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Scientific Article

IMPACTS OF CLIMATE CHANGE ON THE NATURAL DISTRIBUTION OF SPECIES OF LOWLAND HIGH AND LOW IN THE AMAZON

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ABSTRACT

The areas of Amazonian floodplains have added ecological value to their multiple ecosystem services, including water supply, local climate regulation, biodiversity with a marked number of endemic species, and diversity of micro-habitat. Considering the importance of conserving these environments, this study aimed to analyze the behavior and delimit the areas of the natural distribution of forest species *Alchornea castaneifolia* (Willd.) A. Juss and *Laetia corymbulosa* (lowland low), *Maquira coriacea* (H.Karst.) C.C. Berg (Moraceae), and *Ocotea cymbarum* Kunth (high floodplain), besides evaluating the potential impacts of climate change on the future distribution inferring on its conservation. The potential species distribution was modeled using Environmental Modelling & Software, by employing algorithms such as Bioclim, Domain, Maximum Entropy, Random Forests, and Support Vector Machine (SVM). The projections indicate that climate change threatens the occurrence of floodplain species. Under the SSP 585 scenario for both periods, the four species studied will lose areas of climatic adequacy until the end of the 21st century, especially in the Brazilian Amazon. The study shows the need to increase socio-environmental responsibility through conserving current protected areas in freshwater ecosystems and implementing new priority areas for conserving wetlands (Ramsar Sites) in the Amazon. Such measures are essential to ensure in situ conservation and protect them from habitat loss.

Keywords: Forest conservation; Wetlands; Protected areas.

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IMPACTOS DAS MUDANÇAS CLIMÁTICAS NA DISTRIBUIÇÃO NATURAL DE ESPÉCIES DE VÁRZEA ALTA E BAIXA NA AMAZÔNIA

RESUMO – As áreas de várzeas amazônicas possuem valor ecológico agregado aos seus múltiplos serviços ecossistêmicos, incluindo o abastecimento de água, regulagem do clima local, biodiversidade com um número acentuado de espécies endêmicas e com diversidade de micro-habitat. Considerando a importância da conservação desses ambientes, este estudo objetivou analisar o comportamento e delimitar as áreas de distribuição natural das espécies florestais *Alchornea castaneifolia* (Willd.) A. Juss e *Laetia corymbulosa* (várzea baixa) e *Maquira coriacea* (H. Karst.) C.C. Berg (Moraceae) e *Ocotea cymbarum* Kunth (várzea alta), além de avaliar os impactos potenciais das mudanças climáticas sobre a distribuição futura, inferindo sobre a sua conservação. A modelagem de distribuição potencial das espécies foi feita com o uso do Environmental Modelling & Software, a partir dos algoritmos como: Bioclim, Domain, Maximum Entropy, Random Forests e Support Vector Machine (SVM). As projeções indicam que as mudanças climáticas representam ameaça à ocorrência das espécies de várzea. Sob o cenário SSP 585 para ambos os períodos, as quatro espécies estudadas perderão áreas de adequação climática até o final do século XXI, principalmente, na Amazônia brasileira. O estudo mostra a necessidade de aumentar a responsabilidade socioambiental para conservação das áreas protegidas atuais em ecossistemas de água doce e, implementar novas áreas prioritárias para a conservação de zonas úmidas (Sítios Ramsar) na Amazônia. Tais medidas são fundamentais para garantir a conservação in situ e protegê-las de uma perda de habitat.

Palavras-Chave: Conservação florestal; Áreas úmidas; Áreas protegidas.

1. INTRODUCTION

The report of the Intergovernmental Panel on Climate Change (IPCC, 2021) shows that the global average temperature projections for the year 2030 may exceed 1.5º C, while Brazil points to an increase of 7.5º C. These global climate changes threaten biodiversity, urban and natural ecosystems (De Faria et al., 2021), the hydrological cycle, and the maintenance of life on the planet (Huang et al., 2021).

Influenced by hydrographic, climatic, edaphic, and floristic factors, wetland species have an important role in the Amazon region, especially for the balance of the ecosystem, for the maintenance of riparian forests, as a food source for fish and animals, and others (Wittmann et al., 2022). Approximately 70% of the floodplain areas of the Amazon are covered by forests (Wittmann et al., 2006). It is one of the ecosystems impacted by man, mainly due to access facilitated by water transport and the use of floodplains for agriculture (Renó; Novo, 2019).

The remaining floodplain forests are subjected to constant selective cuts to supply local, national, and even international timber markets (Wittmann et al., 2022). In evaluating the east-west gradient of floodplain forest depletion along the Solimões and Amazonas Rivers, it was found that in the eastern region of the basin, there were more degraded landscapes, showing a reduction in biodiversity (Renó; Novo, 2019).

The Amazon is the Brazilian biome with the largest number of protected areas in the country, with more than 50% of its area covered by some category of protection (MMA, 2022). However, the selection of priority areas for conservation is established, mainly, based on data on terrestrial organisms and ecosystems (Frederico et al., 2018), while the conservation of freshwater ecosystems has been in the background.

To promote the conservation and encourage the sustainable use of wetland environments, Brazil, since 1993, has been a signatory to the Ramsar Convention on Wetlands, a treaty that includes actions for the conservation of wetlands, such as the introduction of Ramsar Sites (RS). However, there are currently only nine Ramsar sites in the Brazilian Amazon, and they are estimated to cover less than a fifth of the region's wetlands (Anderson et al., 2019; Hess et al., 2015).

Studies of the potential distribution of forest species through ecological modeling have been carried out to verify their vulnerability to climate change and are essential to inferring the conservation strategies of species. In the methodological approach, it is necessary to use climatic variables and geographic coordinates of the species that can be found in databases, expeditions of research groups, and information recorded in the literature (Cordeiro et al., 2023).

Climate change causes a reduction in the area suitable for the occurrence of several species of biodiversity (Huang et al., 2021). Based on the results of ecological modeling of the current and future potential distribution of species, it is possible to identify the zones of occurrence in different scenarios to understand habitat preferences and apply conservation measures, avoiding a reduction in biodiversity (Cordeiro et al., 2023).

The objective of this study was to analyze the behavior and delimit areas of natural distribution of floodplain forest species in the Amazon, in climate change scenarios to verify the current and future distribution of tree species inferring on the conservation of species. In regions of low floodplain were analyzed *Alchornea castaneifolia* (Willd.) A. Juss (Euphorbiaceae) and *Laetia corymbulosa* Spruce ex Benth. (Salicaceae) and in areas of high floodplain, *Maquira coriacea* (H.Karst.) C.C. Berg (Moraceae) and *Ocotea cymbarum* Kunth (Lauraceae).

2. MATERIAL AND METHODS

The choice of species was based on the classification in high floodplain (HF) and low floodplain (LF) for the representativeness in the distribution of species in the study area.

Wittmann et al. (2006) classified species as HF when they establish themselves below 3 meter above the water level, and when they survive flood levels equal to or greater than 3m, they are classified as LF. From this classification, two species of LF were selected for ecological modeling: *Alchornea castaneifolia* (*A. castaneifolia*) and *Laetia corymbulosa* (*L. corymbulosa*), and two of HF: *Maquira coriacea* (*M. coriacea*) and *Ocotea cymbarum* (*O. cymbarum*).

Species occurrence points were obtained from the database of the Reference Center for Environmental Information (CRIA, 2021), the SpeciesLink platform (CRIA, 2021), and the Global Biodiversity Information Facility (GBIF, 2021). Initially, 332 points were obtained for *A. castaneifolia*, 276 for *L. corymbulosa*, 494 for *M. coriacea*, and 238 for *O. cymbarum*. These were submitted for verification of possible errors and inconsistencies regarding the natural distribution area. To reduce the autocorrelation of occurrence data and a possible sampling bias, very close occurrences located within a radius of less than 5 km were eliminated (Aiello-Lammens et al., 2015). For this, the Microsoft Excel spreadsheet editor and the Geographic Information System (GIS) software QGIS, version 3.16.13, were used. (QGIS Development Team, 2023).

After quality control of the species' points of occurrence, there was a reduction in information to 201 (47.74%) for LF species (107 for *A. castaneifolia* and 94 for *L. corymbulosa*) and 220 (52.26%) for those from HF (137 for *M. coriacea* and 83 for *O. cymbarum*). Figure 1 shows the distribution of species with their respective consistent location points until 2021.

For modeling the species, 19 bioclimatic variables were considered, including minimum and maximum temperatures and rainfall, originating from the WorldClim database version 2.1., whose layers generated in SIG, containing the variables, had a spatial resolution of 2.5 minutes (4 km²).

To control collinearity between bioclimatic variables, a Principal Component Analysis (PCA) was performed. The Main Components (PCs) with the highest contribution in the analysis were selected, responsible for at least 95% of the total variability of the data (Evangelista-Vale et al., 2021) from the R Environment (R Development Core Team, 2021) and its complement RStudio (R Studio Team, 2019).

For the species modeling process, the ENMTML package (Andrade et al., 2020) of the R environment version 4.1.2 was used. The model was adjusted to generate layers containing the distribution of species throughout South America, using for this purpose a vector layer of the region obtained on the TerraBrasilis platform of the National Institute of Space Research, and public access data.

For the selection of the algorithms with the highest predictive quality for the species modeling process, five models were tested: Bioclim - BIO (Nix, 1986), Domain - DOM (Carpenter et al., 1993), Maximum Entropy - MXS (Anderson and Gonzalez, 2011), Random Forests - RDF (Prasad et al., 2006),

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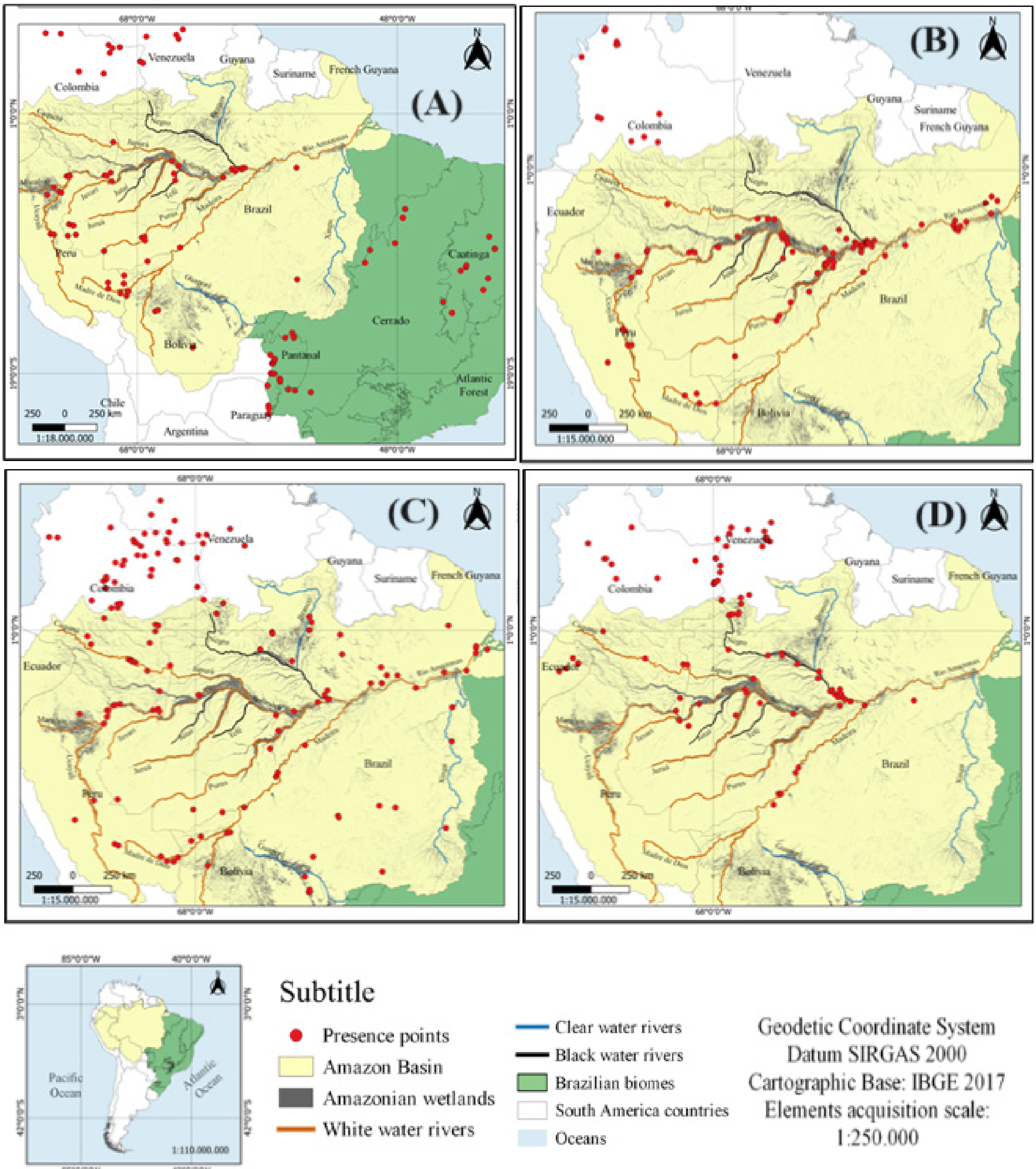

Figure 1 – Areas of occurrence. A) *Alchornea castaneifolia* (LF); B) *Laetia corymbulosa* (LF); C) *Maquira coriacea* (HF); D) *Ocotea cymbarum* (HF).

Figura 1 – Áreas de ocorrência: A) *Alchornea castaneifolia* (LF); B) *Laetia corymbulosa* (LF); C) *Maquira coriacea* (HF); D) *Ocotea cymbarum* (HF).

and Support Vector Machine - SVM (Guo et al., 2005). The models were evaluated based on four different metrics: Area under the curve – AUC (Fielding and Bell, 1997), True Skill Statistic – TSS (Allouche et al., 2006), Jaccard (Leroy et al., 2018), and Sorensen (Leroy et al., 2018). Those with values greater than 0.7 in all metrics were considered good models (Fielding and Bell, 1997; Leroy et al., 2018; Allouche et al., 2006).

From the best metrics tested, a consensus model was built, where the pixel has values 0 and 1, such that 0 corresponds to the locations that are statistically not characterized as climatically suitable for the chosen species (Andrade et al., 2020), as shown in the map in blue (Figure 2). While the value 1 statistically represents the regions with suitable climatic conditions for the species, represented by the color red.

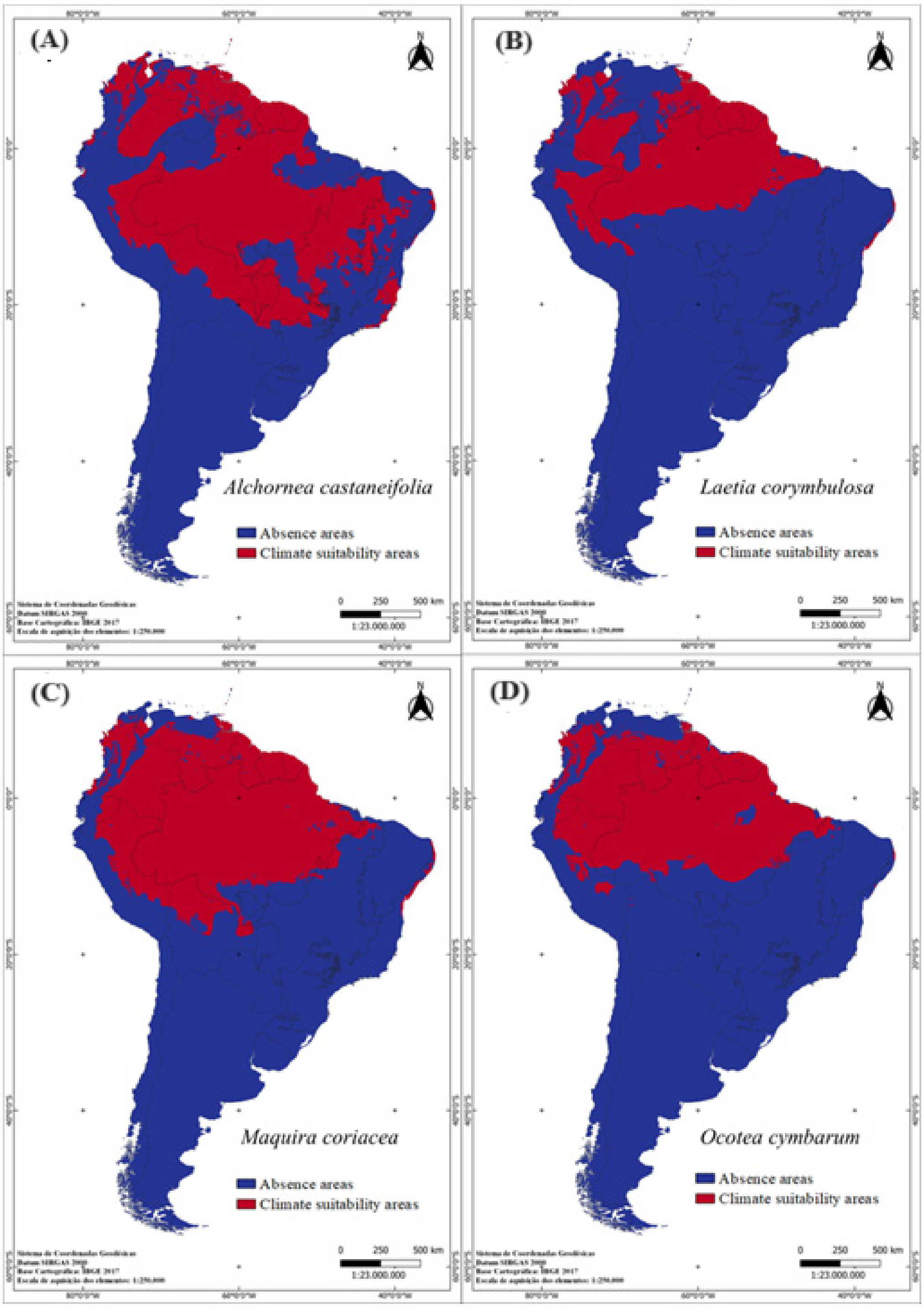

Figure 2 – Consensus maps of the climatic adaptation areas for Amazonian floodplain species: A) *Alchornea castaneifolia* (LF); B) *Laetia corymbulosa* (LF); C) *Maquira coriacea* (HF); D) *Ocotea cymbarum* (HF).

Figura 2 – Mapas de consensos das áreas de adequação climática para espécies da várzea amazônica: A) *Alchornea castaneifolia* (LF); B) *Laetia corymbulosa* (LF); C) *Maquira coriacea* (HF); D) *Ocotea cymbarum* (HF).

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For future projections, the atmospheric circulation model CNRM-CM6-1 of CNRM-CERFACS (National Center for Meteorological Research and European Center for Advanced Research and Training in Scientific Calculus) was used, which is part of the Model Intercomparison Project Phase 6 (CMIP6). The CMIP6 integrates the new IPCC climate models.

For the construction of future models, the same Principal Components (PCs) and algorithms were used for the present models. Thus, climate change was projected for the periods 2041-2060, 2061-2080 and 2081-2100, considering two different scenarios of greenhouse gas (CO2) emissions: SSP245 (more optimistic, in which it is assumed that public policies will be adopted aiming at the mitigation of greenhouse gas emissions in the atmosphere) and SSP585 (more pessimistic, in which it is considered that no measure will be adopted to mitigate these effects) (SSP - Shared Socio-economic Pathways) (IPCC, 2021).

The occurrences of Conservation Units (CUs), Indigenous Lands (IL), and Ramsar Sites (RS) were analyzed for their strategic locations for the conservation effect of the species studied in the study. In the selection, Protected Areas (PAs) were considered those that contain environments of wetlands. The PAs with climatically suitable areas, but that did not present humid areas within their limits, were not considered. In addition, CUs and ILs located within RS, were analyzed as areas of RS. And CUs, which overlapped with IL, were calculated as IL areas.

The layers of vector files in shapefile format containing the limits of CUs and IL were obtained on the TerraBrasilis platform, of the National Institute of Space Research (INPE, 2022). Information about the RS Sites was obtained on the Ramsar Sites Information Service platform.

3. RESULTS

Of the 19 main components generated in the PCA, the first six were used in the modeling process of the species, which together represented about 97% of the total variability of the data. The axes that best explained the variation were observed in the first and second PCs, representing, respectively, 56% and 20% of the total variability of the database.

In PC1, the three most important climatic variables, with higher eigenvector values, were related to air temperatures: minimum temperature in the coldest month (Bio6), average temperature in the coldest quarter (Bio11), and average temperature in the driest quarter (Bio9). In PC2, the most representative variables were related to precipitation: rainfall accumulated in the driest month (Bio14); rainfall accumulated in the driest quarter (Bio17), and rainfall seasonality (Bio15) (Table 1).

Table 1 – Eigenvector values of the six main components (PC) used in the modeling process.

Tabela 1 – Valores de autovetores dos seis Componentes Principais (PC) utilizados no processo de modelagem.

Variables	PC1	PC2	PC3	PC4	PC5	PC6
Bio1	-0.2707	-0.2257	0.1302	-0.0462	0.0612	0.0022
Bio2	0.1767	-0.2413	0.1159	0.4889	-0.1291	0.5284
Bio3	-0.2378	-0.0120	-0.3183	0.1014	0.2300	0.5198
Bio4	0.2489	0.0078	0.3866	-0.0643	-0.2282	-0.0908
Bio5	-0.1927	-0.3193	0.3409	-0.0384	-0.1331	0.0694
Bio6	-0.2940	-0.1193	-0.0036	-0.1567	0.0890	-0.0169
Bio7	0.2492	-0.1248	0.3247	0.1931	-0.2547	0.0897
Bio8	-0.2334	-0.2547	0.2325	0.0629	0.1127	-0.0032
Bio9	-0.2765	-0.1545	-0.0162	-0.1722	0.0048	0.0252

Cont...

Cont...

Variables	PC1	PC2	PC3	PC4	PC5	PC6
Bio10	-0.2304	-0.2633	0.3052	-0.1006	-0.0318	-0.0260
Bio11	-0.2858	-0.1827	0.0033	-0.0302	0.1026	0.0274
Bio12	-0.2630	0.2206	0.0386	0.1832	-0.1994	-0.0609
Bio13	-0.2692	0.0792	-0.1161	0.2335	-0.3329	-0.2086
Bio14	-0.1442	0.3955	0.2416	0.0341	0.1130	0.3041
Bio15	0.0331	-0.3381	-0.4061	0.3321	-0.1420	0.0019
Bio16	-0.2698	0.0876	-0.1038	0.2389	-0.3300	-0.2091
Bio17	-0.1551	0.3949	0.2323	0.0355	0.0830	0.2766
Bio18	-0.1602	0.1883	0.2022	0.5774	0.3222	-0.3318
Bio19	-0.1991	0.2068	-0.0761	-0.2126	-0.5974	0.2389

Bio1= average annual temperature (C); Bio2 = average monthly daily temperature variation (C); Bio3= isothermality; Bio4 = seasonality of temperature; Bio5 = maximum temperature in the hottest month (isn't C); Bio6 = minimum temperature in the coldest month (isn't C); Bio7 = annual temperature change (C); Bio8 = average temperature in the wettest quarter (C); Bio9 = average temperature in the driest quarter (C); Bio10 = average temperature in the hottest quarter (C); Bio11 = average temperature in the coldest quarter (C); Bio12 = rainfall accumulated in the year (mm); Bio13 = rainfall accumulated in the wettest month (mm); Bio14 = rainfall accumulated in the driest month (mm); Bio15 = rainfall seasonality; Bio16 = accumulated rainfall in the wettest quarter (mm); Bio17 = accumulated rainfall in the driest quarter (mm); Bio18 = accumulated rainfall in the hottest quarter (mm) and; Bio19 = accumulated rainfall in the coldest quarter (mm).

The five algorithms used produced satisfactory results for the species and metrics tested, showing evaluation rates greater than 0.7 (Table 2). Regarding the difference between the evaluative metrics, the AUC stood out with the highest values ranging from 0.91 to 0.99, while the results of the TSS model ranged from 0.72 to 0.94.

The consensus model shows that for current climate conditions, the lowland floodplain species *A. castaneifolia* was the one that presented the largest area of climatic adequacy with approximately 7,919,331 km², where 54.36% of this area is concentrated in the region of the Amazon basin but also presents favorable areas in the Cerrado, Pantanal, Caatinga, and Atlantic Forest (Figure 2A). Although the species is limited to floodable environments, *A. castaneifolia* (LF) proved to be adaptable to different conditions, being able to establish itself in different Brazilian phytogeographic domains, except for the Pampa. The remaining species were limited to the Amazon basin.

Due to the endemism of the Amazon floodplains, the species *L. corymbulosa* (LF) (Figure 2B) presented the smallest modeled area, with 4,592,537 km², approximately 59.11% of the Brazilian Amazon area. The two HL species presented in this study have similar climatic suitability areas (Figures 2C and 2D). The species *M. coriacea* was presented in an area of 7,010,489 km², while for *O. cymbarum* it was approximately 5,736,946 km².

The projections of the consensus models for the SSP 245 scenario indicate an increase of about 30% in the climatic adequacy areas of *A. castaneifolia* (LF) for the three periods analyzed (Figure 3). In this scenario, *A. castaneifolia* (LF) showed a significant increase in the distribution area in the Brazilian phytogeographic domains of the Atlantic Forest (+125%), Caatinga (+102%), and Cerrado (+58%).

For the species *L. corymbulosa* (LF) and *O. cymbarum* (HF), the models of SSP 245 estimate a similar behavior, showing an increase in the distribution area in the scenarios for the periods of 2041-2060, of 7% and 4%, respectively. However, in the periods 2061-2080 and 2081-2100, the model showed a loss of favorable areas in relation to the present period. In 2081-2100, for *L. corymbulosa*, the loss would be 6% and for *O. cymbarum*, 8% (Figure 3; Table 3).

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Table 2 – Evaluation of the algorithms used in the modeling process of the species *Alchornea castaneifolia* and *Laetia corymbulosa* of low floodplain (LF) and *Maquira coriacea* and *Ocotea cymbarum* of high floodplain (HF)

Tabela 2 – Avaliação dos algoritmos utilizados no processo de modelagem das espécies *Alchornea castaneifolia* e *Laetia corymbulosa* de várzea baixa (LF) e *Maquira coriacea* e *Ocotea cymbarum* de várzea alta (HF)

Algorithm	AUC	TSS	Jaccard	Sorensen
Alchornea castaneifolia (LF)				
BIO	0.95 (0.03)	0.91 (0.06)	0.91 (0.06)	0.95 (0.04)
DOM	0.93 (0.03)	0.74 (0.07)	0.76 (0.06)	0.86 (0.04)
MXS	0.93 (0.02)	0.78 (0.05)	0.81 (0.04)	0.89 (0.02)
RDF	0.99 (0.01)	0.94 (0.05)	0.94 (0.05)	0.97 (0.03)
SVM	0.98 (0.01)	0.88 (0.03)	0.89 (0.03)	0.94 (0.01)
Laeta corymbulosa (LF)				
BIO	0.94 (0.06)	0.87 (0.12)	0.87 (0.12)	0.93 (0.07)
DOM	0.95 (0.03)	0.83 (0.05)	0.85 (0.04)	0.92 (0.02)
MXS	0.98 (0.03)	0.93 (0.06)	0.93 (0.06)	0.96 (0.03)
RDF	0.99 (0.01)	0.93 (0.03)	0.93 (0.03)	0.96 (0.02)
SVM	0.98 (0.01)	0.88 (0.07)	0.90 (0.06)	0.94 (0.03)
Maquira coriacea (HF)				
BIO	0.96 (0.03)	0.91 (0.06)	0.91 (0.06)	0.95 (0.03)
DOM	0.92 (0.01)	0.72 (0.06)	0.76 (0.05)	0.86 (0.03)
MXS	0.97 (0.01)	0,83 (0.05)	0.85 (0.03)	0.92 (0.02)
RDF	0.99 (0.01)	0.94 (0.06)	0.95 (0.05)	0.97 (0.03)
SVM	0.97 (0.02)	0.89 (0.06)	0.90 (0.06)	0.94 (0.04)
Ocotea cymbarum (HF)				
BIO	0.95 (0.04)	0.90 (0.07)	0.90 (0.07)	0.95 (0.04)
DOM	0.91 (0.04)	0.72 (0.09)	0.77 (0.06)	0.87 (0.04)
MXS	0.93 (0.03)	0.84 (0.06)	0.86 (0.05)	0.92 (0.03)
RDF	0.98 (0.02)	0.90 (0.03)	0.91 (0.03)	0.95 (0.02)
SVM	0.97 (0.01)	0,87 (0.03)	0.88 (0.03)	0.93 (0.02)

For *M. coriacea* (HF), there was an increase in the distribution areas in the scenario SSP 245 (1%) for the periods 2041-2060 and 2061-2080. The SSP 585 scenario showed projections with a greater decline of the areas of climatic adequacy for the species during the three periods analyzed, with the lowest loss of favorable area (-16%) for *A. castaneifolia* (LF) in the period 2081-2100 (Table 3). The species *L. corymbulosa* (HF) and *O. cymbarum* (LF) showed losses of approximately 61% from 2061-2080 in scenario SSP 585, and in a more critical scenario from 2081-2100, they experienced a reduction in areas of approximately 91%. For *M. coriacea* (HF), the models indicated losses of 10% in 2061-2080 and 78% between 2081-2100 (Table 3).

4. DISCUSSION

Although the scenario SSP-585 is considered more extreme, studies indicate that this has become more realistic (homologous to RCP 85 of the 5th IPCC evaluation report), given the current emissions of greenhouse gases (Schwalm et al., 2020). The results

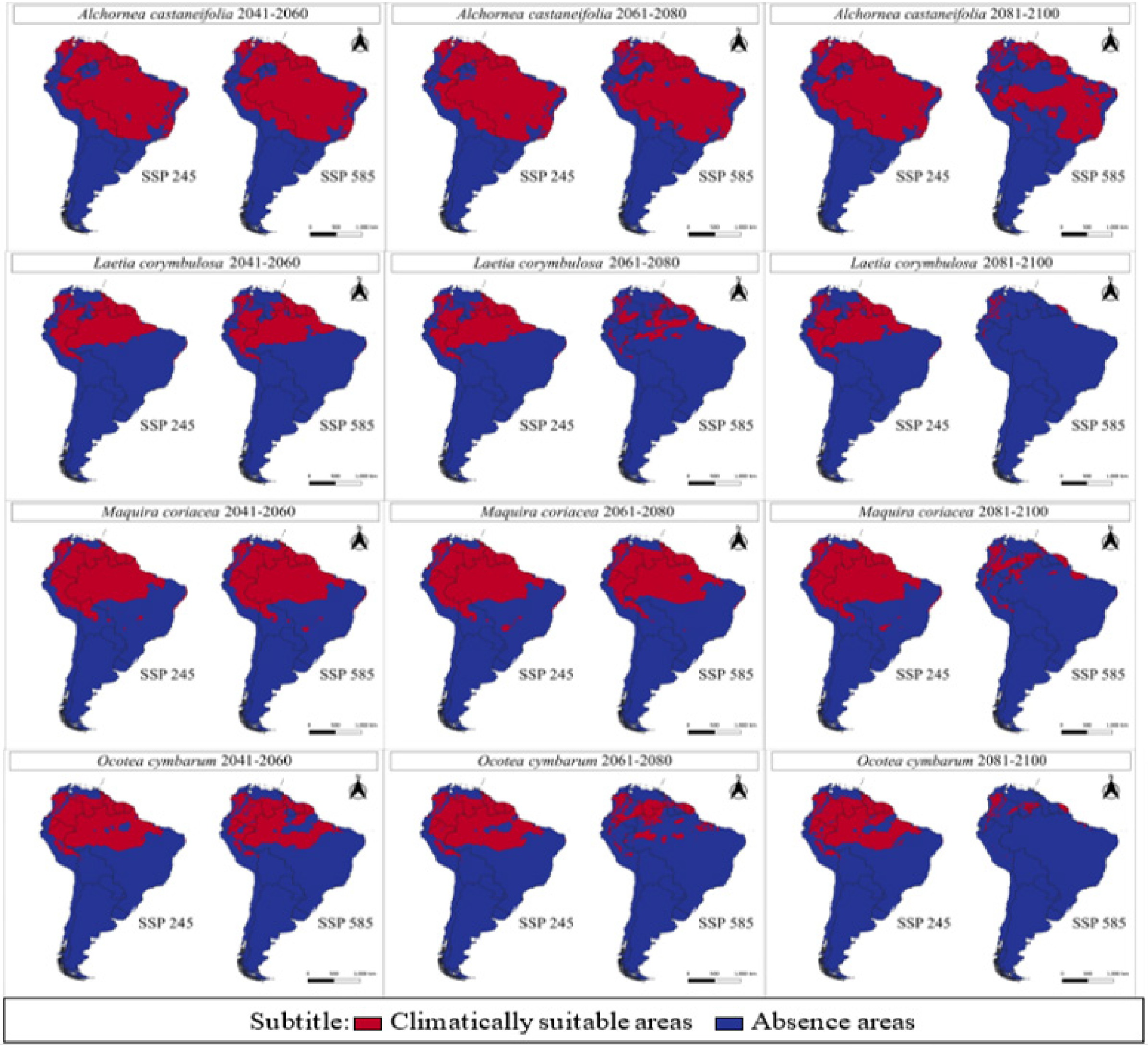

Figure 3 – Maps of climatic suitability under the scenarios SSP 245 and SSP 585 for the years 2041-2060, 2061-2080 and 2081-2100.

Figura 3 – Mapas de adequabilidade climática sob os cenários SSP 245 e SSP 585 para os anos de 2041-2060, 2061-2080 e 2081-2100.

Table 3 – Projections of increase or loss of climate adequacy area (%) in scenarios SSP245 and SSP585 for the three evaluation periods compared to the current period, in South America

Tabela 3 – Projeções de acréscimo ou perda de área de adequação climática (%) nos cenários SSP245 e SSP585 para os três períodos de avaliação em comparação com o período atual na América do Sul

	SSP 245			SSP 585		
Species	**2041-2060**	**2061-2080**	**2081-2100**	**2041-2060**	**2061-2080**	**208-2100**
AC	+27%	+29%	+30%	+28%	+23%	-16%
LC	+7%	+1%	-6%	-4%	-61%	-93%
MO	+1%	+1%	0	-1%	-10%	-78%
OC	+4%	0	-8%	-19%	-64%	-91%

AC= *Alchornea castaneifolia*; LC= *Laetia corymbulosa*; MO= *Maquira coriacea*; OC= *Ocotea cymbarum*; (+) increase; (-) loss

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indicate that climate change will pose threats to the occurrence of Amazon floodplain species, especially in the SSP-585 scenario. The species *M. coriacea* (LF) has pioneer characteristics, including high amplitude of dispersion and rapid growth, being able to germinate and establish itself in large clearings and open areas, and tolerating more hostile environments with high irradiance, high temperature, and low humidity of air and soil (Nebel, 2000).

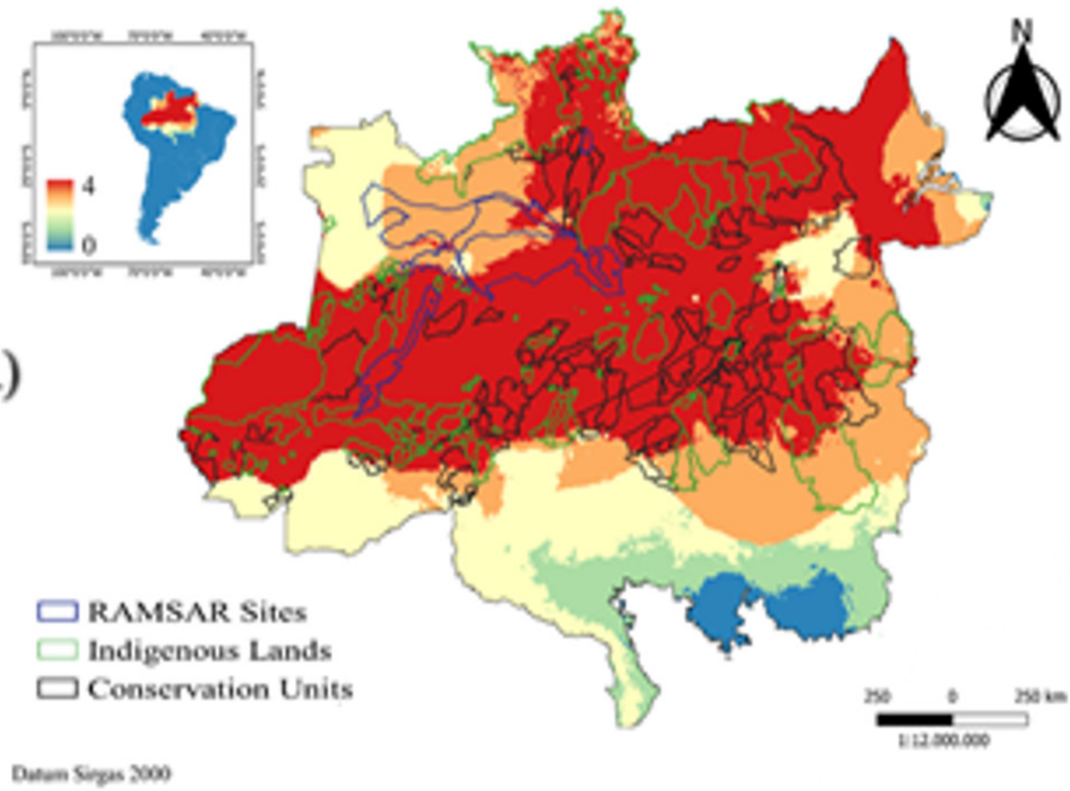
The species *O. cymbarum* has dispersion at short distances, grows slower, and establishes itself in the shade, not tolerating adverse conditions (Wittmann et al., 2009). The results obtained for LF species are consistent, with higher reported area losses for *O. cymbarum*, as it is considered less resistant compared to *M. coriacea* in the aspects of growth, dispersion, and shading tolerance, which are relevant for adaptation.

The HF species, *A. castaneifolia* and *L. corymbulosa*, do not germinate on dry land or in the absence of humidity (Wittmann et al., 2006). The pioneer species, *A. castaneifolia* was the only species to show areas of adaptation in almost all scenarios, except for the period 2081-2100 of SSP 585, possibly because it is not endemic to the Amazon.

Despite this, significant gains in area occurred in the phytogeographic domains of the Cerrado, Caatinga, and Atlantic Forest. However, in the 2081-2100 scenario of SSP 585, the species would remain within about 60% of suitable areas in the Amazon, especially, in the southern region of the basin. The losses would be precisely in the central region, with most of their points of occurrence in the region of extension of a floodplain. The results of the projections of the species studied also varied according to the study by Cordeiro et al. (2023).

In the present period, the areas of climatic suitability for all species are predominantly in the Central, Northern, and Western Amazon regions, totaling 1,976,398 km² (Figure 4A). Of this area, 27% in CUs, 24% in IL, and 4% in RS. The current suitability area comprises around 62% (or 271,074 km²) of the humid areas of the Brazilian Amazon, and just over half (around 32% or 139,909 km²) is under some category of protection: 17% in CUs, 8 % in IL and 7% in RS.

(A)



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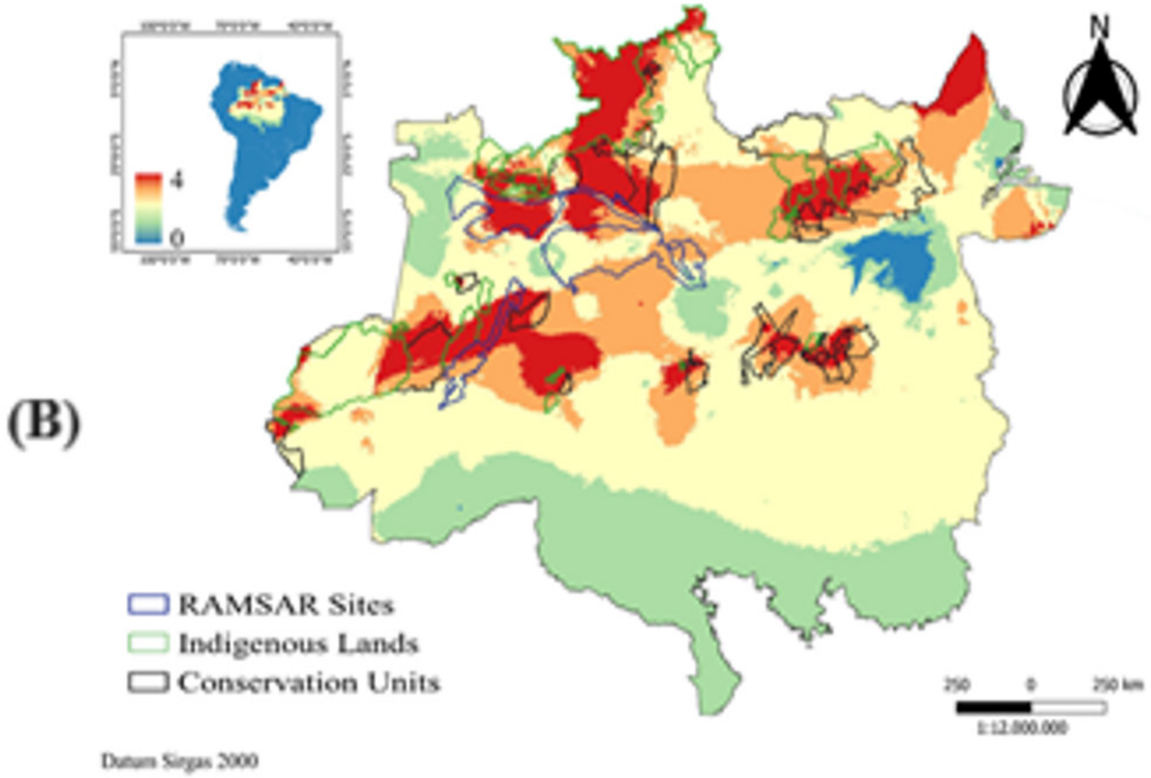

Figure 4 – A) Areas of high climatic adequacy in Amazon Protected Areas (present); B) Areas of high climatic adequacy in Amazon Protected Areas (2061-2080).

Figura 4 – A) Áreas de adequação climática em Áreas Protegidas da Amazônia (presente); B) Áreas de adequação climática em Áreas Protegidas da Amazônia (2061-2080).

The estimates for the years 2061-2080 presented in Figure 4B, show an area of climatic suitability with extending around 427,599 km² totaling a loss of 78% concerning the present. In addition, of the total area estimated by the model (427,599 km²), around 307,705 km² (60%) would be in PAs: 27% in tis; 25% in CUs, and 8% in RS. Regarding wetlands, only 14% (about 60,336 km²) would be in areas of climatic suitability, and only 7% (32,222 km²) would be in PAs, 3% in RS, 3%, in UCs, and 1% in IL.

In total, 61 PAs would remain with areas of climatic suitability in the future projection. The most representative are the Yanomami Indigenous Land (TIY) with 63,429 km² and the Ramsar Regional Site of the Rio Negro with 27,401 km², both in the Rio Negro Basin; the Cujubim Sustainable Development Reserve with 15,216 km², the Javari Valley Indigenous Land with 14,343 km² and the Ramsar Regional Site of the Juruá River with 9,649 km², all along the Solimões River Basin; and the State Forest of Trombetas with 9,781 km² located in the Amazon River basin. These PAs would comprise 30% of the total climate suitability areas (Figure 4B).

Currently, about 54% of the Brazilian Amazon is covered by some PA (CUs cover 28.6% and IL 25.42%) (MMA, 2022). However, the results obtained in the present study indicate that the current configuration would not guarantee the conservation of floodplain species in the face of future climate change and the continuous growth of greenhouse gas emissions. These results are consistent with Anderson et al. (2019), who found that the Amazon AP network does not protect freshwater ecosystems against the risks associated with anthropogenic activities, such as the establishment of hydroelectric plants, deforestation, and pollution. Frederico et al. (2018) show that the composition of protected areas in the Amazon does not guarantee the

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protection of species of aquatic fauna in the region, such as fish and sea turtles.

These results show that most PAs have the predominant objective of protecting terrestrial ecosystems, failing to ensure the conservation of freshwater systems and, consequently, the environment of wetlands. It is necessary to delimit new conservation PAs in situ in the reported regions that will suffer less impact from climate change and to draw strategies for conserving the variability of species at risk of extinction, aiming at ex-situ conservation.

In Brazil, the guidelines adopted for the inclusion of RS require that such areas correspond to PAs, that is, they are equivalent to CUs or IL (MMA, 2022). In a study on land use in the Brazilian RS, Ribeiro et al. (2020) showed that the Amazonian RS are well preserved, presenting a low anthropic disturbance within their limits. However, there are only nine RS in the Amazon, covering 79,373 km² (Anderson et al., 2019), or only 18% of the wetlands of the Brazilian Amazon, which have an estimated area of 437,216 km² (Hess et al., 2015).

In the future climate scenario, the areas of climatic suitability overlap, mainly along the sub-basins of the Rio Negro and Rio Solimões (Figure 5). The two regions are relatively well preserved, given the presence of the Ramsar Regional Site of Rio Negro and the Ramsar Regional Site of Rio Juruá (Ribeiro et al., 2020). Moreover, the two RS do not cover the entire extent of the areas suitable for species, from the climatic point of view, nor the entire extent of wetlands in the region. Furthermore, the flooded forests of the Rio Negro Basin are predominantly formed by areas of igapó, which limits the presence of specific species of floodplain, such as *L. corymbulosa* (Lobo et al., 2019).

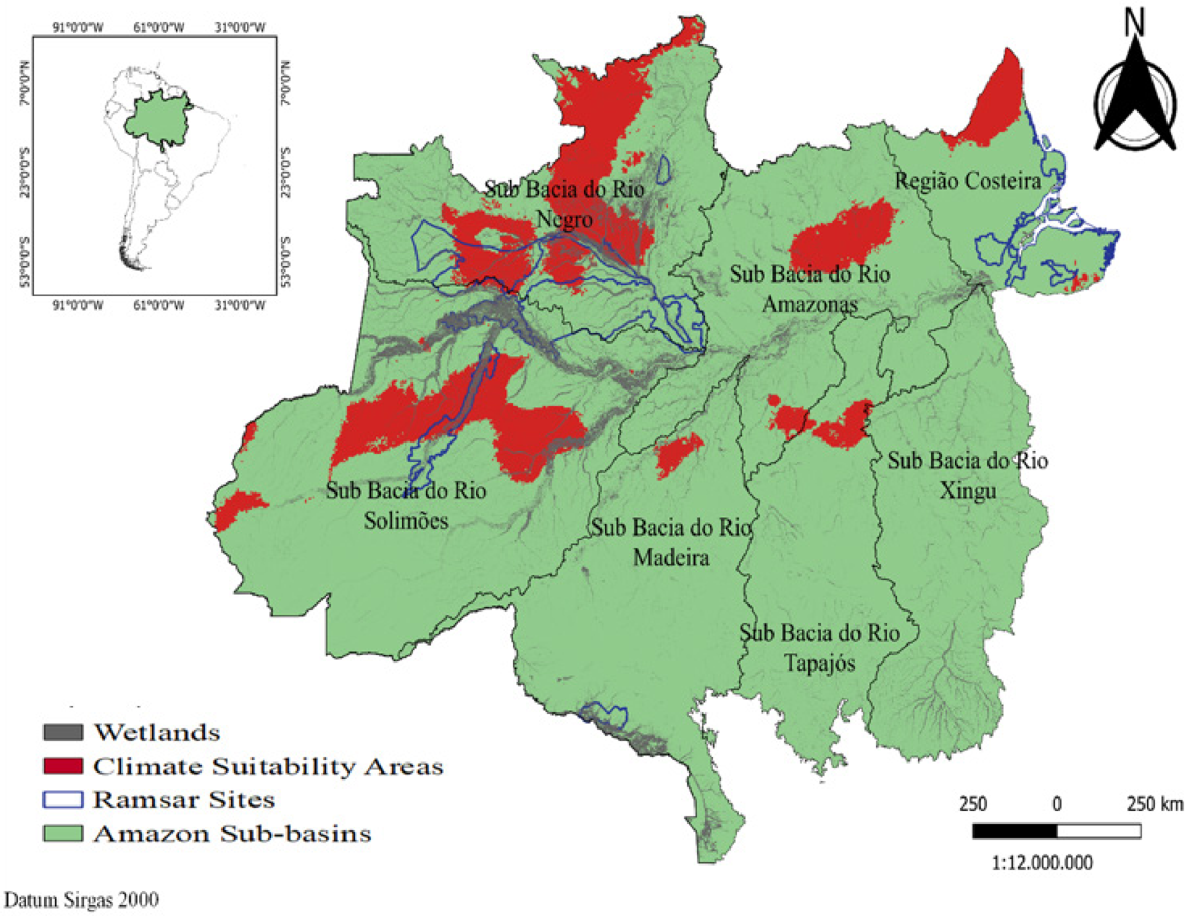

Figure 5 – Priority areas for the conservation of species.

Figura 5 – Áreas prioritárias para a conservação das espécies.

There are overlapping areas in the central region (in the sub-basins of the Amazon River, Madeira, and Tapajós), but to a lesser extent in the eastern coastal region of the Brazilian Amazon (Figure 5). The Central region presents a mosaic of PAs of the Amazon. Nevertheless, its management approaches and conservation measures have a terrestrial bias, not presenting planning for the protection of humid environments. The Madeira River Sub-Basin comprises a large part of the wetlands of the entire Amazon (about 30%) (Hess et al., 2015). It should also be noted that the region does not have any designated area for the conservation of this type of ecosystem.

In recent years, human actions in the eastern and southern regions of the Amazon have intensified, such as deforestation, mining, and the implementation of hydroelectric projects (Evangelista-Vale et al., 2021). These anthropic actions, in addition to increasing pressure on wetlands, potentiate climate change. This scenario puts at risk the PAs and biodiversity of the Amazon, in addition to weakening the conservation status of RS (Ribeiro et al., 2020).

The adoption of more inclusive strategies, merging land and water conservation demands, is necessary to improve the effectiveness of Amazon's network of PAs, changing the current focus, which is concentrated on dryland forests, to also cover freshwater ecosystems in the basin. It is important to expand the current protected areas, such as the reserves of the Negro and Juruá rivers, to encompass more wetlands in these regions. Additionally, new reserves should be established in key locations such as the sub-basins of the Amazon, Madeira, and Tapajós rivers, which are areas with a high concentration of wetlands (Hess et al., 2015).

5. CONCLUSION

The species *Alchornea castaneifolia* (LF), *Laetia corymbulosa* (LF), *Maquira coriacea* (HF), and *Ocotea cymbarum* (HF) appear predominantly in the Amazon Basin, and according to future projections, areas of occurrence will become vulnerable to the effects of climate change in the coming decades in the event of the SSP 585 scenario.

Among the four species studied, *L. corymbulosa*, *O. cymbarum*, and *M. coriacea* are the most threatened in future scenarios of climate change by the variable's temperature, precipitation, and rainfall seasonality.

The current configuration of the Protected Areas (PAs) of the Brazilian Amazon does not guarantee the conservation of the species studied in the face of future climate changes.

The implementation of conservation measures should be treated as a priority in the regions of the Ramsar Regional Sites of the Rio Negro, the Juruá River, the Yanomami Indigenous Lands and the Javari Valley, the Cujubim Sustainable Development Reserve, and the Trombetas State Forest.

The regions conserved in PAs, along the sub-basins of the Amazon, Madeira, and Tapajós rivers, are presented as strategic points for the implementation of new priority areas for the conservation of these environments.

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AUTHOR CONTRIBUTIONS

D.A.T.S, A.A.L, M.S.W, A.V.G and M.T.G.L conceived of the presented idea, the conceptualization and developed the theory. D.A.T.S, A.A.L, M.S.W, A.V.G and S.L.F.R verified the analytical methods, software, and methodology. And R.L and M.T.G.L supervised the findings of this work. All authors discussed the results and contributed to the final manuscript. D.A.T.S wrote the manuscript with support from A.A.L, C.S.B, S.L.F.R and I.L.D.P. R.L., and C.H.S.G.M and M.T.G.L helped supervise the project. D.A.T.S, A.A.L, M.S.W, A.V.G, R.L, S.L.F.R and I.L.D.P contributed to interpreting the results. D.A.T.S, C.S.B and M.T.G.L took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript. D.A.T.S, A.A.L, C.S.B., and I.L.D.P did the data curation, writing-original draft, writingreview, and editing in consultation with C.H.S.G.M, R.L and M.T.G.L. C.H.S.G.M, R.L, A.V.G, S.L.F.R and M.T.G.L authors contributed with funding acquisition. All authors have read and agreed to the published version of the manuscript.

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