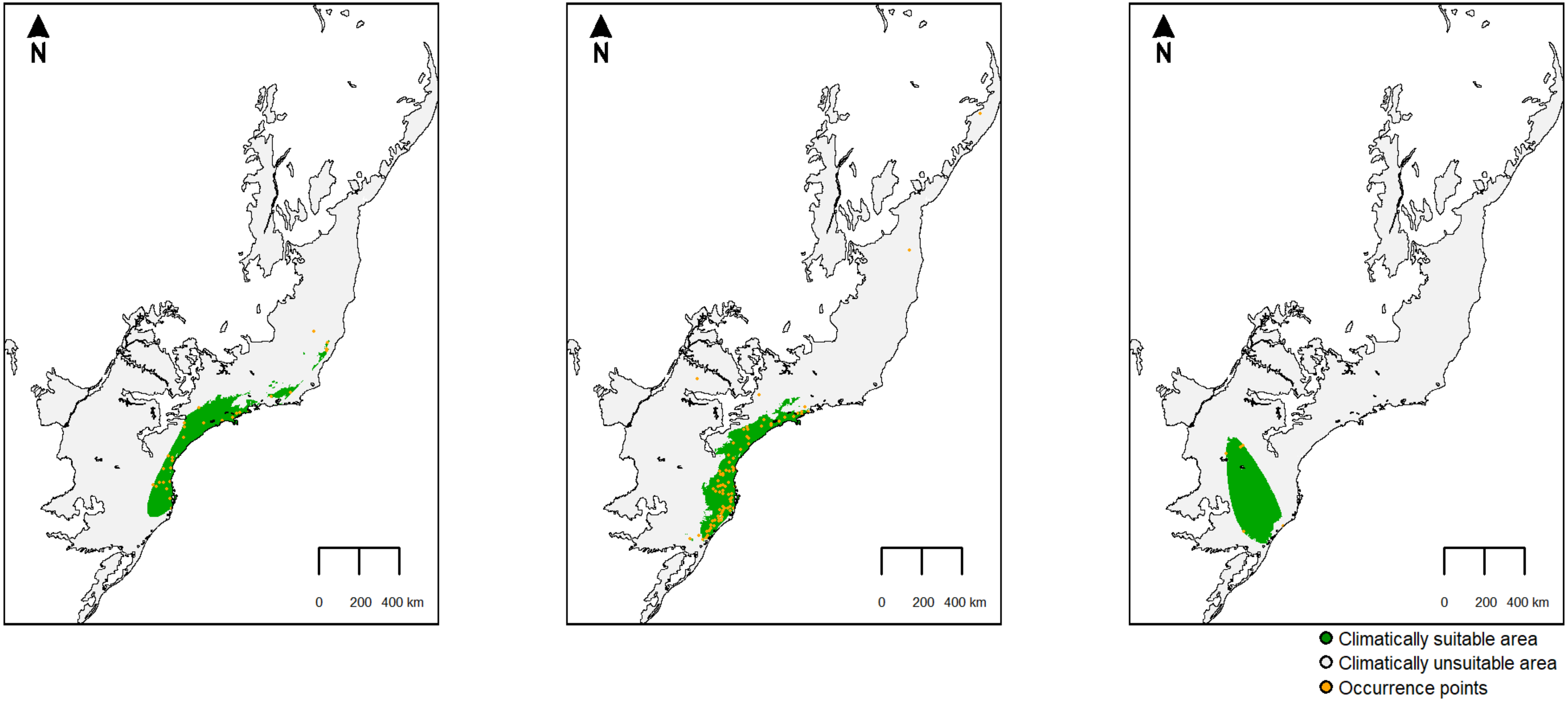
Bactris ferruginea	*Bactris acanthocarpa*	*Attalea burretiana*
81970.49901 km²	87366.95805 km²	91055.53201 km²



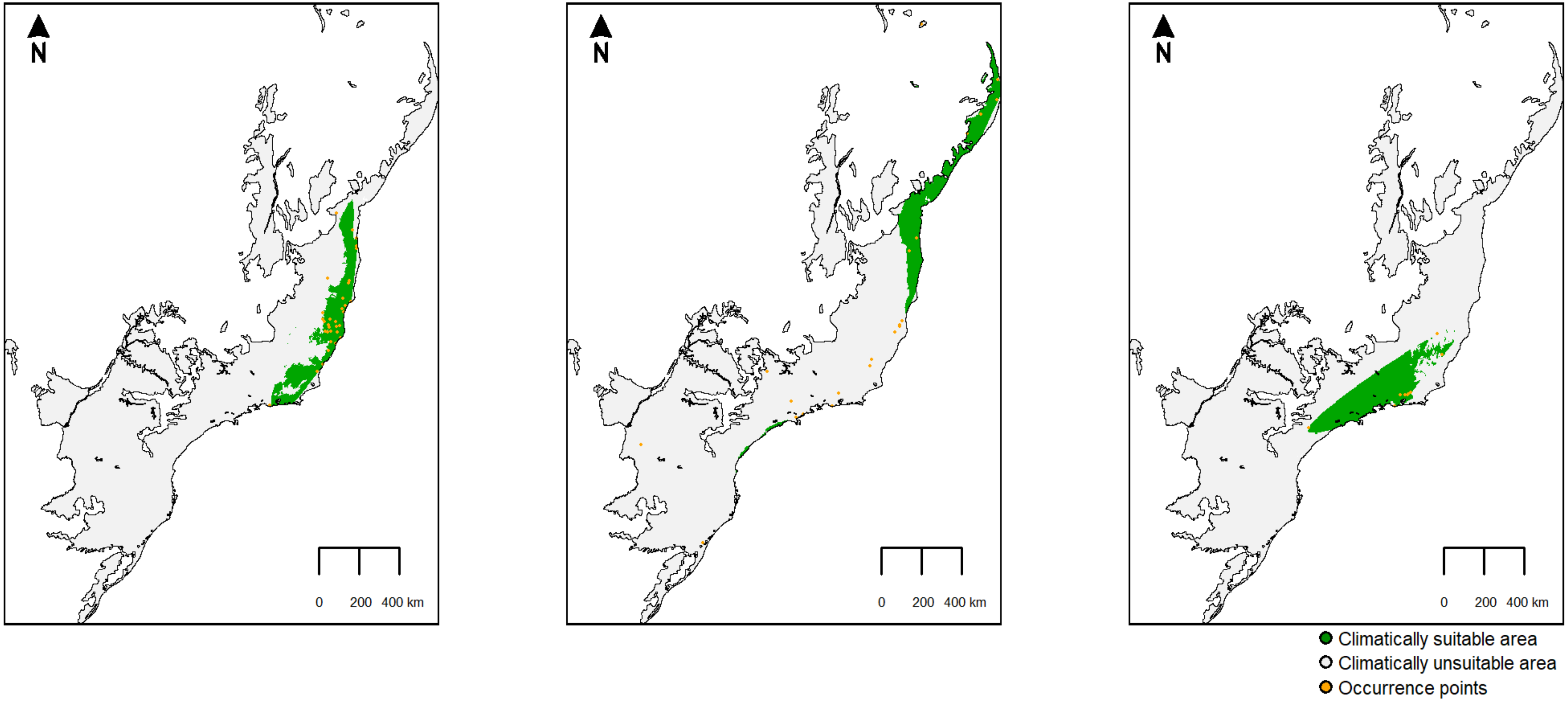




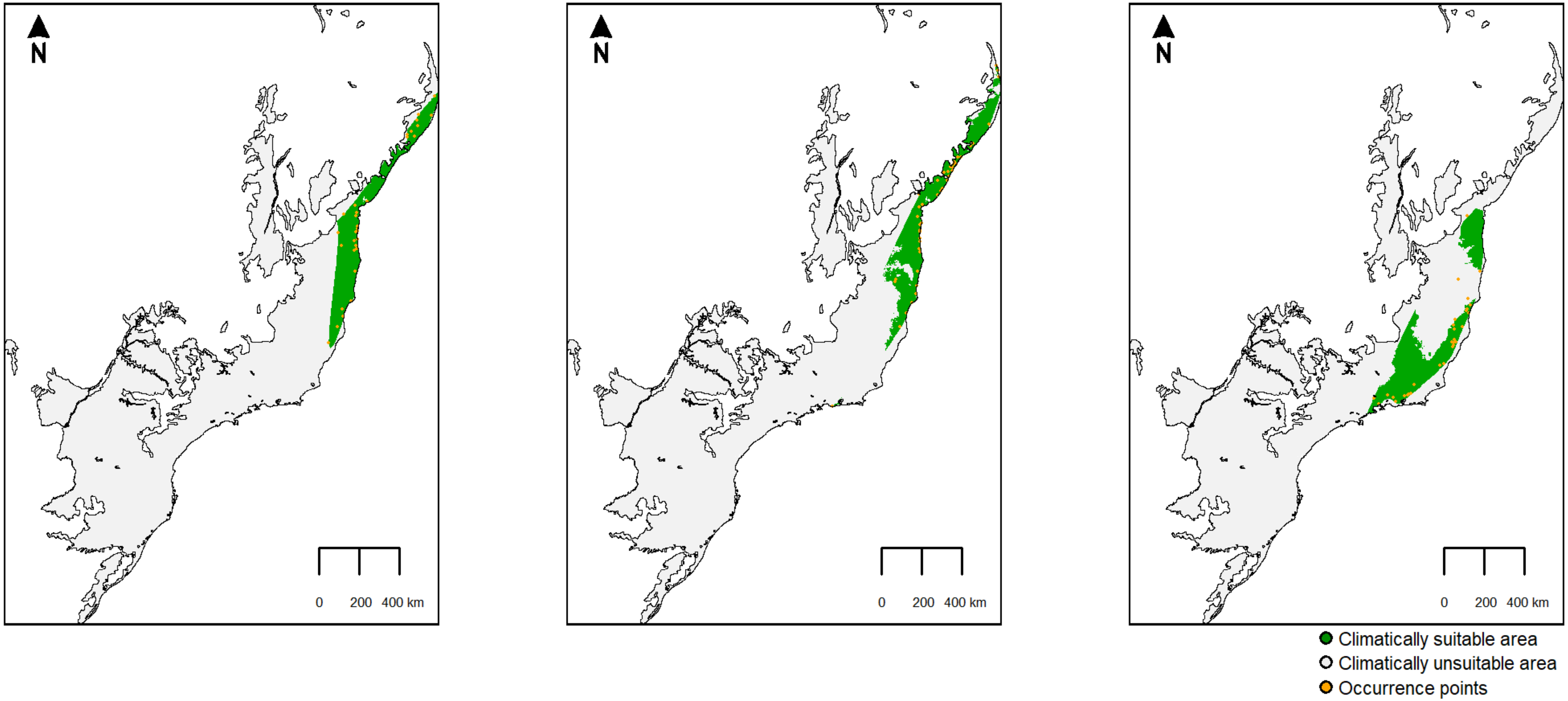
Attalea dubia	*Geonoma gamiova*	*Trithrinax acanthocoma*
92806.42278 km²	94198.56789 km²	98014.36731 km²



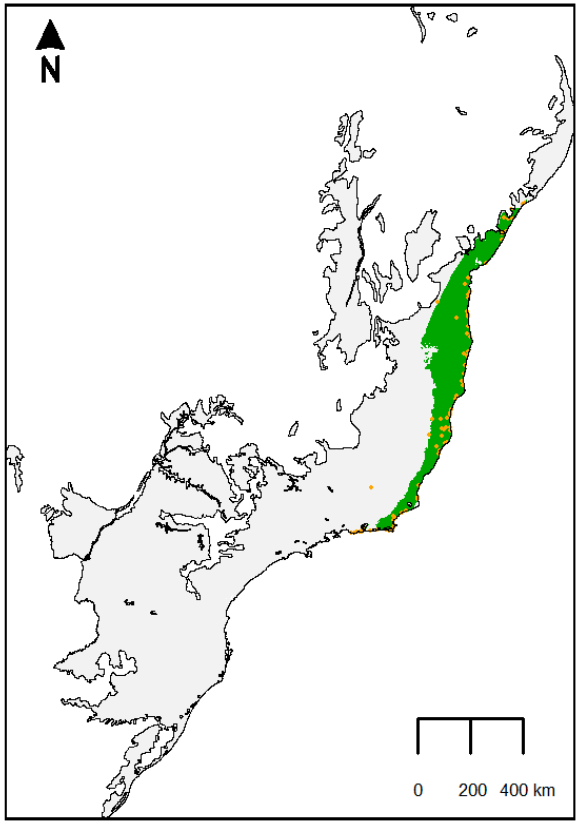
Bactris bahiensis	*Euterpe oleracea*	*Syagrus weddelliana*
103833.7659 km²	111985.5697 km²	113761.7503 km²

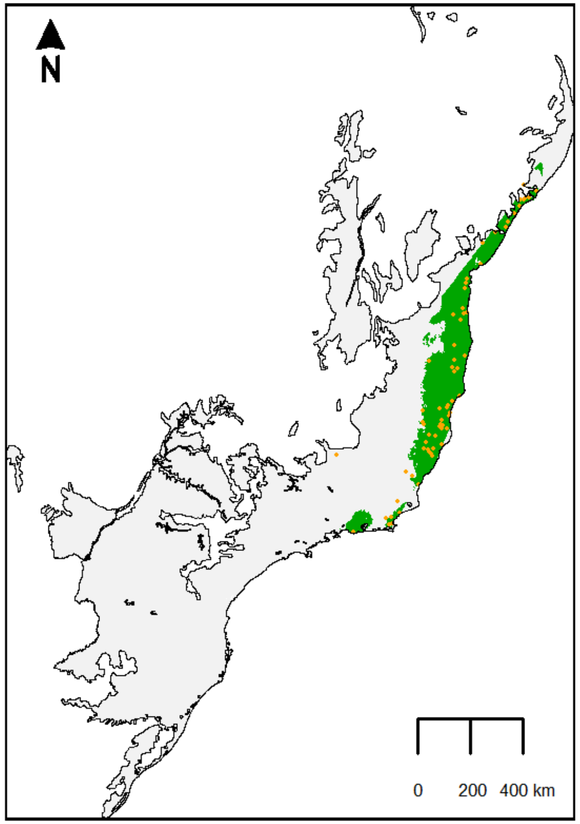


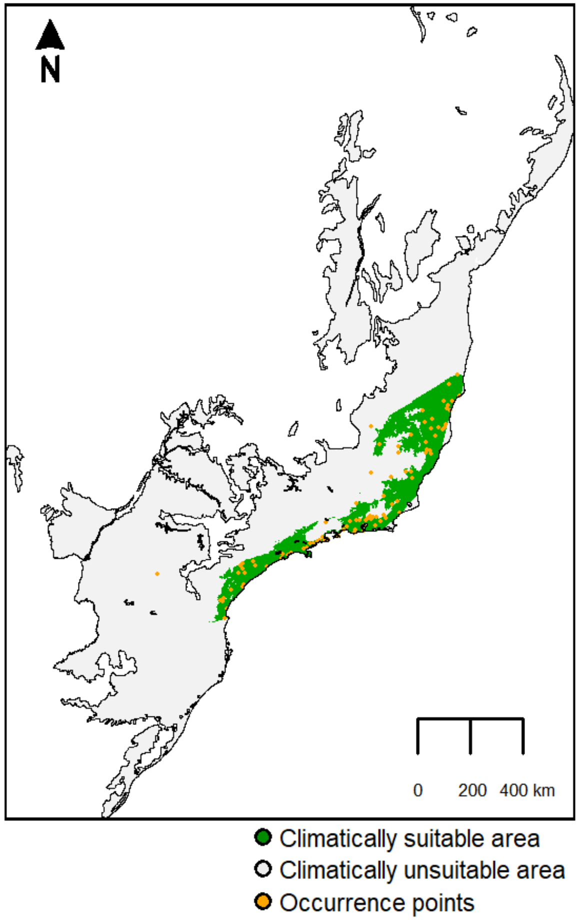
Bactris hirta	*Syagrus schizophylla*	*Bactris caryotifolia*
116486.4815 km²	123881.1614 km²	126679.8351 km²



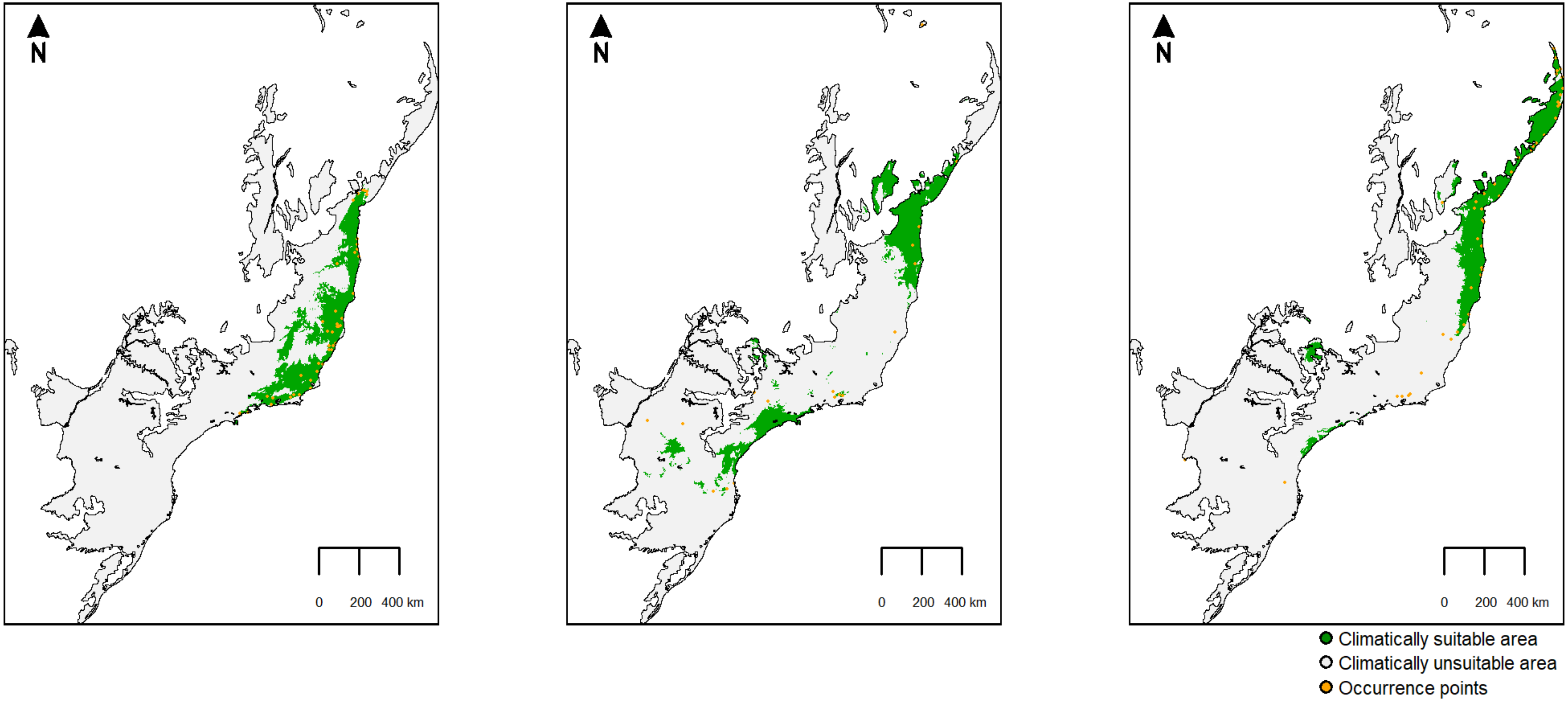
Allagoptera arenaria	*Allagoptera caudescens*	*Astrocaryum aculeatissimum*
134864.8439 km²	137637.8264 km²	138666.4368 km²



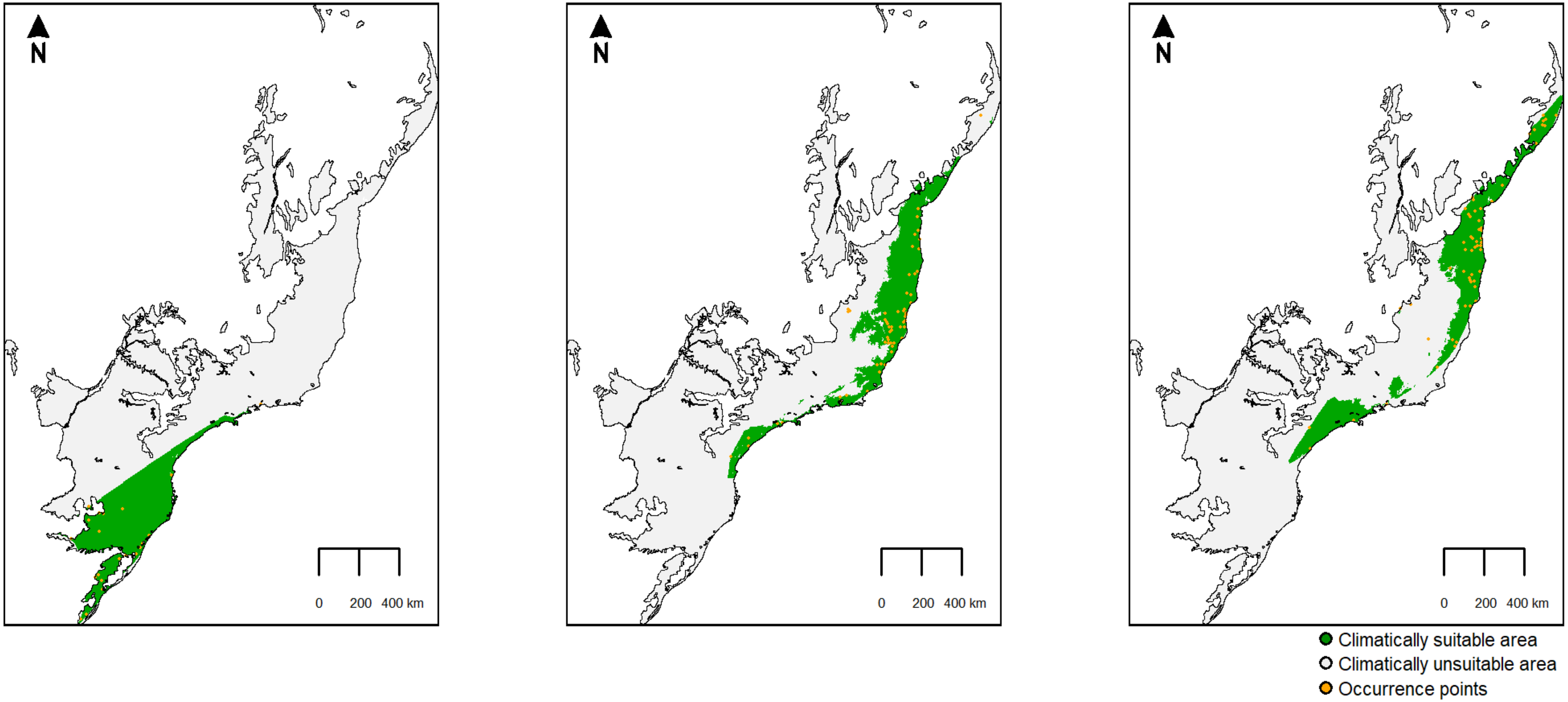




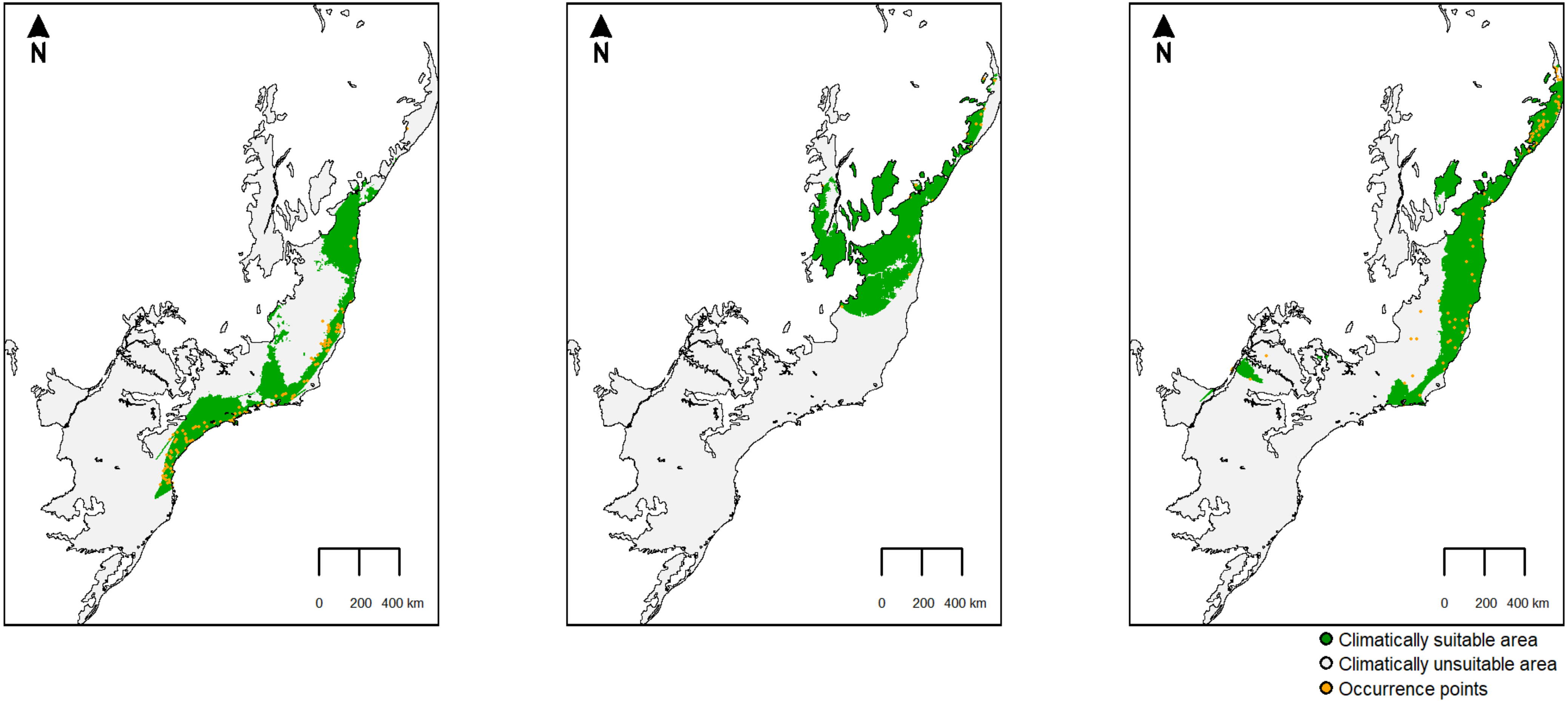
Attalea humilis	*Bactris gasipaes*	*Elaeis guineensis*
156718.1807 km²	159288.0847 km²	161817.8526 km²



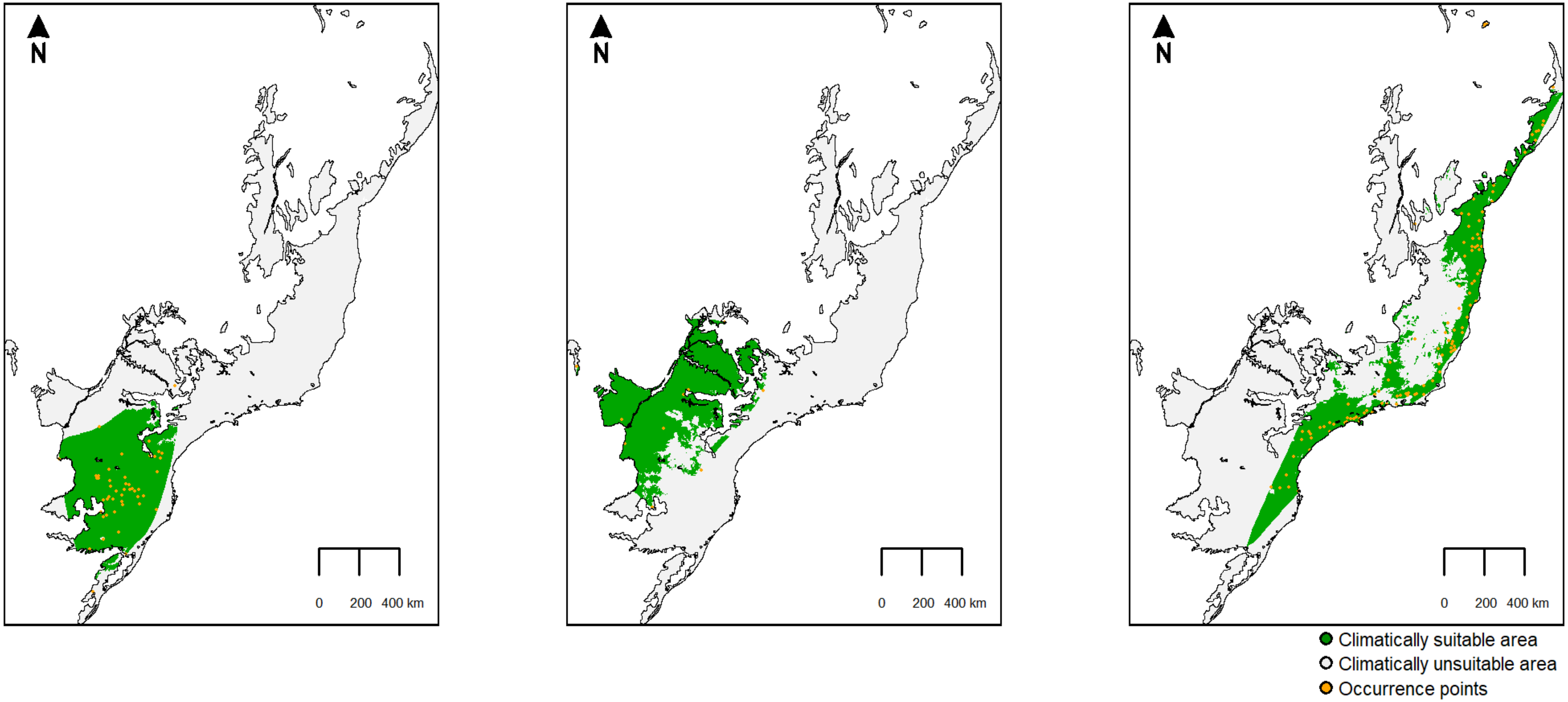
Butia odorata	*Bactris vulgaris*	*Geonoma pauciflora*
194818.9427 km²	219416.956 km²	221296.213 km²



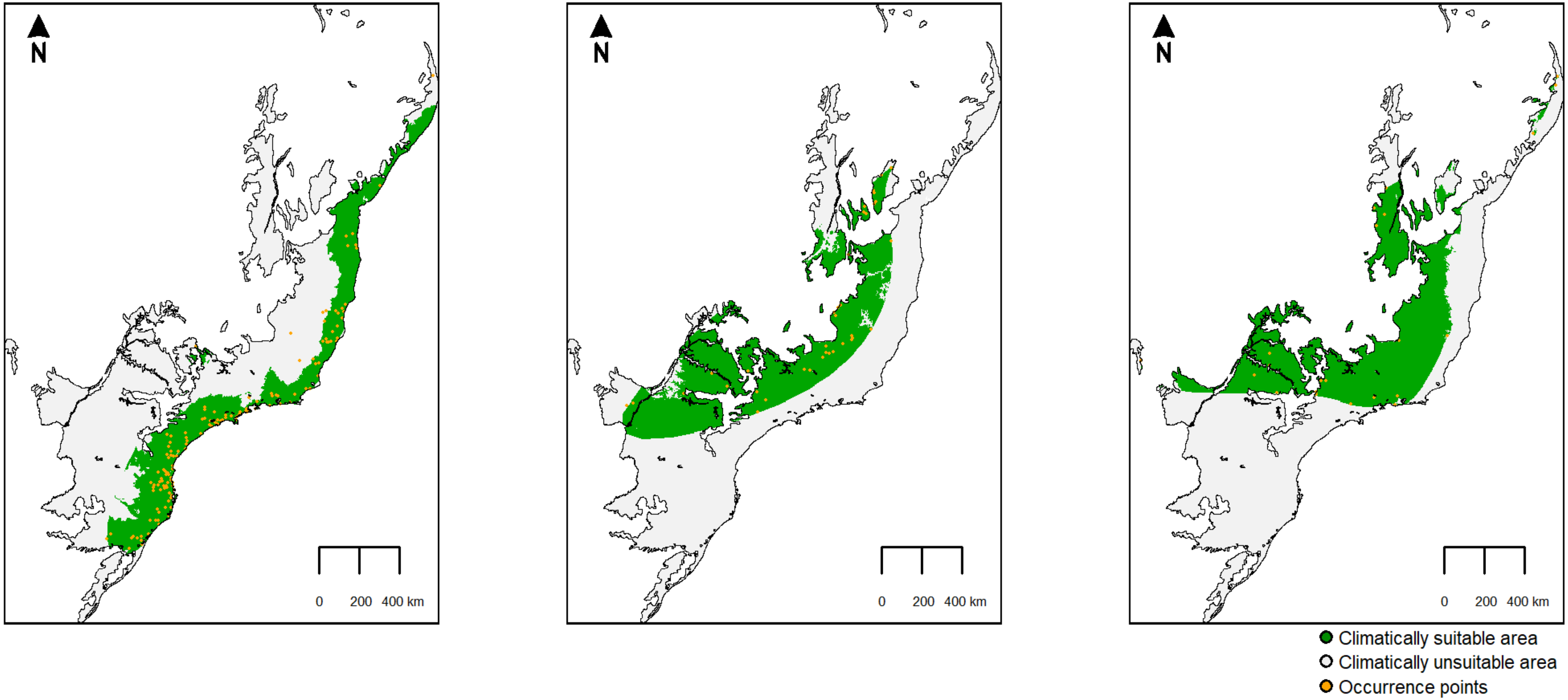
Geonoma elegans	*Attalea oleifera*	*Desmoncus polyacanthos*
224172.9989 km²	260768.1512 km²	269026.6758 km²



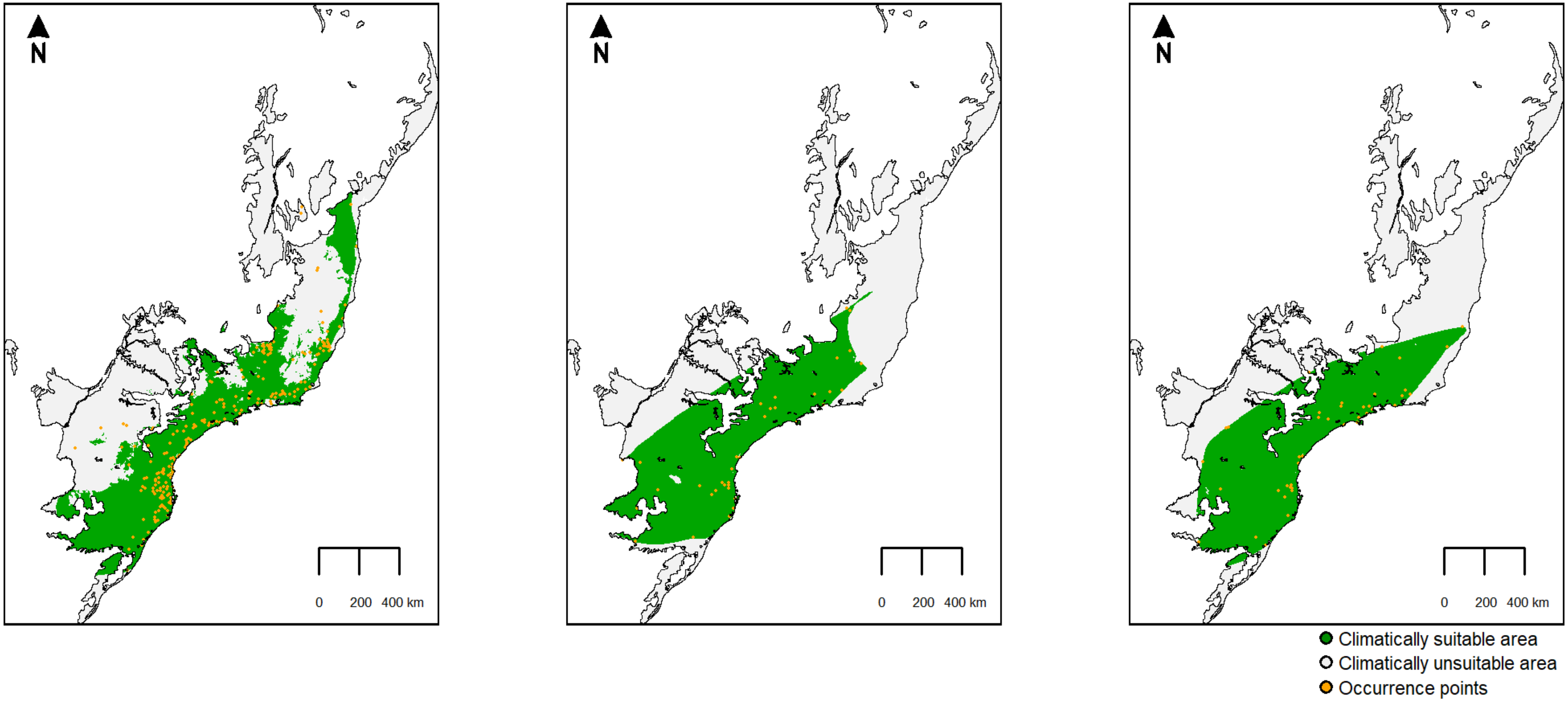
Butia eriospatha	*Butia paraguayensis*	*Geonoma pohliana*
318535.8366 km²	322198.369 km²	328926.2714 km²



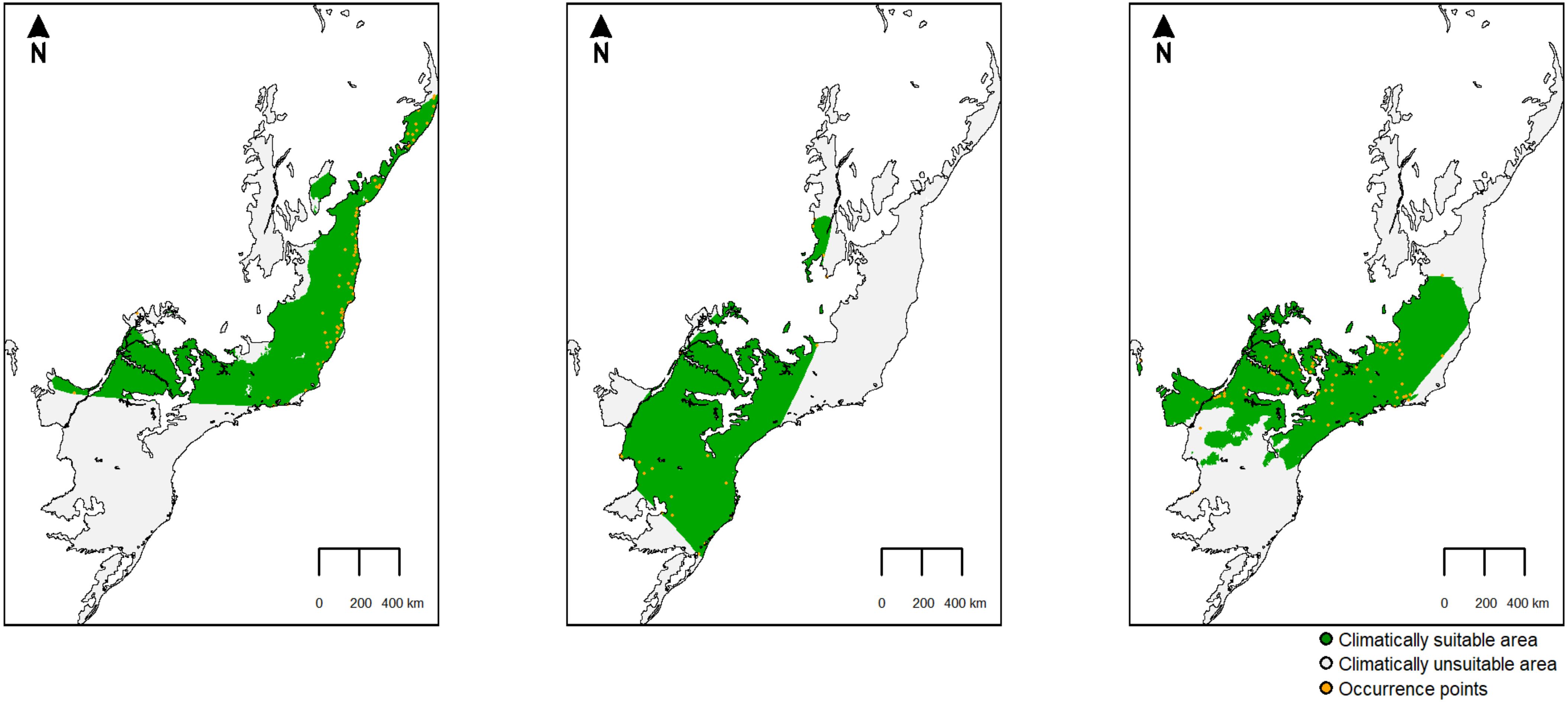
Bactris setosa	*Geonoma brevispatha*	*Syagrus oleracea*
382804.9642 km²	489483.2208 km²	520832.8372 km²



Geonoma schottiana	*Livistona chinensis*	*Archontophoenix cunninghamiana*
523931.487 km²	561988.4285 km²	574728.5145 km²



Desmoncus orthacanthos	*Butia capitata*	*Acrocomia aculeata*
589924.8161 km²	605688.9535 km²	625549.9026 km²



Roystonea oleracea	*Euterpe edulis*	*Syagrus romanzoffiana*
703337.7059 km²	1033146.46 km²	1241571.001 km²

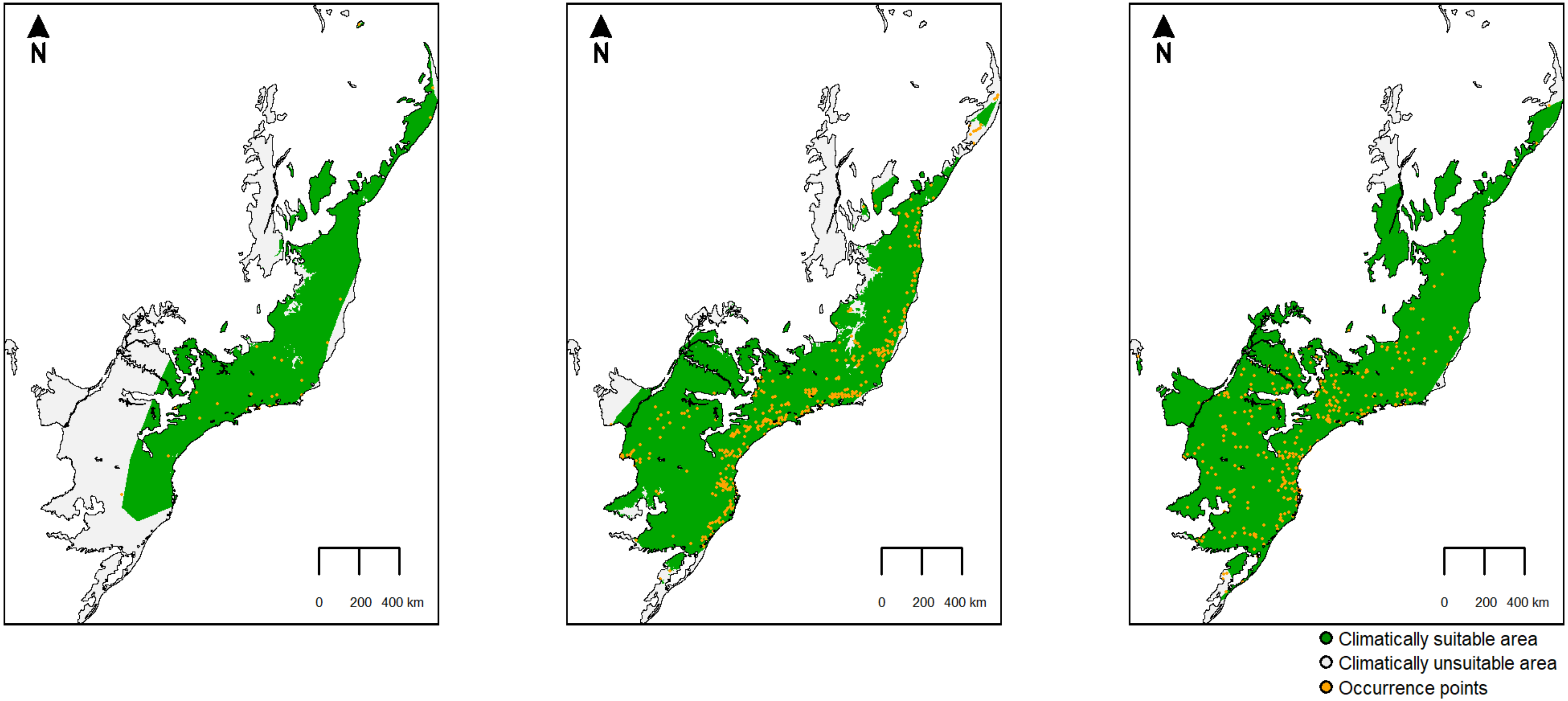


Figure S2: Phylogenetic tree of the 63 palm species

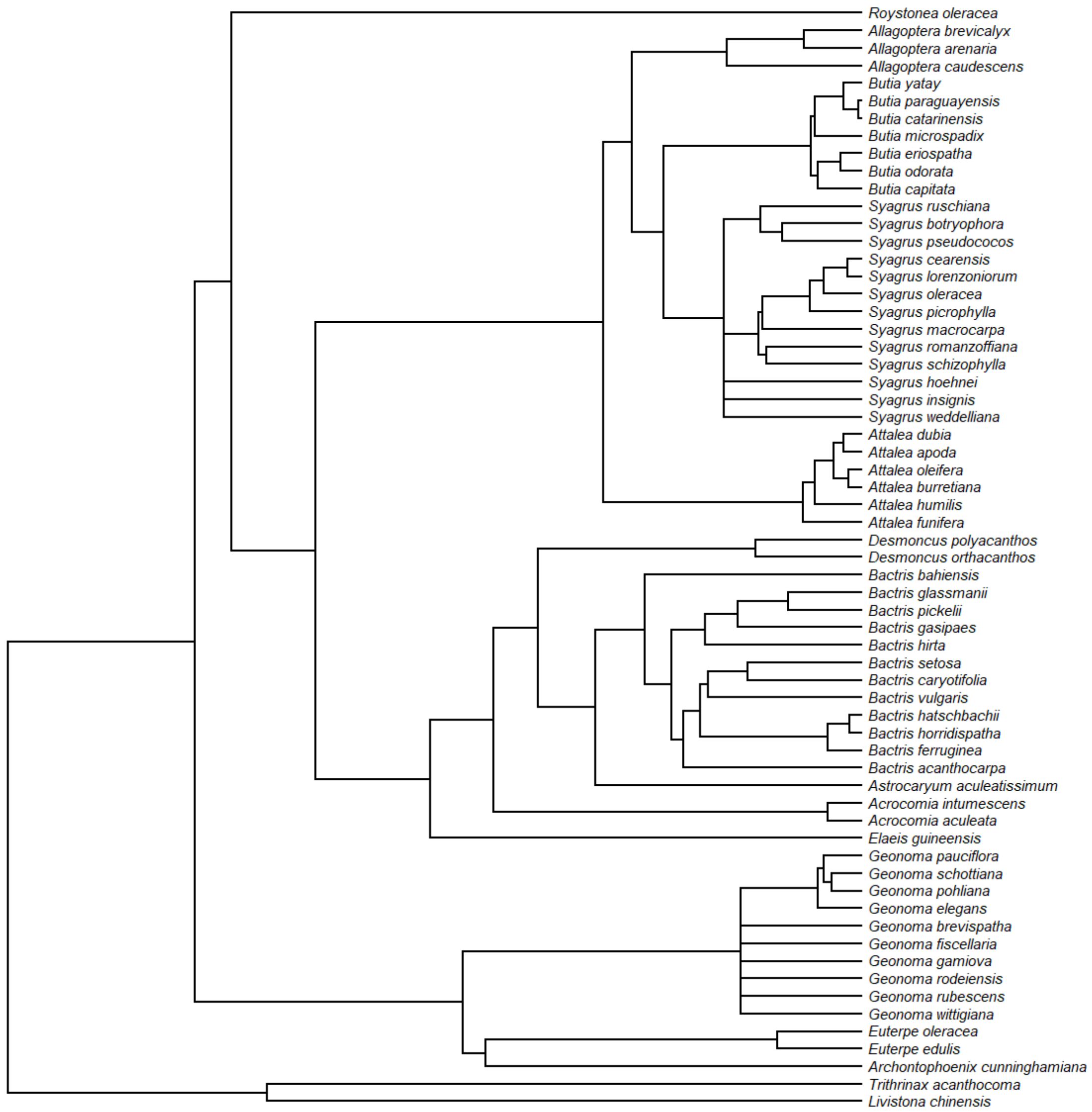


Table S1: Table showing palm species, references, total number of clean records, Atlantic Forest records, and selected bioclimatic variables for each species.

Species	Reference	All records	Atlantic Forest records	Selected bioclimatic variables
Acrocomia aculeata	Cerqueira et al., 2023/ Bello et al., 2017	841	74	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Acrocomia intumescens	Cerqueira et al., 2023	35	20	bio_16/ bio_19/ bio_4/ bio_7/ bio_8
Allagoptera arenaria	Cerqueira et al., 2023/Bello et al., 2017	94	72	bio_1/ bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Allagoptera brevicalyx	Cerqueira et al., 2023	23	17	bio_13/ bio_19/ bio_4/ bio_8
Allagoptera caudescens	Cerqueira et al., 2023	69	65	bio_12/ bio_13/ bio_14/ bio_3/ bio_5
Archontophoenix cunninghamiana	Bello et al., 2017	484	40	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Astrocaryum aculeatissimum	Cerqueira et al., 2023/Bello et al., 2017	91	88	bio_15/ bio_16/ bio_2/ bio_3/ bio_4/ bio_8
Attalea apoda	Cerqueira et al., 2023	5	5	bio_13/ bio_15/ bio_2/ bio_3
Attalea burretiana	Cerqueira et al., 2023	27	23	bio_13/ bio_15/ bio_18/ bio_3/ bio_4/ bio_7/ bio_8
Attalea dubia	Cerqueira et al., 2023/Bello et al., 2017	34	29	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Attalea funifera	Cerqueira et al., 2023	39	32	bio_10/ bio_16/ bio_18/ bio_19/ bio_4/ bio_7/ bio_8
Attalea humilis	Cerqueira et al., 2023	45	41	bio_12/ bio_19/ bio_3/ bio_5
Attalea oleifera	Cerqueira et al., 2023/Bello et al., 2017	28	15	bio_12/ bio_14/ bio_18/ bio_3/ bio_4/ bio_8
Attalea seabrensis *	Cerqueira et al., 2023	10	0	
Attalea voeksii **	Cerqueira et al., 2023	1		
Bactris acanthocarpa	Cerqueira et al., 2023/Bello et al., 2017	268	39	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5/ bio_8
Bactris bahiensis	Cerqueira et al., 2023	34	33	bio_12/ bio_14/ bio_3/ bio_5
Bactris caryotifolia	Cerqueira et al., 2023	32	30	bio_12/ bio_18/ bio_19/ bio_3/ bio_5
Bactris ferruginea	Cerqueira et al., 2023	50	48	bio_12/ bio_14/ bio_18/ bio_19/ bio_3/ bio_8
Bactris gasipaes	Bello et al., 2017	551	17	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Bactris glassmanii	Cerqueira et al., 2023	29	23	bio_17/ bio_19/ bio_4/ bio_8
Bactris hatschbachii	Cerqueira et al., 2023	12	11	bio_12/ bio_17/ bio_3/ bio_4/ bio_5
Bactris hirta	Cerqueira et al., 2023	280	31	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5/ bio_8

Bactris horridispatha	Cerqueira et al., 2023	14	11	bio_12/ bio_15/ bio_16/ bio_18/ bio_3/ bio_4/ bio_8
Bactris pickelli	Cerqueira et al., 2023	31	23	bio_10/ bio_19/ bio_2/ bio_3/ bio_4/ bio_8
Bactris setosa	Cerqueira et al., 2023/Bello et al., 2017	160	136	bio_12/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Bactris soeiroana **	Cerqueira et al., 2023	3		
Bactris timbuiensis **	Cerqueira et al., 2023	4		
Bactris vulgaris	Cerqueira et al., 2023	59	57	bio_11/ bio_13/ bio_15/ bio_19/ bio_3/ bio_8/ bio_9
Butia capitata	Bello et al., 2017	160	20	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Butia catarinensis	Cerqueira et al., 2023	19	17	bio_12/ bio_13/ bio_18/ bio_2/ bio_5/ bio_7/ bio_9
Butia eriospatha	Cerqueira et al., 2023	59	47	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Butia exilata **	Cerqueira et al., 2023	4		
Butia microspadix	Cerqueira et al., 2023	12	5	bio_12/ bio_18/ bio_2/ bio_4/ bio_7/ bio_8
Butia odorata	Cerqueira et al., 2023	201	21	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Butia paraguayensis	Cerqueira et al., 2023	95	10	bio_12/ bio_13/ bio_18/ bio_2/ bio_5/ bio_7/ bio_8/ bio_9
Butia pubispatha **	Cerqueira et al., 2023	1		
Butia yatay	Cerqueira et al., 2023	63	3	bio_1 /bio_10 /bio_13 /bio_14 /bio_15 /bio_18 /bio_19 /bio_2 /bio_8 /bio_9
Desmoncus orthacanthos	Cerqueira et al., 2023	238	67	bio_13 /bio_15 /bio_18 /bio_19 /bio_2 /bio_4 /bio_8
Desmoncus polyacanthos	Cerqueira et al., 2023	423	74	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4/ bio_5
Elaeis guineenses	Bello et al., 2017	1003	45	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Euterpe edulis	Cerqueira et al., 2023/Bello et al., 2017	446	351	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Euterpe oleracea	Bello et al., 2017	309	21	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_5
Geonoma bondariana **	Cerqueira et al., 2023	2		
Geonoma brevispatha	Cerqueira et al., 2023	107	36	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Geonoma conduruenses **	Cerqueira et al., 2023	2		
Geonoma elegans	Cerqueira et al., 2023/Bello et al., 2017	110	100	bio_10/ bio_12/ bio_18/ bio_19/ bio_2/ bio_3/ bio_7
Geonoma fiscellaria	Cerqueira et al., 2023	6	6	bio_13/ bio_15/ bio_2/ bio_3/ bio_4/ bio_5
Geonoma gamiova	Cerqueira et al., 2023/Bello et al., 2017	82	80	bio_12/ bio_16/ bio_19/ bio_2/ bio_5/ bio_7/ bio_8
Geonoma gastoniana **	Cerqueira et al., 2023	3		
Geonoma littoralis **	Cerqueira et al., 2023	1		
Geonoma kuhlmannii **	Cerqueira et al., 2023	4		

Geonoma pauciflora	Cerqueira et al., 2023/Bello et al., 2017	68	57	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5
Geonoma pohliana	Cerqueira et al., 2023	129	108	bio_13/ bio_15/ bio_18/ bio_19/ bio_3/ bio_7/ bio_8
Geonoma rodeiensis	Cerqueira et al., 2023	10	10	bio_12/ bio_14/ bio_3/ bio_5
Geonoma rubescens	Cerqueira et al., 2023	16	15	bio_11/ bio_15/ bio_16/ bio_3/ bio_6/ bio_9
Geonoma schottiana	Cerqueira et al., 2023/Bello et al., 2017	232	209	bio_12/ bio_15/ bio_16/ bio_18/ bio_2/ bio_7/ bio_8
Geonoma trinervis **	Cerqueira et al., 2023	0		
Geonoma wittigiana	Cerqueira et al., 2023	7	7	bio_13/ bio_15/ bio_3/ bio_4/ bio_8
Livistona chinensis	Bello et al., 2017	523	35	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Phoenix sylvestris *	Bello et al., 2017	241	0	
Roystonea oleraceae	Bello et al., 2017	106	27	bio_1/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3
Syagrus amicorum **	Cerqueira et al., 2023	2		
Syagrus ×andrequiceana **	Cerqueira et al., 2023	1		
Syagrus botryophora	Cerqueira et al., 2023	33	28	bio_17/ bio_18/ bio_19/ bio_2/ bio_5/ bio_8
Syagrus ×camposportoana **	Cerqueira et al., 2023	1		
Syagrus cearensis	Cerqueira et al., 2023	51	12	bio_14/ bio_16/ bio_18/ bio_19/ bio_2/ bio_4/ bio_8
Syagrus ×cipoensis **	Cerqueira et al., 2023	1		
Syagrus guaratinguensis **	Cerqueira et al., 2023	0		
Syagrus hoehnei	Cerqueira et al., 2023	11	10	bio_13/ bio_17/ bio_3/ bio_4/ bio_9
Syagrus insignis	Cerqueira et al., 2023	13	13	bio_13/ bio_2/ bio_3
Syagrus itapebiensis **	Cerqueira et al., 2023	1		
Syagrus kellyana **	Cerqueira et al., 2023	1		
Syagrus ×lacerdamourae **	Cerqueira et al., 2023	0		
Syagrus lorenzoniorum	Cerqueira et al., 2023	6	6	bio_12/ bio_14/ bio_5
Syagrus macrocarpa	Cerqueira et al., 2023	11	9	bio_10/ bio_13/ bio_15/ bio_18/ bio_19/ bio_3/ bio_4/ bio_7
Syagrus oleracea	Bello et al., 2017	84	22	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4/ bio_5
Syagrus picrophylla	Cerqueira et al., 2023	13	10	bio_17/ bio_18/ bio_19/ bio_2/ bio_5/ bio_7/ bio_8
Syagrus pseudococos	Cerqueira et al., 2023/Bello et al., 2017	28	25	bio_12/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5
Syagrus romanzifollia **	Bello et al., 2017	0		

Syagrus romanzoffiana	Cerqueira et al., 2023/Bello et al., 2017	1372	289	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4
Syagrus ruschiana	Cerqueira et al., 2023/Bello et al., 2017	17	17	bio_16/ bio_4/ bio_7/ bio_8
Syagrus santosii **	Cerqueira et al., 2023	1		
Syagrus schizophylla	Cerqueira et al., 2023	72	43	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Syagrus ×serroana **	Cerqueira et al., 2023	1		
Syagrus ×tostana **	Cerqueira et al., 2023	1		
Syagrus weddelliana	Cerqueira et al., 2023	15	9	bio_14/ bio_18/ bio_19/ bio_2/ bio_3/ bio_5/ bio_8
Trithrinax acanthocoma	Cerqueira et al., 2023	8	5	bio_14/ bio_18/ bio_19/ bio_2/ bio_8

* Species without occurrence records in the Atlantic Forest after geographical bias correction, which were excluded from Ecological Niche Modeling.

** Species without the minimum of 5 occurrence records after geographical bias correction, which were excluded from Ecological Niche Modeling.

Table S2: List of 63 palm species with their functional traits and corresponding references.

Species	Habitat	Max Stem Height (m)	Max Stem Dia (cm)	Average Fruit Length (cm)	Average Fruit Width (cm)
Acrocomia aculeata ▪	Open-area	12	50	4.25	4.6
Acrocomia intumescens ▪	Forest-interior	8 ŧ	50 ˘ ˘	4.6	4.6
Allagoptera arenaria ▪	Open-area	0.2	15	1.6	1.15
Allagoptera brevicalyx ▪	Open-area	2	20 ˘ ˘	1.75	1.25
Allagoptera caudescens ▪	Open-area	8	25	4.25	3.25
Archontophoenix cunninghamiana ▪	Open-area	30	30	1.25	1.1
Astrocaryum aculeatissimum ▪	Open-area	8	15	5.5	3.5
Attalea apoda ▪	Open-area	13	36.7 ˘ ˘	6	3.3
Attalea burretiana ▪	Forest-interior	30 ŧ	40 ŧ ŧ	7.27	4.55
Attalea dubia ▪	Open-area	25	35	6.25	3
Attalea funifera ▪	Open-area	15	30	12.5	6
Attalea humilis ▪	Open-area	1 ŧ	-	6.5	5.25
Attalea oleifera ▪	Open-area	30	45	9	5
Bactris acanthocarpa ▪	Forest-interior	2	7	1.4	1.4
Bactris bahiensis ▪	Open-area	3	1	1.5	1.1
Bactris caryotifolia ▪	Forest-interior	1.5	2	1.4	1.4
Bactris ferruginea ▪	Open-area	10	10	1.65	1.65
Bactris gasipaes ▪	Open-area	18	25	5	4
Bactris glassmanii ▪	Open-area	3	2	1.3	1.3
Bactris hatschbachii ▪	Forest-interior	5	2.5	2.05	2
Bactris hirta ▪	Open-area	3	2	0.75	0.75
Bactris horridispatha ▪	Forest-interior	6	3	3.25	2.4
Bactris pickelii ▪	Forest-interior	3	1.5	1.35	1.35
Bactris setosa ▪	Forest-interior	6	4	1.25	1.75
Bactris vulgaris ▪	Open-area	3	3.5	1.7	1.7
Butia capitata ▪	Open-area	6	50	2.65	1.7
Butia catarinensis ▪	Open-area	0.8 ŧ	30 ŧ	2.5	1.2
Butia eriospatha ▪	Open-area	6	50	1.9	1.75
Butia microspadix ▪	Open-area	-	-	2	1.05
Butia odorata ▪	Open-area	9 ŧ	30 ŧ	2.2	1.85

Butia paraguayensis ▪	Open-area	4	20	2.95	1.85
Butia yatay ▪	Open-area	12	40	3.6	2.65
Desmoncus orthacanthos ▪	Open-area	20	3	1.49	1.42
Desmoncus polyacanthos ▪	Forest-interior	37	3.5	2	1
Elaeis guineensis ▪	Open-area	30	50	4.25	2.5
Euterpe edulis ▪	Forest-interior	12	15	1.2	1.2
Euterpe oleracea ▪	Forest-interior	20	20	1.5	1.5
Geonoma brevispatha ƚ	Forest-interior	3	4	0.95	0.7
Geonoma elegans ▪	Forest-interior	3	1	0.95	0.72
Geonoma fiscellaria ƚ	Forest-interior	4.5	4	1.6	1.4
Geonoma gamiova =	Forest-interior	3.4	3	1.225	0.95
Geonoma pauciflora ▪	Forest-interior	3	1.5	0.96	0.78
Geonoma pohliana ▪	Forest-interior	7.5	7	1	0.735
Geonoma rodeiensis ▪▪	Forest-interior	3	3.15 ˘˘	1	0.84 ˘˘
Geonoma rubescens ƚ	Forest-interior	2.2	2.5	1	0.9
Geonoma schottiana ▪	Forest-interior	4	4	0.93	0.825
Geonoma wittigiana ƚ	Forest-interior	2.2	1.4	0.6 = =	0.55
Livistona chinensis ▪	Open-area	20	30	3	2.8
Roystonea oleracea ▪	Open-area	40	66	1.5	0.9
Syagrus botryophora ▪	Open-area	18	25	4.25	2.6
Syagrus cearensis ▪	Open-area	10	18	3.75	3.5
Syagrus hoehnei ≈	Forest-interior	5	15	3.15	2.6
Syagrus insignis ≈ ≈	Forest-interior	11	10	2.05	1.8
Syagrus lorenzoniorum ▪	Forest-interior	4	16	2.75	2.5
Syagrus macrocarpa ▪	Forest-interior	10	20	7.75	3.75
Syagrus oleracea ▪	Open-area	20	30	5.5	2.35
Syagrus picrophylla ▪	Forest-interior	8	20	3.5	2.3
Syagrus pseudococos ▪	Forest-interior	15	25	6.5	3.9
Syagrus romanzoffiana ▪	Open-area	17	50	2.5	1.5
Syagrus ruschiana ▪	Open-area	8	12	2.5	2
Syagrus schizophylla ▪	Open-area	4	15	2.75	2
Syagrus weddelliana ˘	Forest-interior	3	10	1.85	1.75
Trithrinax acanthocoma ƚ	Open-area	15	35	0.94 ˘˘	1.85

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˘ ˘ Genus average

Table S3: Model selection results for PGLS analysis

Rank	Model	df	AICc	delta	weight
1	log Range Size ~ log Max Stem Height	2	281.844	0	0.27817
2	log Range Size ~ log Average Fruit Width	2	282.114	0.27035	0.243
3	log Range Size ~ log Max Stem Height + log Average Fruit Width	3	282.756	0.91152	0.17635
4	log Range Size ~ Habitat + log Max Stem Height	3	284.029	2.18511	0.09329
5	log Range Size ~ Habitat + log Average Fruit Width	3	284.292	2.44803	0.08179
6	log Range Size ~ Habitat + log Max Stem Height + log Average Fruit Width	4	285.036	3.19223	0.05638
7	NULL	1	285.177	3.33254	0.05256
8	log Range Size ~ Habitat	2	287.269	5.425	0.01846

CHAPTER 2

Angeli, J., Talora, D. C, Heming, N. H., Alves-Ferreira, G., **Cazetta, E.** ASSESSING CLIMATE CHANGE IMPACTS ON ATLANTIC FOREST PALMS: THE ROLE OF TRAITS IN SPECIES' DISTRIBUTION SHIFTS.

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Assessing Climate Change Impacts on Atlantic Forest Palms: The Role of Traits in Species' Distribution Shifts

Júlia Angeli [1 2 3], Daniela Custódio Talora[1 3], Gabriela Alves-Ferreira [1 3], Neander Marcel Heming[1 3], Eliana Cazetta[1 2 3]

[1]Programa de Pós-graduação em Ecologia e Conservação da Biodiversidade, Departamento de Ciências Biológicas, Universidade Estadual de Santa Cruz, Ilhéus, BA 45662-900, Brazil

[2]Ecological Interactions of Tropical Plants Lab

[3]Applied Ecology and Conservation Lab

[*]Corresponding author: Júlia Angeli (juliaangeli34@gmail.com)

ABSTRACT

Climate change is expected to significantly impact biodiversity, including shifts in the distribution of palm species. Understanding how climate change affects distribution patterns and identifying traits that influence species' responses can contribute to their conservation. Using ecological niche models and functional traits of 63 palm species from the Brazilian Atlantic Forest, we investigated: (i) the impact of different climate scenarios on the geographic distribution of Atlantic Forest palm species, identifying the most threatened species, and (ii) which traits of palms associated with the greatest gains or losses of suitable areas under future climate change scenarios. The majority of the biome is projected to maintain high levels of alpha diversity, although substantial losses are expected, particularly along the northern coast and in central areas of the Atlantic Forest, which currently harbor the highest concentrations of species richness. Our projections indicate that over 61% of palm species will experience a reduction in their climatically suitable areas across all future scenarios. Species with restricted distributions and taller stems are particularly vulnerable to these losses. These findings reinforce the need to closely monitor how species will lose suitable areas due to climate change, allowing for continuous adjustments in conservation strategies to mitigate impacts and ensure the protection of biodiversity in this highly vulnerable biome. Furthermore, we highlight the importance of considering different traits when assessing species' extinction risk based on future projections, which can enhance conservation actions, especially for those most vulnerable to climate change.

Key-words: global warming, Arecaceae; species distribution; ecological niche models; richness; range shift, traits.

1. Introduction

Anthropogenic climate change is already bringing profound impacts on biodiversity (Coleman and Bragg, 2021). According to the latest IPCC report (*IPCC Sixth Assessment Synthesis Report, 2023*), global surface temperature is projected to continue rising in the short term (2021–2040), mainly due to increased cumulative CO2 emissions under various modeled scenarios. In lower-emission scenarios, the temperature is likely to increase by 1.5°C, while in higher-emission scenarios, the projected increase ranges from 2.7°C (intermediate emission scenario) to 4.4°C (high-emission scenario). Moreover, many changes in the climate system, such as increased frequency and intensity of heat extremes and heavy precipitation events, will be directly exacerbated by rising global warming (IPCC, 2023). Changes in temperature and precipitation patterns could lead to shifts in species distributions as they seek better climatic conditions (Lenoir and Svenning, 2015), resulting in reductions or expansions of their ranges (Garcia et al., 2014; Sekercioglu et al., 2008) and impacting ecological interactions (Walther, 2010). Consequently, these shifts in species distributions may severely impair ecosystem functioning (Nunez et al., 2019).

Plants are particularly affected by climate change (Walther, 2003). These effects go beyond biodiversity loss (Slingsby et al., 2017) but also alter the geographic distribution of plant species (Parmesan, 2006) and drive migrations to more favorable environmental conditions (Kelly and Goulden, 2008), resulting in expanded or reduced of suitable areas (Garcia et al., 2014). Species’ responses to these changes may partially depend on traits that influence persistence and expansion under future climate scenarios (Angert et al., 2011). Species with advantageous traits may cope better with climate change, whereas the absence of such traits could lead to population declines and even extinctions (Kühn et al., 2021). Thus, traits can help explain how species respond to distribution shifts driven by climate change (Estrada et al., 2016), as demonstrated for other biological groups (Alves-Ferreira et al., 2022; Mota et al., 2022). Consequently, projecting future potential distributions of plant species under different climate scenarios and understanding how functional traits mediate these shifts are essential for assessing the impacts of climate change and developing effective conservation strategies.

Palms (Arecaceae) are a plant family sensitive to climatic gradients (Bjorholm et al., 2005). This diverse group includes approximately 2,500 pantropical species, with South America as the center of endemism for this family (Pintaud et al., 2008). Palms are crucial for maintaining tropical ecosystems (Eiserhardt et al., 2011) and are often considered keystone species in the tropics (Blach-Overgaard et al., 2009). They also play a fundamental role as fruit providers for a wide variety of frugivorous animals, which are essential for seed dispersal processes (Galetti et al., 2001; Zona and Henderson, 1989). Studies show that water availability and temperature are critical climatic determinants for palm distribution (Bjorholm et al., 2005; Blach-Overgaard et al., 2009; Kreft et al., 2006; Svenning et al., 2008). Consequently, this family and its associated ecosystem services are affected by climate change (Blach-Overgaard et al., 2015; Butler and Larson, 2020; Costa et al., 2022; Eiserhardt et al., 2011), with potential increases in their geographic ranges (Vaz and Nabout, 2016; Walther et al., 2007) or loss of suitable areas in the future (Blach-Overgaard et al., 2009; Sales et al., 2021). Palms are characteristic of tropical and subtropical regions worldwide (Dransfield et al., 2008), including the Atlantic Forest, one of the world's most threatened and climate-vulnerable biomes (Bellard et al., 2014).

The objectives of this study were: (i) to investigate the impact of different climate scenarios on the richness and geographic distribution of Atlantic Forest palm species, identifying the most threatened species, and (ii) to determine which palm traits are associated with the greatest gains or losses of suitable areas under future climate change scenarios. It is expected that palms with restricted geographical ranges and forest interior species, primarily found in closed-canopy forests, will be more vulnerable to climate change, showing a decrease in the geographic ranges under future climate scenarios (Blach-Overgaard et al., 2015; Lee et al., 2015). Furthermore, species expected to gain suitable areas in future scenarios are predicted to exhibit traits such as shorter stem height, due to greater tolerance to drought and seasonal conditions. Acaulescent palms or those with short stems minimize water loss through the stem, increasing their resilience to water stress and favoring their persistence in drier environments (Cássia-Silva et al., 2022). These species are also expected to have larger fruits, which favor better establishment in high-temperature conditions and result in greater reproductive success (Göldel et al., 2015; Westoby et al., 1996). Moreover, larger seeds, often associated with larger fruits, are typically dispersed by larger frugivores, enabling longer dispersal distances (Jenkins et al., 2007), a beneficial trait in the context of climate change.

2.Methods

2.1. Study Area

This study was performed in the Brazilian Atlantic Forest, one of the most threatened biomes in the world and one that is facing the effects of climate change (Bellard et al., 2014; Colombo and Joly, 2010). The Atlantic Forest is considered one of the world's main biodiversity hotspots, with high species richness, elevated levels of endemism, and a small remaining portion of its original forest cover (Myers et al., 2000). Since colonization in the 16th century, the biome has undergone intense transformations due to human activity, leading to forest deforestation and fragmentation, which has significantly impacted its biodiversity (Joly et al., 2014). Until 2005, deforestation prevailed, accompanied by a reduction in the number of forest fragments; after this period, a relative stability in forest cover and an increase in the number of fragments were observed, although more than 97% of these are smaller than 50 hectares, with few larger fragments. Currently, forest vegetation in the Atlantic Forest covers only 22.9% of its original area, reflecting a significant loss of habitat. (Vancine et al., 2024).

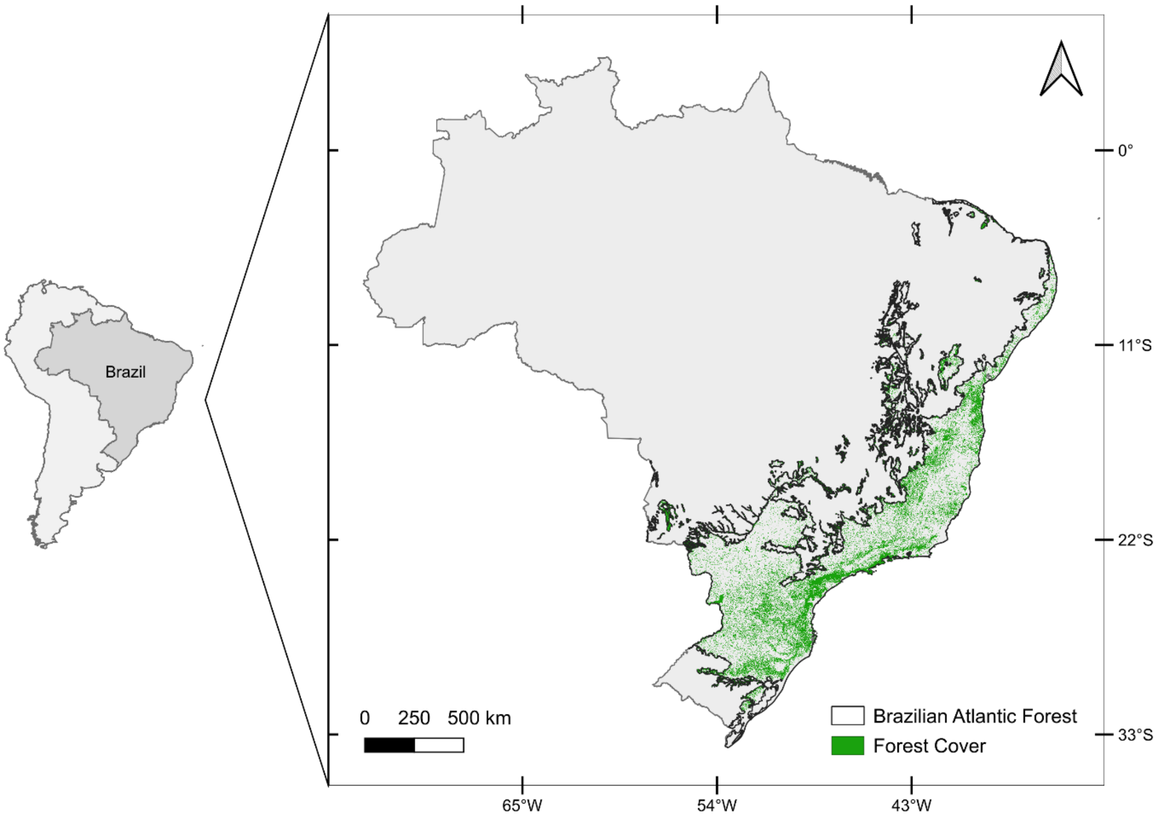

Figure 1: Map of the Brazilian Atlantic Forest, showing current forest cover in green.

2.2 Palm data

We selected the palm species that occur in the Atlantic Forest based on the literature (Bello et al., 2017; Cerqueira et al., 2023) incorporating both native and exotic species (including four exotic species). Then, we gathered occurrence records from the Global Biodiversity Information Facility (GBIF; www.gbif.org), a platform that consolidates data from various sources and is commonly used for predicting species distribution (Heberling et al., 2021). Additional coordinates were also obtained from the databases: SpeciesLink, Integrated

Digitized Biocollections, and iNaturalist. The nomenclature and synonyms used follow the *Flora Brasileira: Arecaceae (Palmeiras)* (Lorenzi et al., 2010) and Cerqueira et al. (2023). After obtaining the data, we cleaned the coordinates by removing inaccurate records, including those with incomplete coordinates and those corresponding to municipality centroids (Zizka et al., 2019). Additionally, we removed occurrences that were less than 10 km apart from their nearest neighbors through the *spThin* optimization algorithm (Aiello-Lammens et al., 2015), improving ecological niche model performance (Boria et al., 2014). Our final dataset consisted of 63 palm species with at least 5 occurrence records (Table S1) recorded in the Brazilian Atlantic Forest.

For each palm species, we used key plant traits commonly associated with species distribution and responses to anthropogenic changes: stem height, stem diameter, fruit length, and fruit width (Bjorkman et al., 2018; Cornelissen et al., 2003; Göldel et al., 2015; Westoby, 1998). These data were obtained from the global palm trait database, PalmTraits 1.0 (Kissling et al., 2019). For acaulescent species, we assigned values of zero, and for species, such as *Attalea humilis,* that occur both in acaulescent and stem solitary growth form, we assigned the maximum stem height. Additional information for certain species was gathered from *Flora Brasileira: Arecaceae (Palmeiras)* (Lorenzi et al., 2010), the *Flora e Funga do Brasil* project (Arecaceae in *Flora e Funga do Brasil*, 2024), and other literature sources (Table S2). Missing values for maximum stem diameter were filled for four species (*Acrocomia intumescens*, *Allagoptera brevicalyx*, *Attalea apoda* and *Geonoma rodeiensis*) using the average maximum stem diameter of their respective genera. Similarly, the average fruit width of *Geonoma rodeiensis* was calculated using genus-level data. For the only species in the genus *Trithrinax* included in our list, missing fruit length data was supplemented with the average fruit length of *Trithrinax* species available in PalmTraits 1.0 (Kissling et al., 2019).

Additionally, we incorporated habitat classification from the study by Benchimol et al. (2017), which reflects the preferred habitat of each species. We also consulted *Flora Brasileira: Arecaceae* (Lorenzi et al., 2010) and specialists to supplement habitat information. Species classified as "forest-interior" are those predominantly found in dense-canopy forests, while "open-area" species mainly occur in open environments or less dense-canopy forests. Although some species may occur in both habitat types, we adopted classifications based on each species' primary preference.

Table 1: Functional traits of 63 palm species in the Atlantic Forest, including mean, maximum, and minimum values.

Traits	Type	Mean (max, min)
Habitat	Categorical (Open area, Forest interior)	
Maximum stem height	Continuous	10.26 m (0 e 40)
Maximum stem diameter	Continuous	19.55 cm (0 e 66)
Mean fruit length	Continuous	2.96 cm (0.6 e 12.5)
Mean fruit width	Continuous	2.12 cm (0.55 e 6)

2.3 Climate data

We obtained 19 bioclimatic variables from the WorldClim v2.1 platform (Fick and Hijmans, 2017) at a resolution of 2.5° (~4.5 km²) (Table S3). These variables are derived from precipitation and temperature measurements for the period of 1970–2000 (hereafter known as baseline). We obtained the equivalent temperature and precipitation variables for the 2050 and 2070 periods, considering two Global Climate Models (GCMs): IPSL-CM6A-LR and MIROC6, and two Shared Socio-economic Pathways (SSPs): 245 and 585, that represent optimistic and pessimistic greenhouse gas concentration scenarios, respectively (O'Neill et al., 2014). We calculated a correlation matrix to reduce collinearity issues among the bioclimatic variables, using Pearson correlation coefficients with a cutoff value of 75% and the select_vars function from the R package ENMwizard (Heming et al., 2019). We selected only the bioclimatic variables that exhibited correlation below the cutoff limit. The selected climatic variables for each species are listed in Table S1.

2.4 Ecological Niche Models (ENMs)

Ecological niche models (ENMs) estimate the relationship between environmental variables and known species occurrences, enabling geographic projections of species distributions over time (Elith et al., 2011). To model the niches of 63 palm species, we used the MaxEnt algorithm (version 3.4.1; Phillips et al., 2017) implemented through the ENMwizard package (Heming et al., 2019). MaxEnt requires only occurrence data and bioclimatic variables (Phillips et al., 2006) and is widely recognized for its high performance and accuracy, even when applied to small samples (Hernandez et al., 2006). The calibration area was created with a 1.5° buffer around the minimum convex polygon (MCP) of all occurrences. The models were fitted using options for Feature classes (FC) and Regularization multipliers (RMs), including all combinations of the following classes: linear (L), product (P), and quadratic (Q), along with RM values (ranging from 0.5 to 5, with increments of 0.5), resulting in 70 models per species. These two parameters are important in defining the complexity of MaxEnt models, where RMs control for regulating overfitting, and FCs represent transformations of the original bioclimatic variables (Muscarella et al., 2014).

To validate and assess the predictive capacity of the models, we applied two methods of geographical partitioning on the occurrence records: block or jackknife, using the ENMevaluate_b function from the ENMwizard package (Heming et al., 2019). The jackknife partitioning method was used for species with fewer than 15 occurrence records (Shcheglovitova and Anderson, 2013). This method involves removing one point from the dataset at a time and building a new model without the removed point (Pearson et al., 2007). In contrast, the block method divides the occurrence points into four spatially independent blocks, performing four iterations in which one block is used to evaluate the model while the others are used for calibration (Roberts et al., 2017).

We constructed a consensus model for each species from the top 10% of MaxEnt models based on the criteria of the lowest omission rate (OR) and the highest mean area under the curve (AUC) (Boria et al., 2017). The performance metrics of the model (AUC and OR) were calculated using the ENMeval package (Muscarella et al., 2014). The potential continuous distributions of each species were then converted into a binary vector (climatically suitable and unsuitable areas) by applying a threshold that excludes 10% of the occurrence points with the lowest environmental suitability values (Liu et al., 2005). Then we projected them into future climate scenarios (GCMs and SSPs) and the potential continuous distributions of each species were then converted into a binary vector (1 = presence and 0 = absence) by applying a threshold that excludes 10% of the occurrence points with the lowest environmental suitability values (Liu et al., 2005).

To correct the overestimation produced by ecological niche models, we created a minimum convex polygon around all filtered occurrence records within the study area and used this polygon to refine the binary models. This adjustment ensured that the resulting maps were free from overprediction. Buffers were not applied to these maps, as the limited dispersal capacity of palms (Blach-Overgaard et al., 2010; Carrete et al., 2022; Tella et al., 2020) would not affect the pixel size of each species' map.

2.5 Data Analysis

Alpha diversity (species richness) was calculated by summing the binary species maps for each climatic scenario (baseline and future – 2050 SSPs 245 and 585; and 2070 SSPs 245 and 585) through the "rast.sr" function from the R package *phyloraster* (Alves-Ferreira et al., 2024). Subsequently, we computed the difference between species richness in the baseline and future scenarios (delta) using the "delta.grid" function from *phyloraster* (Alves-Ferreira et al., 2024). Positive "delta richness" values indicate species gains in the future, while negative values denote species losses. Finally, we calculated the change in suitable area using the ratio (future area / current area) for each species in each future scenario relative to the baseline scenario, where 0 indicates total loss of suitable area, 1 indicates stability of suitable area, values greater than 1 indicate an expansion of suitable area, and values below 1 indicate a contraction.

The relationship between traits and changes in species distribution may be influenced by phylogeny (Angert et al., 2011). Closely related species tend to share similar traits (Losos, 2008). Considering this, we incorporated phylogeny into our analyses and constructed Phylogenetic Generalized Least Squares (PGLS) regression models to assess the influence of predictor variables on the response variable, which is the ratio of change in suitable area for each future climate scenario. The phylogeny was based on the maximum clade credibility tree calculated using the "maxCladeCred" function from the R package *phangorn* (Schliep, 2011), derived from the 1000 Constraints trees of the species-level palm phylogeny from Faurby et al. (2017). The tree was pruned to include only the 63 species in our study, and missing species were added using the "phylo.maker" function from the R package *V.PhyloMaker2*. The resulting tree is available in Newick format and can be visualized in Figure S1.

We used the "vif.cor" function from the R package *usdm* (Naimi et al., 2014) to check the collinearity among predictor variables (Habitat, maximum stem height, maximum stem diameter, average fruit length, average fruit width, and baseline distribution area) with a threshold of 0.5. Thus, we perform the PGLS with the following variables: Habitat, maximum stem height, average fruit width, and baseline distribution area.

We assessed the additive effects of predictor variables on the ratio between future and baseline suitable areas using the "pgls" function from the R package *caper* (Orme et al., 2013). We built four global models (one for each response variable) that included all predictor variables. From the global models, we generated all possible models by removing one trait at a time until reaching the null model, using the "dredge" function from the R package *MuMIn* (Bartoń, 2023), resulting in 16 models for each response variable (Tables S5–S8). The best models were selected based on the lowest AIC (Burnham and Anderson, 2004). The homoscedasticity and normality of the model residuals were checked through visual inspection and normality tests.

3. Results

3.1 Richness patterns and Climatically Suitable Area

The ecological niche models showed good performance, with an average AUC of 0.86 (range: 0.7–0.98) and an OR of 0.18 (range: 0–0.5). However, 14 species had moderate fits, with AUC values ranging from 0.5 to 0.66.

Most Atlantic Forest areas are predicted to maintain alpha diversity (richness) (Figure 2) in future scenarios. However, significant losses are also anticipated. Our results indicated that some regions of the Atlantic Forest are projected to lose species under future climate change scenarios (Figure 3a-d). The greatest losses in palm species richness were predicted for the northern coast of the Atlantic Forest and central areas of the biome - some regions that currently exhibit the highest levels of species richness - with losses ranging from 6 to 9 species. Conversely, some regions are projected to experience gains in species richness, with increases of up to 7 species.

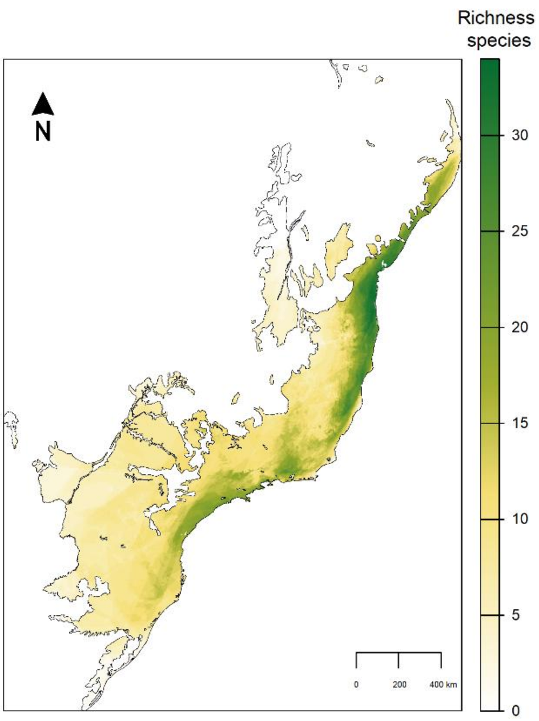

Figure 2: Species Richness - Map illustrating the variation in palm species richness in the baseline scenario, with darker green areas representing regions of higher species richness and lighter yellow shades indicating areas with fewer species. White regions highlight areas where no palm species are present.

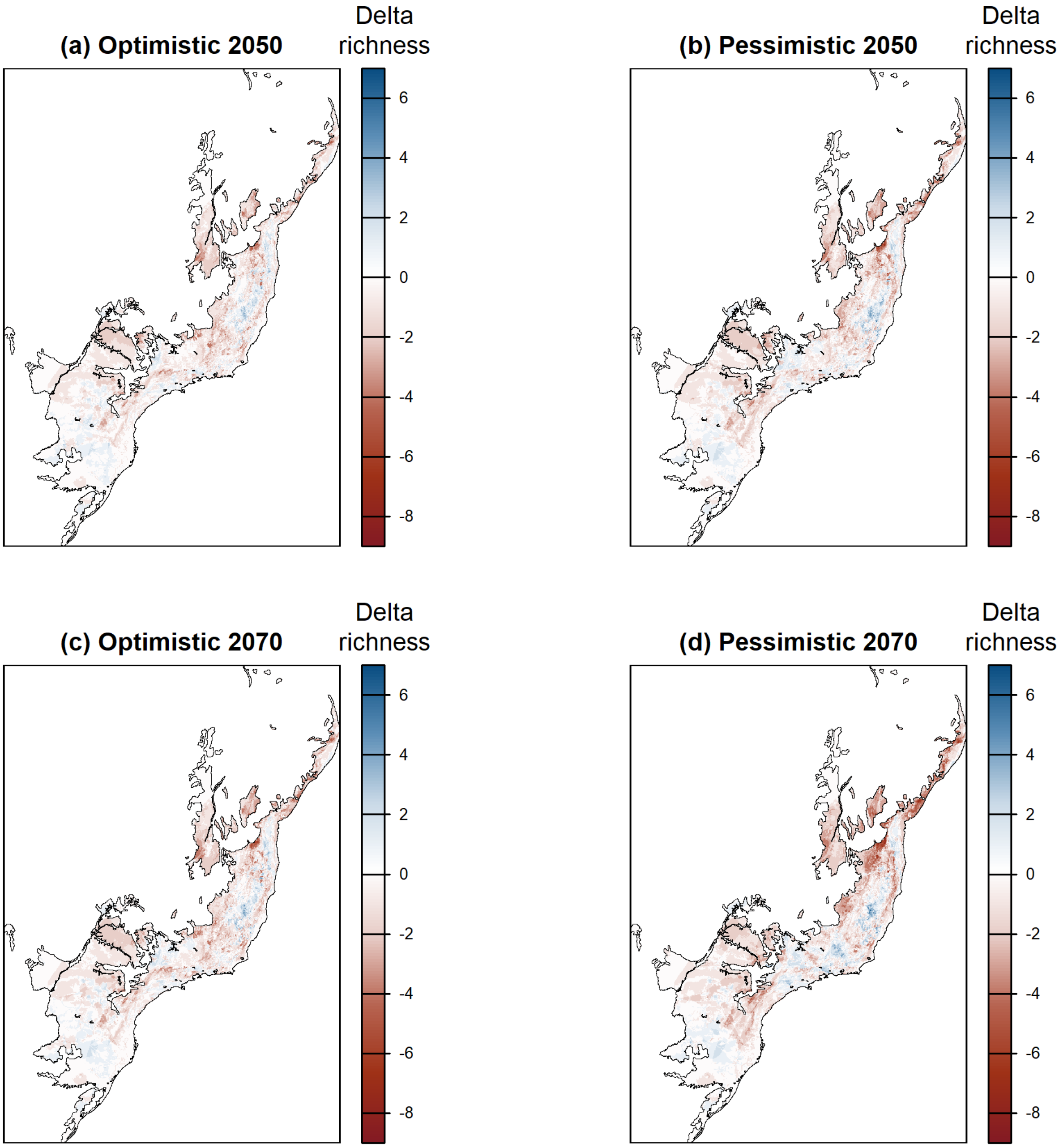

Figure 3: Delta Species Richness – The maps illustrate the variation in species richness between the baseline and future climate scenarios. Delta richness for: (a) the optimistic 2050 scenario; (b) the pessimistic 2050 scenario; (c) the optimistic 2070 scenario; (d) the pessimistic 2070 scenario. Blue areas represent regions with an increase in species richness, red areas indicate regions with a decrease, and white areas denote regions where species richness remains unchanged compared to the baseline scenario.

The ratio of suitable area change ranged from 0 to 2.02 (Table S4). Our projections indicate that by 2050, 71% of palm species will experience a decrease in suitable areas under the optimistic scenario, while 66% of species will lose climatically suitable areas under the pessimistic scenario. By 2070, we project that 68% of the species will reduce their potential distribution under the optimistic scenario, and 61% will reduce their areas under the pessimistic scenario (ratio < 1). Additionally, under the pessimistic scenario, both in 2050 and 2070, the species *Syagrus insignis* is projected to lose its entire climatically suitable area (ratio = 0). The species *Attalea apoda* is projected to lose more than 90% of its climatically suitable area in the 2050 scenarios and the 2070 optimistic scenario (Figure S2 a,c) and the species *Acrocomia intumescens* is projected to lose more than 90% of its climatically suitable area in the 2070 pessimistic scenario (Figure S2 - d). In contrast, species such as *Geonoma rodeiensis, Bactris glassmanii, Syagrus romanzoffiana, Trithrinax acanthocoma, Attalea humilis, Bactris bahiensis, Butia paraguayensis, Bactris vulgaris, Astrocaryum aculeatissimum Attalea funifera, Geonoma elegans, Bactris ferruginea, Syagrus lorenzoniorum, Desmoncus orthacanthos, Acrocomia aculeata* and *Desmoncus polyacanthos* may gain climatically suitable areas in all future scenarios (ratio > 1) (Figure S2 a-d). Under optimistic scenarios, up to 31% of species are projected to expand their potential distribution, while under pessimistic scenarios, up to 38% of species are expected to gain climatically suitable areas (Figure S2).

3.2 Palm Traits

Our analysis revealed that the potential distribution area under the baseline scenario explains the potential distribution area changes in all future climatic scenarios. The models with the lowest AICc for each scenario showed significant values ($p<0.05$, Table 2) for baseline distribution area. Specifically, palm species with more restricted distribution areas exhibited a lower potential distribution area change, indicating a reduction in potential distribution area across all future climatic scenarios (Figure 4, Table 2).

In the model for the response variable "Area change (Pessimistic 2070)", maximum stem height also proved to be a relevant variable, showing a significant effect ($p<0.05$, Table 2). This suggests that as stem height increases, the potential distribution area change decreases (Figure 5). In contrast, for the other three climatic scenarios (Optimistic 2050 and 2070, and Pessimistic 2050), maximum stem height was not included in the best model, nor were fruit width and habitat, which were not relevant in any of the analyzed scenarios.

Table 2 - Model selection results based on the lowest AIC for each response variable. Coefficients of the variables included in each model are presented, along with significance levels (***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, •$p = 0.05$).
n.a. indicates that the variable was not included in the best model;
- indicates that the variable was not included in the global model.

	Optimistic 2050	Pessimistic 2050	Optimistic 2070	Pessimistic 2070
Intercept	-0.008	-0.136	-0.113	0.772
Habitat	n.a.	n.a.	n.a.	n.a.
Baseline distribution area (log)	0.083 ***	0.091***	0.092 ***	0.057 •
Average Fruit Width (log)	n.a.	n.a.	n.a.	-
Average Fruit Width	-	-	-	n.a.
Max Stem Height (log)	n.a.	n.a.	n.a.	-
Max Stem Height	-	-	-	-0.023 **
Residual standard error	0.102	0.115	0.116	0.136
Degrees of freedom	61	61	61	60
Adjusted R-squared	0.176	0.171	0.170	0.132
F-statistic	14.29	13.82	13.71	5.72
p-value (residuals Normality test)	0.194	0.378	0.249	0.346
Model weight	0.412	0.380	0.419	0.327

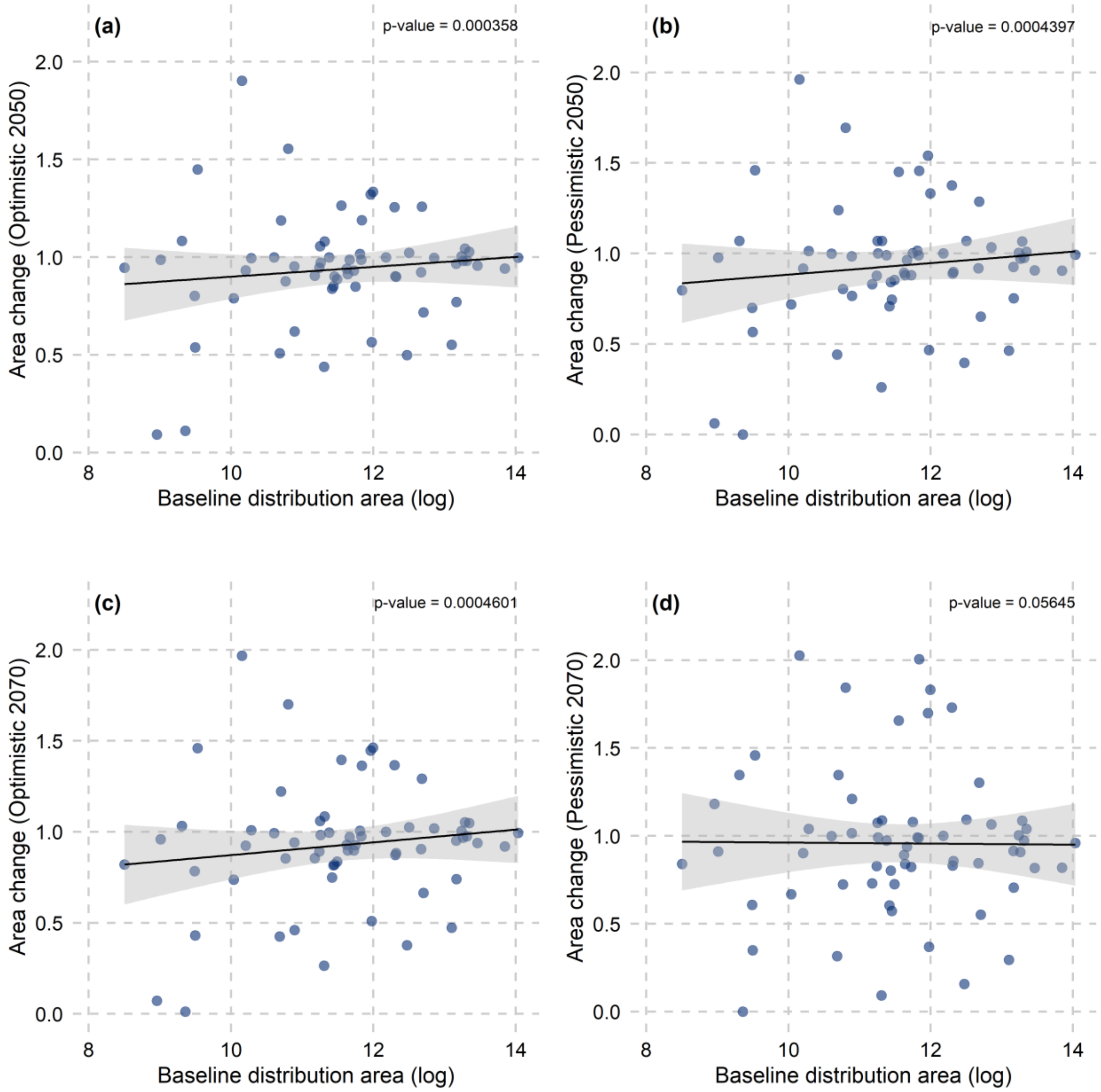

Figure 4: The effect of the potential distribution area in the baseline scenario of palms on the potential distribution area change across future climate scenarios. Each point on the graph represents one of the 63 palm species from the Atlantic Forest. The variation in area change is shown for species with more restricted and widely distributed areas, with significance assessed using phylogenetic generalized least squares (PGLS) regression models. The shaded areas around the regression lines represent the standard error of the estimates. The p-value is presented for each response variable.

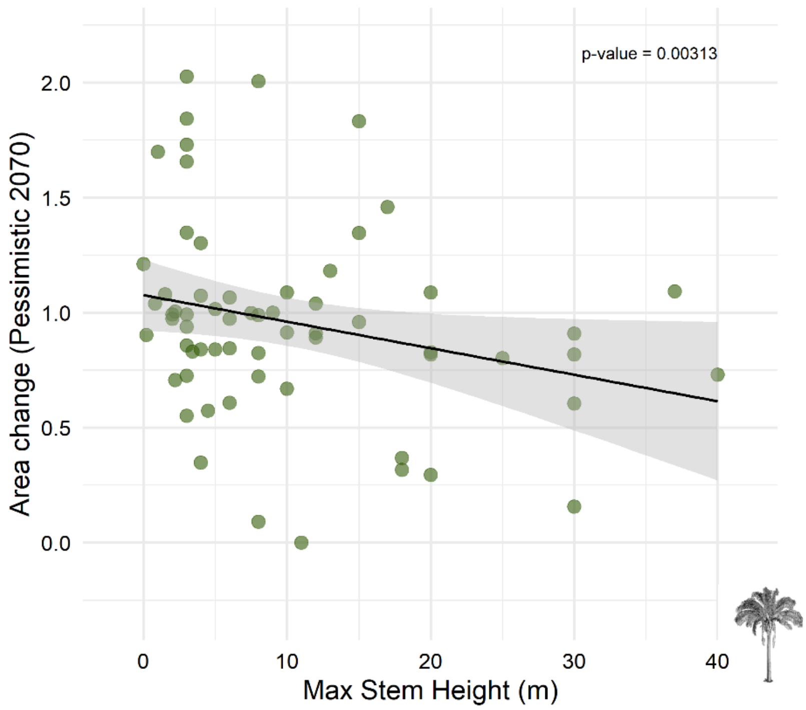

Figure 5: The effect of maximum stem height on area changes under the 2070 pessimistic climate scenario. Each point represents one of the 63 palm species from the Atlantic Forest. The variation in area change is illustrated for species with the smallest and largest stem heights, with significance assessed using phylogenetic generalized least squares (PGLS) regression models. The shaded areas around the regression lines represent the standard error of the estimates, and the p-value is provided. The palm illustrations used were sourced from Elias et al., 2018.

4. Discussion

Climate change has significantly impacted the distribution of plant species, and our projections for the Atlantic Forest reveal substantial changes in palm species richness, with dynamic patterns of losses and gains across the biome. More pessimistic scenarios indicate the potential complete loss of climatically suitable areas for some species, while others may expand their ranges under future climate conditions. Our results also show that palms with restricted distributions and greater stem heights are particularly susceptible to losses of suitable areas, emphasizing the need to integrate functional traits into management strategies in biodiverse and threatened biomes such as the Atlantic Forest.

Our findings reveal a dynamic of losses and gains in palm species, highlighting a complex structural reorganization of the biome in response to climate change already seen for other angiosperms (Zwiener et al., 2017). While a large portion of the biome is expected to maintain species richness levels similar to current conditions, projections indicate significant species losses in highly diverse regions, such as the northern coastal and central areas of the biome. In contrast, less diverse areas showed a mixed scenario, with potential for both losses and gains, suggesting a redistribution of biodiversity throughout the biome. These findings align with previous projections indicating that certain regions of the Atlantic Forest may experience an increase in plant species richness under future climate change scenarios (Zwiener et al., 2017). Palm species richness, in particular, is strongly influenced by climatic factors, with water availability and precipitation emerging as the main determinants of this diversity (Bjorholm et al., 2005; Renniger & Phillips, 2016). Consequently, climate changes that project drier conditions may exacerbate these dynamics, disproportionately impacting high-richness areas and altering current distribution patterns of palm species.

Our results highlight that most species are projected to face a decrease in climatically suitable areas, particularly under optimistic scenarios for 2050 (71%) and 2070 (68%). Species such as *Syagrus insignis*, *Attalea apoda*, and *Acrocomia intumescens* are particularly vulnerable, with losses exceeding 90% of their suitable areas. These projections corroborate previous studies that also indicated substantial declines in climatically suitable areas for palms of the genus *Astrocaryum* and *Euterpe* under climate change (Cordeiro et al., 2023; Marques et al., 2024). For example, *Euterpe edulis* was projected to lose climatically suitable areas in our study, the some pattern found by Sales et al. (2021). In contrast, some species, such as *Geonoma rodeiensis, Bactris glassmanii, Syagrus romanzoffiana, Trithrinax acanthocoma, Attalea humilis, Bactris bahiensis, Butia paraguayensis, Bactris vulgaris, Astrocaryum aculeatissimum Attalea funifera, Geonoma elegans, Bactris ferruginea, Syagrus lorenzoniorum, Desmoncus orthacanthos, Acrocomia aculeata* and *Desmoncus polyacanthos* may expand their distributions under all future scenarios. These differences reflect species-specific climatic sensitivities and the potential for biogeographic reorganization within the biome, which could significantly impact biodiversity and ecosystem services (Zwiener et al., 2017). Thus, our findings underscore the urgent need for conservation strategies prioritizing the most vulnerable species, alongside the management of resilient species, to preserve biodiversity and ensure the maintenance of ecosystem services in the biome.

Our results also revealed that the baseline distribution area is positively correlated with changes in climatically suitable areas across all future climate scenarios. This suggests that species with more restricted distributions tend to reduce their future distribution areas, while species with broader distributions have the potential to expand their areas. Species with restricted ranges are expected to lose more area than widely distributed ones, as they tend to be more specialized, with narrower ecological niches and, consequently, may be more vulnerable to climate change (Schwartz et al., 2006; Slatyer et al., 2013). On the other hand, species with broader distribution areas, being more generalist and occupying a wider range of habitats, exhibit greater tolerance to different environmental conditions and, therefore, have the potential to benefit from these changes by exploring new suitable areas (Boulangeat et al., 2012).

As predicted, our results indicated a negative relationship between stem height and the proportion of suitable area in future climate change scenarios. This suggests that as stem height increases, the potential distribution area of the species tends to decrease, reinforcing the idea that acaulescent or short-stemmed palms are more resilient in drier environments and under water stress conditions (Cássia-Silva et al., 2022). These findings align with a study conducted on Australian plant species, which revealed that in future climatic scenarios, the most vulnerable species are those that are relatively tall, in combination with leaf and seed characteristics (Andrew et al., 2022). Indeed, large trees are more sensitive to drought due to their higher ecological vulnerability, as resistance to water stress tends to increase with tree height (Bennet et al., 2015). Large trees need to transport water over greater distances, which involves overcoming the effects of gravity and the additional resistance generated by the length of the hydraulic pathway, resulting in greater challenges related to water conduction (Ryan et al., 2006).

5. Conclusion

This study highlights regions within the Atlantic Forest with the highest potential for palm species loss and gain, with the greatest projected losses for the northern coast and central areas of the biome. We estimate changes in climatically suitable areas, both in terms of losses and potential expansions, providing a broader view of the future of palms in the biome. For example, species such as *Syagrus insignis*, *Attalea apoda*, and *Acrocomia intumescens* are projected to lose all or the majority of their suitable habitat under future climate scenarios, highlighting their heightened vulnerability to climate change. Our results also indicate that species with more restricted distributions and taller stems are more likely to lose suitable areas in future climate change scenarios compared to species with wider distributions and shorter stems. These findings reinforce the importance of integrating species' functional traits into conservation strategies, especially for those most vulnerable to climate change (Gallagher et al., 2021). By considering life history traits, it is possible to identify species that are likely to face greater challenges, allowing for more effective conservation actions to be prioritized. The conservation of palms is essential for maintaining the biodiversity of the Atlantic Forest, a biome highly threatened by human activities. Thus, integrating data on functional traits into conservation policies is crucial for mitigating the impacts of climate change and ensuring the resilience of this vital ecosystem.

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Author contributions:

Júlia Angeli: Conceptualization, Data Curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing. **Daniela Custódio Talora:** Conceptualization, Supervision, Validation, Writing - Review & Editing. **Gabriela Alves-Ferreira:** Formal analysis, Methodology, Software. **Neander Marcel Heming:** Formal analysis, Methodology, Software, Validation. **Eliana Cazetta:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing - Review & Editing.

Conflict of interest

The authors declare no conflicts of interest.

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Supplementary material

Figure S1: Phylogenetic tree of the 63 palm species

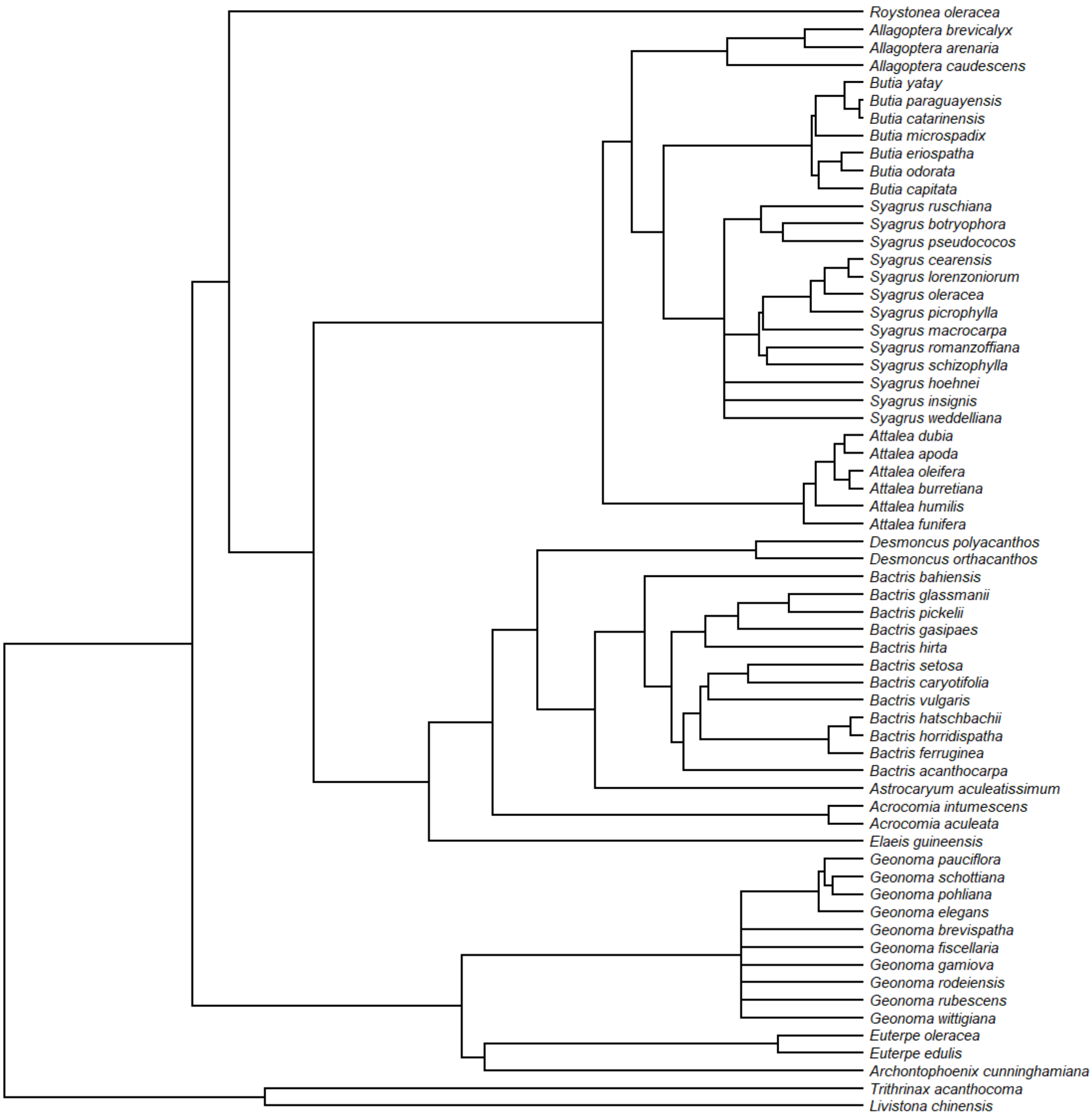
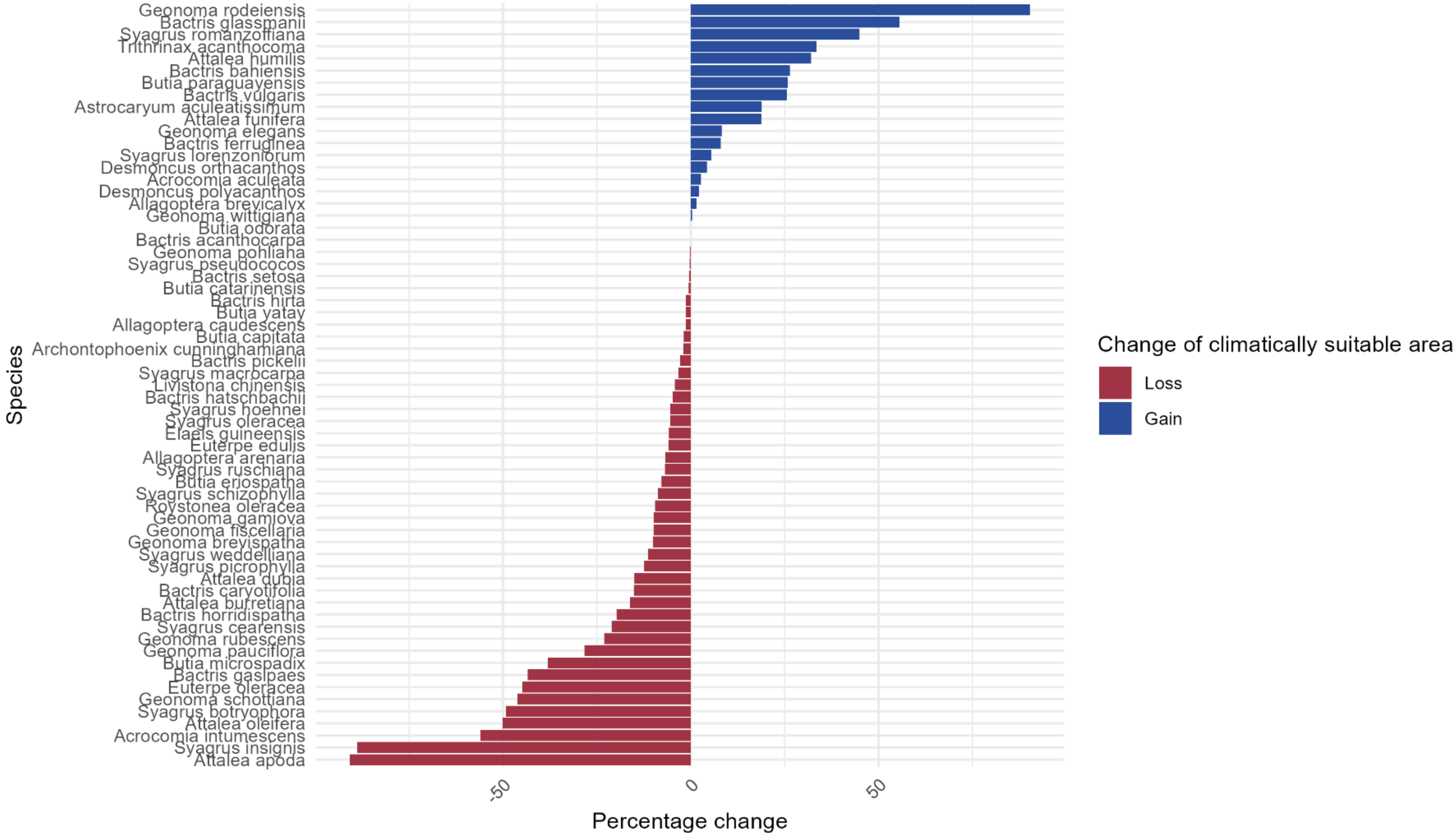
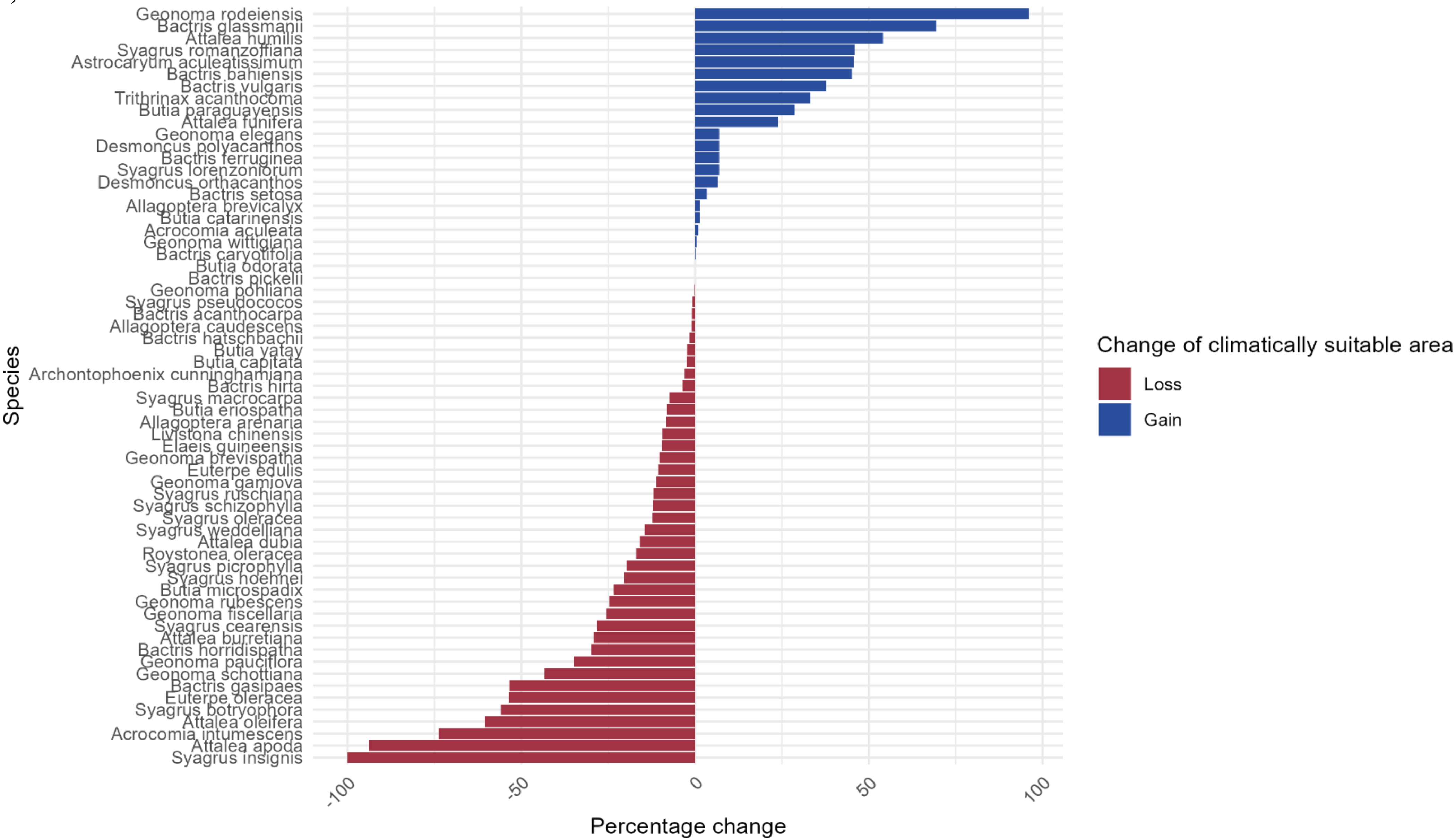


Figure S2: The graphs illustrate the percentage of area lost (red) and the percentage of area gained (blue) in each future climate change scenario, for each palm species.

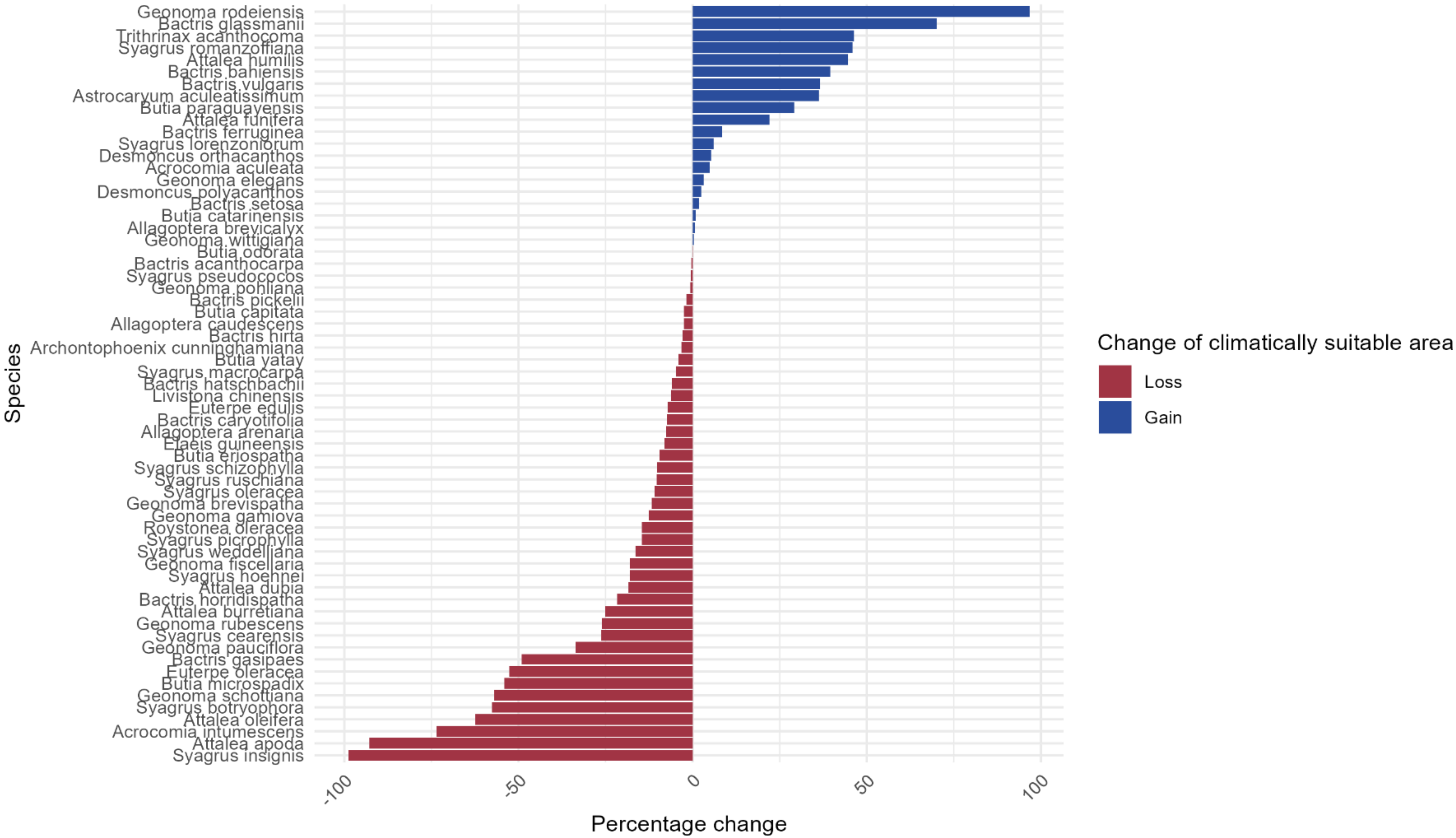
(a) Optimistic 2050



(b) Pessimistic 2050



(c) Optimistic 2070



(d) Pessimistic 2070

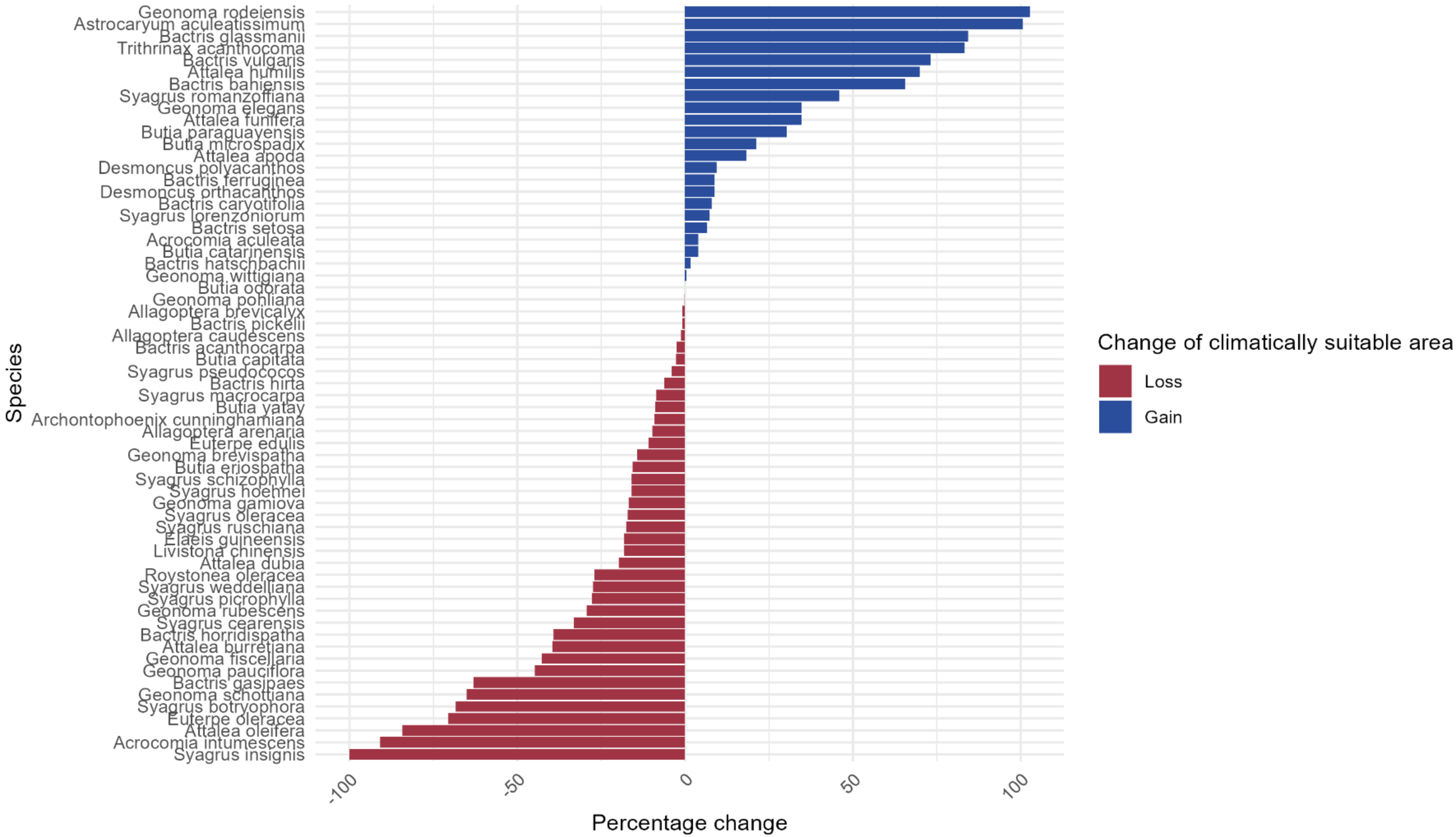


Table S1: Table showing palm species, references, total number of clean records, Atlantic Forest records, and selected bioclimatic vari ables for each species.

Species	Reference	All records	Atlantic Forest records	Selected bioclimatic variables
Acrocomia aculeata	Cerqueira et al., 2023/ Bello et al., 2017	841	74	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Acrocomia intumescens	Cerqueira et al., 2023	35	20	bio_16/ bio_19/ bio_4/ bio_7/ bio_8
Allagoptera arenaria	Cerqueira et al., 2023/Bello et al., 2017	94	72	bio_1/ bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Allagoptera brevicalyx	Cerqueira et al., 2023	23	17	bio_13/ bio_19/ bio_4/ bio_8
Allagoptera caudescens	Cerqueira et al., 2023	69	65	bio_12/ bio_13/ bio_14/ bio_3/ bio_5
Archontophoenix cunninghamiana	Bello et al., 2017	484	40	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Astrocaryum aculeatissimum	Cerqueira et al., 2023/Bello et al., 2017	91	88	bio_15/ bio_16/ bio_2/ bio_3/ bio_4/ bio_8
Attalea apoda	Cerqueira et al., 2023	5	5	bio_13/ bio_15/ bio_2/ bio_3
Attalea burretiana	Cerqueira et al., 2023	27	23	bio_13/ bio_15/ bio_18/ bio_3/ bio_4/ bio_7/ bio_8
Attalea dubia	Cerqueira et al., 2023/Bello et al., 2017	34	29	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Attalea funifera	Cerqueira et al., 2023	39	32	bio_10/ bio_16/ bio_18/ bio_19/ bio_4/ bio_7/ bio_8
Attalea humilis	Cerqueira et al., 2023	45	41	bio_12/ bio_19/ bio_3/ bio_5
Attalea oleifera	Cerqueira et al., 2023/Bello et al., 2017	28	15	bio_12/ bio_14/ bio_18/ bio_3/ bio_4/ bio_8
Attalea seabrensis *	Cerqueira et al., 2023	10	0	
Attalea voeksii **	Cerqueira et al., 2023	1		
Bactris acanthocarpa	Cerqueira et al., 2023/Bello et al., 2017	268	39	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5/ bio_8
Bactris bahiensis	Cerqueira et al., 2023	34	33	bio_12/ bio_14/ bio_3/ bio_5
Bactris caryotifolia	Cerqueira et al., 2023	32	30	bio_12/ bio_18/ bio_19/ bio_3/ bio_5
Bactris ferruginea	Cerqueira et al., 2023	50	48	bio_12/ bio_14/ bio_18/ bio_19/ bio_3/ bio_8
Bactris gasipaes	Bello et al., 2017	551	17	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Bactris glassmanii	Cerqueira et al., 2023	29	23	bio_17/ bio_19/ bio_4/ bio_8
Bactris hatschbachii	Cerqueira et al., 2023	12	11	bio_12/ bio_17/ bio_3/ bio_4/ bio_5
Bactris hirta	Cerqueira et al., 2023	280	31	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5/ bio_8

Bactris horridispatha	Cerqueira et al., 2023	14	11	bio_12/ bio_15/ bio_16/ bio_18/ bio_3/ bio_4/ bio_8
Bactris pickelli	Cerqueira et al., 2023	31	23	bio_10/ bio_19/ bio_2/ bio_3/ bio_4/ bio_8
Bactris setosa	Cerqueira et al., 2023/Bello et al., 2017	160	136	bio_12/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Bactris soeiroana **	Cerqueira et al., 2023	3		
Bactris timbuiensis **	Cerqueira et al., 2023	4		
Bactris vulgaris	Cerqueira et al., 2023	59	57	bio_11/ bio_13/ bio_15/ bio_19/ bio_3/ bio_8/ bio_9
Butia capitata	Bello et al., 2017	160	20	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Butia catarinensis	Cerqueira et al., 2023	19	17	bio_12/ bio_13/ bio_18/ bio_2/ bio_5/ bio_7/ bio_9
Butia eriospatha	Cerqueira et al., 2023	59	47	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Butia exilata **	Cerqueira et al., 2023	4		
Butia microspadix	Cerqueira et al., 2023	12	5	bio_12/ bio_18/ bio_2/ bio_4/ bio_7/ bio_8
Butia odorata	Cerqueira et al., 2023	201	21	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Butia paraguayensis	Cerqueira et al., 2023	95	10	bio_12/ bio_13/ bio_18/ bio_2/ bio_5/ bio_7/ bio_8/ bio_9
Butia pubispatha **	Cerqueira et al., 2023	1		
Butia yatay	Cerqueira et al., 2023	63	3	bio_1 /bio_10 /bio_13 /bio_14 /bio_15 /bio_18 /bio_19 /bio_2 /bio_8 /bio_9
Desmoncus orthacanthos	Cerqueira et al., 2023	238	67	bio_13 /bio_15 /bio_18 /bio_19 /bio_2 /bio_4 /bio_8
Desmoncus polyacanthos	Cerqueira et al., 2023	423	74	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4/ bio_5
Elaeis guineenses	Bello et al., 2017	1003	45	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Euterpe edulis	Cerqueira et al., 2023/Bello et al., 2017	446	351	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8/ bio_9
Euterpe oleracea	Bello et al., 2017	309	21	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_5
Geonoma bondariana **	Cerqueira et al., 2023	2		
Geonoma brevispatha	Cerqueira et al., 2023	107	36	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Geonoma conduruenses **	Cerqueira et al., 2023	2		
Geonoma elegans	Cerqueira et al., 2023/Bello et al., 2017	110	100	bio_10/ bio_12/ bio_18/ bio_19/ bio_2/ bio_3/ bio_7
Geonoma fiscellaria	Cerqueira et al., 2023	6	6	bio_13/ bio_15/ bio_2/ bio_3/ bio_4/ bio_5
Geonoma gamiova	Cerqueira et al., 2023/Bello et al., 2017	82	80	bio_12/ bio_16/ bio_19/ bio_2/ bio_5/ bio_7/ bio_8
Geonoma gastoniana **	Cerqueira et al., 2023	3		
Geonoma littoralis **	Cerqueira et al., 2023	1		
Geonoma kuhlmannii **	Cerqueira et al., 2023	4		

Geonoma pauciflora	Cerqueira et al., 2023/Bello et al., 2017	68	57	bio_13/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5
Geonoma pohliana	Cerqueira et al., 2023	129	108	bio_13/ bio_15/ bio_18/ bio_19/ bio_3/ bio_7/ bio_8
Geonoma rodeiensis	Cerqueira et al., 2023	10	10	bio_12/ bio_14/ bio_3/ bio_5
Geonoma rubescens	Cerqueira et al., 2023	16	15	bio_11/ bio_15/ bio_16/ bio_3/ bio_6/ bio_9
Geonoma schottiana	Cerqueira et al., 2023/Bello et al., 2017	232	209	bio_12/ bio_15/ bio_16/ bio_18/ bio_2/ bio_7/ bio_8
Geonoma trinervis **	Cerqueira et al., 2023	0		
Geonoma wittigiana	Cerqueira et al., 2023	7	7	bio_13/ bio_15/ bio_3/ bio_4/ bio_8
Livistona chinensis	Bello et al., 2017	523	35	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3/ bio_8
Phoenix sylvestris *	Bello et al., 2017	241	0	
Roystonea oleraceae	Bello et al., 2017	106	27	bio_1/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_3
Syagrus amicorum **	Cerqueira et al., 2023	2		
Syagrus ×andrequiceana **	Cerqueira et al., 2023	1		
Syagrus botryophora	Cerqueira et al., 2023	33	28	bio_17/ bio_18/ bio_19/ bio_2/ bio_5/ bio_8
Syagrus ×camposportoana **	Cerqueira et al., 2023	1		
Syagrus cearensis	Cerqueira et al., 2023	51	12	bio_14/ bio_16/ bio_18/ bio_19/ bio_2/ bio_4/ bio_8
Syagrus ×cipoensis **	Cerqueira et al., 2023	1		
Syagrus guaratinguensis **	Cerqueira et al., 2023	0		
Syagrus hoehnei	Cerqueira et al., 2023	11	10	bio_13/ bio_17/ bio_3/ bio_4/ bio_9
Syagrus insignis	Cerqueira et al., 2023	13	13	bio_13/ bio_2/ bio_3
Syagrus itapebiensis **	Cerqueira et al., 2023	1		
Syagrus kellyana **	Cerqueira et al., 2023	1		
Syagrus ×lacerdamourae **	Cerqueira et al., 2023	0		
Syagrus lorenzoniorum	Cerqueira et al., 2023	6	6	bio_12/ bio_14/ bio_5
Syagrus macrocarpa	Cerqueira et al., 2023	11	9	bio_10/ bio_13/ bio_15/ bio_18/ bio_19/ bio_3/ bio_4/ bio_7
Syagrus oleracea	Bello et al., 2017	84	22	bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4/ bio_5
Syagrus picrophylla	Cerqueira et al., 2023	13	10	bio_17/ bio_18/ bio_19/ bio_2/ bio_5/ bio_7/ bio_8
Syagrus pseudococos	Cerqueira et al., 2023/Bello et al., 2017	28	25	bio_12/ bio_19/ bio_2/ bio_3/ bio_4/ bio_5
Syagrus romanzifollia **	Bello et al., 2017	0		

Syagrus romanzoffiana	Cerqueira et al., 2023/Bello et al., 2017	1372	289	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_4
Syagrus ruschiana	Cerqueira et al., 2023/Bello et al., 2017	17	17	bio_16/ bio_4/ bio_7/ bio_8
Syagrus santosii **	Cerqueira et al., 2023	1		
Syagrus schizophylla	Cerqueira et al., 2023	72	43	bio_10/ bio_13/ bio_14/ bio_15/ bio_18/ bio_19/ bio_2/ bio_8/ bio_9
Syagrus ×serroana **	Cerqueira et al., 2023	1		
Syagrus ×tostana **	Cerqueira et al., 2023	1		
Syagrus weddelliana	Cerqueira et al., 2023	15	9	bio_14/ bio_18/ bio_19/ bio_2/ bio_3/ bio_5/ bio_8
Trithrinax acanthocoma	Cerqueira et al., 2023	8	5	bio_14/ bio_18/ bio_19/ bio_2/ bio_8

* Species without occurrence records in the Atlantic Forest after geographical bias correction, which were excluded from Ecological Niche Modeling.

** Species without the minimum of 5 occurrence records after geographical bias correction, which were excluded from Ecological Niche Modeling.

Table S2: List of 63 palm species with their functional traits and corresponding references.

Species	Habitat	Max Stem Height (m)	Max Stem Dia (cm)	Average Fruit Length (cm)	Average Fruit Width (cm)
Acrocomia aculeata ▪	Open-area	12	50	4.25	4.6
Acrocomia intumescens ▪	Forest-interior	8 ƚ	50 ˘ ˘	4.6	4.6
Allagoptera arenaria ▪	Open-area	0.2	15	1.6	1.15
Allagoptera brevicalyx ▪	Open-area	2	20 ˘ ˘	1.75	1.25
Allagoptera caudescens ▪	Open-area	8	25	4.25	3.25
Archontophoenix cunninghamiana ▪	Open-area	30	30	1.25	1.1
Astrocaryum aculeatissimum ▪	Open-area	8	15	5.5	3.5
Attalea apoda ▪	Open-area	13	36.7 ˘ ˘	6	3.3
Attalea burretiana ▪	Forest-interior	30 ƚ	40 ƚ ƚ	7.27	4.55
Attalea dubia ▪	Open-area	25	35	6.25	3
Attalea funifera ▪	Open-area	15	30	12.5	6
Attalea humilis ▪	Open-area	1 ƚ	-	6.5	5.25
Attalea oleifera ▪	Open-area	30	45	9	5
Bactris acanthocarpa ▪	Forest-interior	2	7	1.4	1.4
Bactris bahiensis ▪	Open-area	3	1	1.5	1.1
Bactris caryotifolia ▪	Forest-interior	1.5	2	1.4	1.4
Bactris ferruginea ▪	Open-area	10	10	1.65	1.65
Bactris gasipaes ▪	Open-area	18	25	5	4
Bactris glassmanii ▪	Open-area	3	2	1.3	1.3
Bactris hatschbachii ▪	Forest-interior	5	2.5	2.05	2
Bactris hirta ▪	Open-area	3	2	0.75	0.75
Bactris horridispatha ▪	Forest-interior	6	3	3.25	2.4
Bactris pickelii ▪	Forest-interior	3	1.5	1.35	1.35
Bactris setosa ▪	Forest-interior	6	4	1.25	1.75
Bactris vulgaris ▪	Open-area	3	3.5	1.7	1.7
Butia capitata ▪	Open-area	6	50	2.65	1.7
Butia catarinensis ▪	Open-area	0.8 ƚ	30 ƚ	2.5	1.2
Butia eriospatha ▪	Open-area	6	50	1.9	1.75
Butia microspadix ▪	Open-area	-	-	2	1.05
Butia odorata ▪	Open-area	9 ƚ	30 ƚ	2.2	1.85

Butia paraguayensis ▪	Open-area	4	20	2.95	1.85
Butia yatay ▪	Open-area	12	40	3.6	2.65
Desmoncus orthacanthos ▪	Open-area	20	3	1.49	1.42
Desmoncus polyacanthos ▪	Forest-interior	37	3.5	2	1
Elaeis guineensis ▪	Open-area	30	50	4.25	2.5
Euterpe edulis ▪	Forest-interior	12	15	1.2	1.2
Euterpe oleracea ▪	Forest-interior	20	20	1.5	1.5
Geonoma brevispatha ƚ	Forest-interior	3	4	0.95	0.7
Geonoma elegans ▪	Forest-interior	3	1	0.95	0.72
Geonoma fiscellaria ƚ	Forest-interior	4.5	4	1.6	1.4
Geonoma gamiova ⁼	Forest-interior	3.4	3	1.225	0.95
Geonoma pauciflora ▪	Forest-interior	3	1.5	0.96	0.78
Geonoma pohliana ▪	Forest-interior	7.5	7	1	0.735
Geonoma rodeiensis ▪▪	Forest-interior	3	3.15 ˘˘	1	0.84 ˘˘
Geonoma rubescens ƚ	Forest-interior	2.2	2.5	1	0.9
Geonoma schottiana ▪	Forest-interior	4	4	0.93	0.825
Geonoma wittigiana ƚ	Forest-interior	2.2	1.4	0.6 ⁼⁼	0.55
Livistona chinensis ▪	Open-area	20	30	3	2.8
Roystonea oleracea ▪	Open-area	40	66	1.5	0.9
Syagrus botryophora ▪	Open-area	18	25	4.25	2.6
Syagrus cearensis ▪	Open-area	10	18	3.75	3.5
Syagrus hoehnei ≈	Forest-interior	5	15	3.15	2.6
Syagrus insignis ≈ ≈	Forest-interior	11	10	2.05	1.8
Syagrus lorenzoniorum ▪	Forest-interior	4	16	2.75	2.5
Syagrus macrocarpa ▪	Forest-interior	10	20	7.75	3.75
Syagrus oleracea ▪	Open-area	20	30	5.5	2.35
Syagrus picrophylla ▪	Forest-interior	8	20	3.5	2.3
Syagrus pseudococos ▪	Forest-interior	15	25	6.5	3.9
Syagrus romanzoffiana ▪	Open-area	17	50	2.5	1.5
Syagrus ruschiana ▪	Open-area	8	12	2.5	2
Syagrus schizophylla ▪	Open-area	4	15	2.75	2
Syagrus weddelliana ˘	Forest-interior	3	10	1.85	1.75
Trithrinax acanthocoma ƚ	Open-area	15	35	0.94 ˘˘	1.85

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˘ ˘ Genus average

Table S3: Bioclimatic variables derived from temperature and precipitation data obtained from WorldClim v2.1 (Fick and Hijmans, 2017).

Variable	Description
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Table S4: Change in suitable area for each species across future scenarios relative to baseline scenario (Ratio: Future Area / Current Area), where 0 indicates total loss of suitable area, 1 indicates stability, values greater than 1 indicate expansion, and values below 1 indicate contraction.

Species	Ratio optimistic 2050	Ratio pessimistic 2050	Ratio optimistic 2070	Ratio pessimistic 2070
Acrocomia aculeata	1.03	1.01	1.05	1.04
Acrocomia intumescens	0.44	0.26	0.26	0.09
Allagoptera arenaria	0.93	0.92	0.92	0.90
Allagoptera brevicalyx	1.02	1.01	1.01	0.99
Allagoptera caudescens	0.99	0.99	0.97	0.99
Archontophoenix cunninghamiana	0.98	0.97	0.97	0.91
Astrocaryum aculeatissimum	1.19	1.46	1.36	2.01
Attalea apoda	0.09	0.06	0.07	1.18
Attalea burretiana	0.84	0.71	0.75	0.60
Attalea dubia	0.85	0.84	0.82	0.80
Attalea funifera	1.19	1.24	1.22	1.35
Attalea humilis	1.32	1.54	1.45	1.70
Attalea oleifera	0.50	0.40	0.38	0.16
Bactris acanthocarpa	1.00	0.99	1.00	0.97
Bactris bahiensis	1.26	1.45	1.40	1.66
Bactris caryotifolia	0.85	1.00	0.93	1.08
Bactris ferruginea	1.08	1.07	1.08	1.09
Bactris gasipaes	0.57	0.47	0.51	0.37
Bactris glassmanii	1.56	1.69	1.70	1.84
Bactris hatschbachii	0.95	0.98	0.94	1.02
Bactris hirta	0.99	0.96	0.97	0.94
Bactris horridispatha	0.80	0.70	0.78	0.61
Bactris pickelii	0.97	1.00	0.98	0.99
Bactris setosa	1.00	1.03	1.02	1.07
Bactris vulgaris	1.26	1.38	1.37	1.73
Butia capitata	0.98	0.98	0.98	0.97
Butia catarinensis	0.99	1.01	1.01	1.04
Butia eriospatha	0.92	0.92	0.90	0.84

Butia microspadix	0.62	0.77	0.46	1.21
Butia odorata	1.00	1.00	1.00	1.00
Butia paraguayensis	1.26	1.29	1.29	1.30
Butia yatay	0.99	0.98	0.96	0.91
Desmoncus orthacanthos	1.04	1.07	1.05	1.09
Desmoncus polyacanthos	1.02	1.07	1.02	1.09
Elaeis guineensis	0.94	0.90	0.92	0.82
Euterpe edulis	0.94	0.89	0.93	0.89
Euterpe oleracea	0.55	0.46	0.47	0.29
Geonoma brevispatha	0.90	0.90	0.88	0.86
Geonoma elegans	1.08	1.07	1.03	1.35
Geonoma fiscellaria	0.90	0.74	0.82	0.57
Geonoma gamiova	0.90	0.89	0.87	0.83
Geonoma pauciflora	0.72	0.65	0.66	0.55
Geonoma pohliana	1.00	1.00	0.99	1.00
Geonoma rodeiensis	1.90	1.96	1.97	2.03
Geonoma rubescens	0.77	0.75	0.74	0.71
Geonoma schottiana	0.54	0.57	0.43	0.35
Geonoma wittigiana	1.00	1.00	1.00	1.00
Livistona chinensis	0.96	0.91	0.94	0.82
Roystonea oleracea	0.91	0.83	0.85	0.73
Syagrus botryophora	0.51	0.44	0.42	0.32
Syagrus cearensis	0.79	0.72	0.74	0.67
Syagrus hoehnei	0.95	0.80	0.82	0.84
Syagrus insignis	0.11	0.00	0.01	0.00
Syagrus lorenzoniorum	1.06	1.07	1.06	1.07
Syagrus macrocarpa	0.97	0.93	0.95	0.91
Syagrus oleracea	0.95	0.88	0.89	0.83
Syagrus picrophylla	0.88	0.80	0.85	0.72
Syagrus pseudococos	1.00	0.99	0.99	0.96
Syagrus romanzoffiana	1.45	1.46	1.46	1.46
Syagrus ruschiana	0.93	0.88	0.90	0.82
Syagrus schizophylla	0.91	0.88	0.90	0.84

Syagrus weddelliana	0.89	0.85	0.84	0.73
Trithrinax acanthocoma	1.33	1.33	1.46	1.83

Table S5 - Model selection for the response variable: area change ratio under the optimistic 2050 scenario.

Rank	Model	df	AICc	delta	weight
1	Ratio Optimistic 2050 ~ log Current Area	2	65.14	0	0.412
2	Ratio Optimistic 2050 ~ Habitat + log Current Area	3	67.23	2.09	0.144
3	Ratio Optimistic 2050 ~ log Current Area + log Max Stem Height	3	67.29	2.15	0.140
4	Ratio Optimistic 2050 ~ log Current Area + log Average Fruit Width	3	67.32	2.18	0.138
5	Ratio Optimistic 2050 ~ Habitat + log Current Area + log Max Stem Height	4	69.44	4.30	0.048
6	Ratio Optimistic 2050 ~ log Current Area + log Average Fruit Width + log Max Stem Height	4	69.46	4.32	0.047
7	Ratio Optimistic 2050 ~ Habitat + log Current Area + log Average Fruit Width	4	69.50	4.35	0.046
8	Ratio Optimistic 2050 ~ Habitat + log Current Area + log Average Fruit Width + log Max Stem Height	5	71.67	6.52	0.015
9	NULL	1	76.27	11.12	0.001
10	Ratio Optimistic 2050 ~ log Max Stem Height	2	76.96	11.82	0.001
11	Ratio Optimistic 2050 ~ log Average Fruit Width	2	77.68	12.54	0.001
12	Ratio Optimistic 2050 ~ Habitat	2	78.36	13.22	0.000
13	Ratio Optimistic 2050 ~ Habitat + log Max Stem Height	3	79.01	13.87	0.000
14	Ratio Optimistic 2050 ~ log Average Fruit Width + log Max Stem Height	3	79.14	14.00	0.000
15	Ratio Optimistic 2050 ~ Habitat + log Average Fruit Width	3	75.84	14.70	0.000
16	Ratio Optimistic 2050 ~ Habitat + log Average Fruit Width + log Max Stem Height	4	81.27	16.13	0.000

Table S6 - Model selection for the response variable: area change ratio under the pessimistic 2050 scenario.

Rank	Model	df	AICc	delta	weight
1	Ratio Pessimistic 2050 ~ log Current Area	2	79.84	0	0.380
2	Ratio Pessimistic 2050 ~ log Current Area + log Max Stem Height	3	81.57	1.73	0.159
3	Ratio Pessimistic 2050 ~ log Current Area + log Average Fruit	3	81.60	1.76	0.157
4	Ratio Pessimistic 2050 ~ Habitat + log Current Area	3	82.04	2.20	0.126
5	Ratio Pessimistic 2050 ~ log Current Area + log Average Fruit Width + log Max Stem Height	4	83.74	3.90	0.054
6	Ratio Pessimistic 2050 ~ Habitat + log Current Area + log Max Stem Height	4	83.85	4.01	0.051
7	Ratio Pessimistic 2050 ~ Habitat + log Current Area + log Average Fruit Width	4	83.88	4.04	0.050
8	Ratio Pessimistic 2050 ~ Habitat + log Current Area + log Average Fruit Width + log Max Stem Height	5	86.10	6.26	0.016
9	NULL	1	90.57	10.72	0.001
10	Ratio Pessimistic 2050 ~ log Max Stem Height	2	92.55	12.71	0.000
11	Ratio Pessimistic 2050 ~ log Average Fruit Width	2	92.56	12.72	0.000
12	Ratio Pessimistic 2050 ~ Habitat	2	92.70	12.85	0.000
13	Ratio Pessimistic 2050 ~ log Average Fruit Width + log Max Stem Height	3	94.72	14.88	0.000
14	Ratio Pessimistic 2050 ~ Habitat + log Max Stem Height	3	94.75	14.91	0.000
15	Ratio Pessimistic 2050 ~ Habitat + log Average Fruit Width	3	94.76	14.92	0.000
16	Ratio Pessimistic 2050 ~ Habitat + log Average Fruit Width + log Max Stem Height	4	97.00	17.16	0.000

Table S7 - Model selection for the response variable: area change ratio under the optimistic 2070 scenario.

Rank	Model	df	AICc	delta	weight
1	Ratio Optimistic 2070 ~ log Current Area	2	80.98	0	0.419
2	Ratio Optimistic 2070 ~ log Current Area + log Average Fruit Width	3	83.13	2.14	0.143
3	Ratio Optimistic 2070 ~ Habitat + log Current Area	3	83.17	2.19	0.140
4	Ratio Optimistic 2070 ~ log Current Area + log Max Stem Height	3	83.18	2.20	0.139
5	Ratio Optimistic 2070 ~ Habitat + log Current Area + log Average Fruit Width	4	85.39	4.41	0.046
6	Ratio Optimistic 2070 ~ log Current Area + log Average Fruit Width + log Max Stem Height	4	85.40	4.42	0.046
7	Ratio Optimistic 2070 ~ Habitat + log Current Area + log Max Stem Height	4	85.45	4.47	0.044
8	Ratio Optimistic 2070 ~ Habitat + log Current Area + log Average Fruit Width + log Max Stem Height	5	85.46	6.76	0.014
9	NULL	1	87.74	10.64	0.002
10	Ratio Optimistic 2070 ~ log Max Stem Height	2	91.62	11.91	0.001
11	Ratio Optimistic 2070 ~ log Average Fruit Width	2	92.89	12.22	0.001
12	Ratio Optimistic 2070 ~ Habitat	2	93.21	12.77	0.000
13	Ratio Optimistic 2070 ~ log Average Fruit Width + log Max Stem Height	3	95.04	14.06	0.000
14	Ratio Optimistic 2070 ~ Habitat + log Max Stem Height	3	95.07	14.09	0.000
15	Ratio Optimistic 2070 ~ Habitat + log Average Fruit Width	3	95.41	14.42	0.000
16	Ratio Optimistic 2070 ~ Habitat + log Average Fruit Width + log Max Stem Height	4	97.31	16.32	0.000

Table S8 - Model selection for the response variable: area change ratio under the pessimistic 2070 scenario.

Rank	Model	df	AICc	delta	weight
1	Ratio Pessimistic 2070 ~ log Current Area + Max Stem Height	3	102.00	0	0.327
2	Ratio Pessimistic 2070 ~ Habitat + log Current Area	4	103.50	1.50	0.154
3	Ratio Pessimistic 2070 ~ Max Stem Height	2	103.64	1.64	0.143
4	Ratio Pessimistic 2070 ~ log Current Area + Average Fruit Width + Max Stem Height	4	103.90	1.90	0.126
5	Ratio Pessimistic 2070 ~ Habitat + Max Stem Height	3	105.11	3.11	0.069
6	Ratio Pessimistic 2070 ~ Habitat + log Current Area + Average Fruit Width + Max Stem Height	5	105.45	3.45	0.058
7	Ratio Pessimistic 2070 ~ Average Fruit Width + Max Stem Height	3	105.79	3.79	0.049
8	Ratio Pessimistic 2070 ~ Habitat + Average Fruit Width + Max Stem Height	4	107.32	5.32	0.022
9	NULL	1	108.67	6.66	0.011
10	Ratio Pessimistic 2070 ~ log Current Area	2	109.03	7.03	0.009
11	Ratio Pessimistic 2070 ~ log Current Area + Average Fruit Width	3	109.62	7.62	0.007
12	Ratio Pessimistic 2070 ~ Average Fruit Width	2	109.93	7.93	0.006
13	Ratio Pessimistic 2070 ~ Habitat	2	110.58	8.58	0.004
14	Ratio Pessimistic 2070 ~ Habitat + log Current Area	3	111.05	9.05	0.003
15	Ratio Pessimistic 2070 ~ Habitat + log Current Area + Average Fruit Width	4	111.63	9.63	0.002
16	Ratio Pessimistic 2070 ~ Habitat + Average Fruit Width	3	111.86	9.86	0.002

Conclusão geral

As mudanças climáticas, evidenciadas pelo aquecimento global e aumento da frequência de eventos extremos, como ondas de calor e inundações, reforçam a urgência de compreender e mitigar seus impactos sobre as espécies. Compreender a distribuição espacial da biodiversidade e suas respostas a essas mudanças é essencial para desenvolver estratégias de conservação eficazes, garantindo a sobrevivência de espécies fundamentais, como as palmeiras, que desempenham um papel-chave na estrutura e no funcionamento das florestas. Nosso primeiro capítulo identificou regiões de alta riqueza de palmeiras na Mata Atlântica, especialmente nos litorais nordeste e sudeste do Brasil, reforçando a importância de concentrar esforços de conservação nessas áreas de biodiversidade tão rica. Observamos que algumas espécies possuem áreas de distribuição muito restritas, como *Syagrus insignis*, *Attalea apoda* e *Butia yatay*, o que as torna particularmente vulneráveis à perda de habitat e às mudanças ambientais. Isso destaca a necessidade de ações específicas para reduzir os riscos de extinção dessas espécies. Além disso, ao identificarmos traços funcionais relacionados ao tamanho da área de distribuição, como altura do caule e largura do fruto, percebemos como essas características podem ser ferramentas úteis para guiar estratégias de conservação, especialmente em regiões como a Mata Atlântica, onde a fragmentação e a perda de biodiversidade são preocupantes.

No segundo capítulo, as projeções apontam para uma redução significativa na diversidade de palmeiras em regiões de alta riqueza, como o litoral norte e as áreas centrais da Mata Atlântica, enquanto em áreas menos diversas, o cenário é misto, com tanto perdas quanto ganhos. Além disso, os resultados sugerem que algumas espécies podem enfrentar a perda total das áreas climaticamente adequadas, enquanto outras podem expandir suas distribuições, se adaptando às condições climáticas futuras. Observamos também que as palmeiras com distribuição mais restrita e caules mais altos tendem a ser mais vulneráveis à perda de áreas climáticas adequadas.

Portanto, é fundamental que as políticas de conservação e manejo de áreas protegidas integrem não apenas a preservação dos habitats, mas também o monitoramento constante das condições ambientais e dos traços funcionais das espécies. Isso é crucial para assegurar a sobrevivência das palmeiras e para manter a biodiversidade da Mata Atlântica. Com as mudanças climáticas avançando de forma acelerada, é urgente adotarmos uma abordagem estratégica e eficaz, que busque minimizar as perdas, ao mesmo tempo que fomente a adaptação e a recuperação das espécies mais vulneráveis. Assim, poderemos garantir a resiliência da Mata Atlântica e sua capacidade de enfrentar os desafios climáticos no futuro.