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Papers

The Influence of Environmental Variables on the Distribution of Mangroves in Northeast Brazil

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Abstract
This research aims to spatialize mangroves and correlate them with environmental variables, exploring potential variation in the distribution of mangrove and salt flat forests in relation to areas with different rainfall patterns and drought periods within the same Brazilian region. CBERS-4A satellite images and manual vectorization of mangrove and apicum forest polygons in QGIS v. 3.10.14 software were used, as well as fieldwork. Pearson's correlation analysis, carried out using RStudio software, considered variables such as rainfall, dry months, mangrove species, fragmentation, and area size. The results indicate that variations in rainfall and the number of dry months have a strong influence on the distribution of mangroves. For example, in the Piranhas-Açu hypersaline estuary (RN), a large fragmentation of mangrove forests was observed, with 1.379 polygons mapped in an area of 2.396 ha, receiving 500 mm of annual rainfall and having 8 dry months. In the Timonha (CE) and Itarema (CE) estuaries, with 1000 mm of rain and 6 dry months, 131 and 118 polygons were identified, respectively, on 2482 and 1093 ha. In contrast, the Mamanguape River estuary (PB), with the highest annual rainfall of 1750 mm and only 3 dry months, has a distribution of 4256 ha in 24 polygons. As for the salt flats, the Piranhas-Açu (RN) has a fragmentation of 674 polygons in an area of 4858 ha and the Mamanguape River estuary (PB) has six polygons mapped in an area of 2.4 ha. The research highlights the impacts of climatic variables on the distribution of mangroves, anthropogenic interference in land use due to economic activities and the negative effects of fragmentation, underscoring the importance of conservation and proper management of these vital ecosystems.

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INTRODUCTION

Mangroves are ecosystems located on the continental and marine interface, with daily dynamics due to tidal action, conditioning the inherent characteristics of the species that develop in this brackish environment with high concentrations of organic matter (Tomlinson, 1986).

According to Schaeffer-Novelli, Vale and Cintrón (2015), mangroves have features characterized as a continuum: *lavado* (mudflats / tidal flats), *mangue* (mangrove forest) and *apicum* (salt flats). The first is a bank of muddy or sandy sediment, without vegetation, which is constantly flooded by the tides. The mangrove forest is typified by woody vegetation that colonizes the extensive halomorphic substrates. *Apicum*, also known as hypersaline plains or salt marshes, are areas of supramare, the upper tidal reach of the water from an estuary or ocean, and can coincide with the upper limit of mangrove dominance in the transition to mainland areas.

Through their ecological functions, these environments generate various ecosystem services for society (Costanza *et al.*, 1997; Barbier *et al.*, 2011; Vo *et al.*, 2012; Meireles, 2012; Lee *et al.*, 2014; Duke, 2014; Mukherjee *et al.*, 2014; Costa *et al.*, 2022), with detrimental human pressures that lead to environmental degradation (Lacerda *et al.*, 2021).

The changes that have occurred on the semi-arid coast can be listed as the reduction in precipitation rates and consequent hypersalinity in estuaries; a decrease in land-ocean flows; coastal erosion; rising sea levels; global warming and extreme weather events; eutrophication and loss of biodiversity due to human activities (Soares *et al.*, 2021).

These changes have significant consequences for the provision of ecosystem services, such as food security, requiring studies to analyze the potential impact of changes in coastal dynamics on the structure and functioning of coastal and marine ecosystems (Soares *et al.*, 2021). It is important to understand the structure and functioning of mangroves to provide knowledge and generate strategic planning and conservation actions (ICMBio, 2018; Pinheiro *et al.*, 2023).

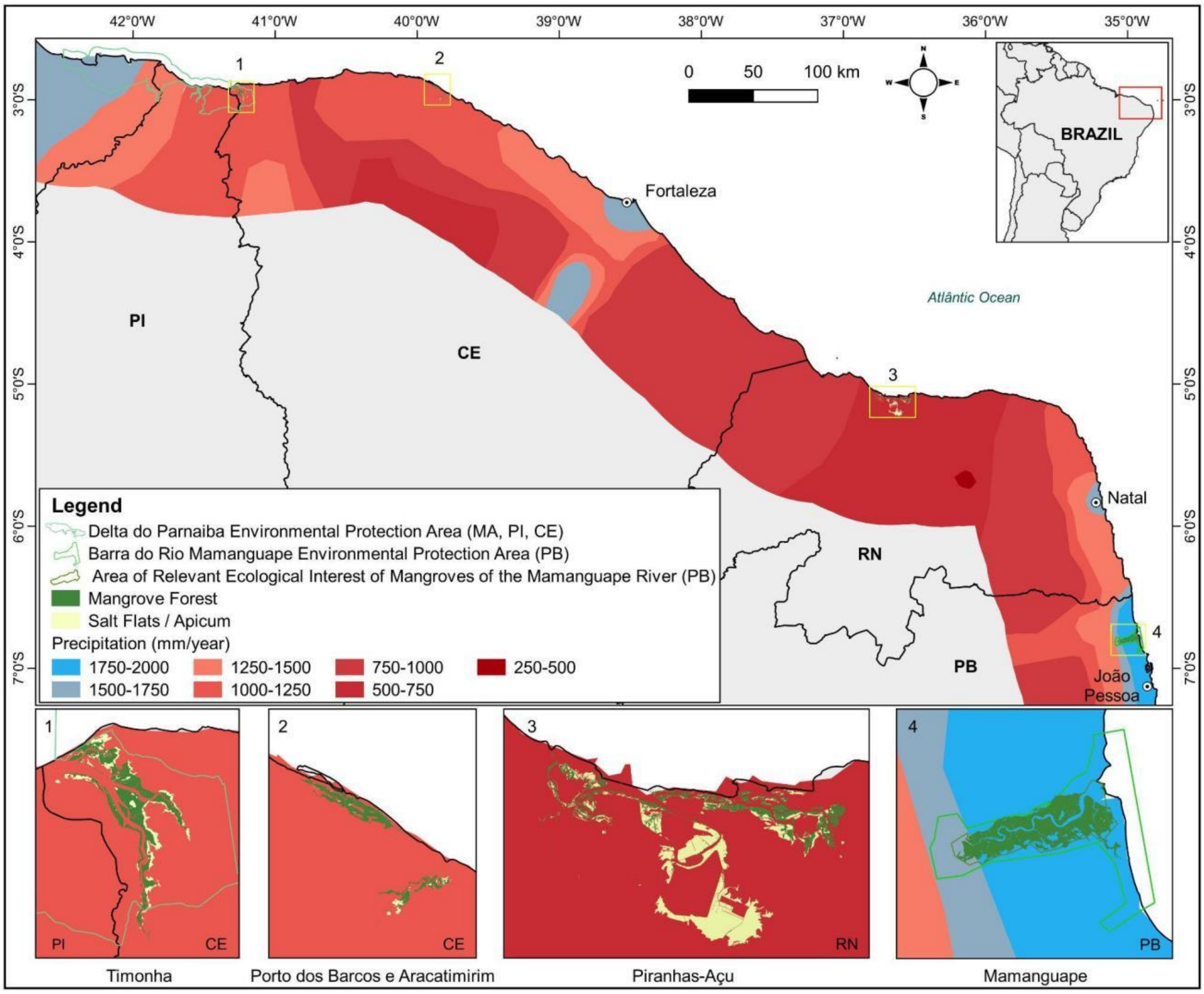
Considering mangroves in different climatic contexts, i.e. in areas with different rainfall patterns and periods of drought within the same Brazilian region, the research's main guiding question is: is there a difference in the distribution of mangrove forest and *apicum* features located in environments with climatic differences in the Northeast region of Brazil? Therefore, this research aims to spatialize mangroves and correlate them with environmental factors, to verify whether there is variation in the distribution of mangrove and apicum forest architecture in different climatic conditions.

METHODOLOGY

Study area

The study area comprises four areas, the mangroves of the Timonha River (CE) - Area 1, Itarema (CE) - Area 2, Piranhas-Açu (RN) - Area 3, and Mamanguape (PB) - Area 4 (Figure 1).

Figure 1- Map of the mangroves study locations



Source: Diniz *et al* (2016), IBGE (2021), ICMBIo (2022). Elaborated by the authors (2024).

The Northeast Coast study area is characterized by two distinct climatic types: the Equatorial Zone Tropical Climate (Brazilian Semi-Arid Coast) and the Humid Tropical (Reef Coast) (Diniz *et al.*, 2016). The Timonha River estuary (area 1) is located in the semi-arid municipalities of Chaval and Barroquinha, in the west of the state of Ceará, in the Área de Proteção Ambiental (APA) Delta do Parnaíba (Brasil, 1996). This is a Brazilian category of sustainable use conservation unit that protects areas with relevant environmental attributes, while allowing regulated human activities compatible with ecological preservation.

Also on the semi-arid coast, the estuarine-lagoon systems of Porto dos Barcos and the Aracatimirim river, in the municipality of Itarema/Ceará (area 2), were studied. In the state of Rio Grande do Norte, the Piranhas-Açu river estuary is located between the municipalities of Porto do Mangue and Macau (area 3), a region popularly known as the Costa Branca Pole, due to the high production of sea salt (Diniz *et al.*, 2020).

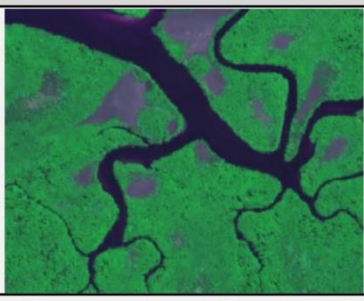
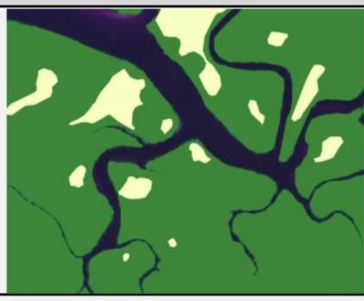
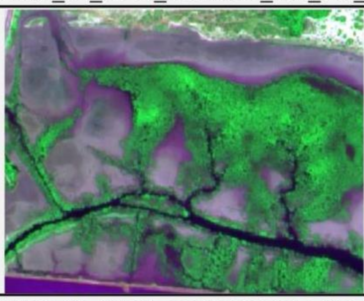
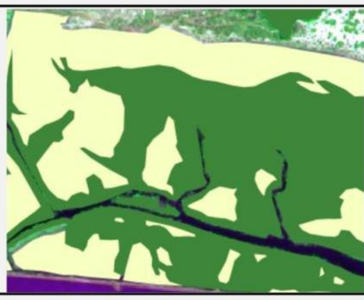
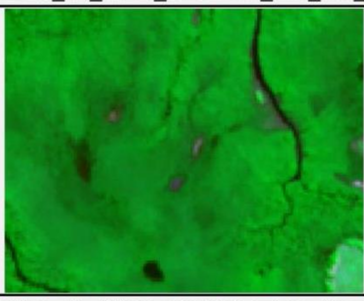
The Mamanguape River estuary is located in the state of Paraíba, in the municipalities of Marcação and Rio Tinto (area 4), and is part of two conservation units. The Área de Relevante Interesse Ecológico (ARIE) Manguezais da Foz do Rio Mamanguape, is a protected natural area dedicated to preserving ecosystems while balancing environmental conservation with human activities (Brasil, 1985). Its boundaries overlapped by the Área de Proteção Ambiental (APA) da Barra do Rio Mamanguape,delimited area that aim to protect biological diversity and organize land use to ensure the sustainable use of natural resources(Brasil, 1993).

Methodological procedures

The mangrove feature “mangrove forest” was identified based on the structure characterized by Schaeffer-Novelli, Vale and Cintrón (2015). For spatialization, the Visual Image Interpretation methodology was applied (Jensen, 2000; Florenzano, 2011), drawing up an interpretation key for visual analysis and vectorization of the polygons (Figure 2), on a scale of 1:10,000, with the aid of the QGIS v. 3.10.14 software (Essen/GNU - General Public License©) (QGIS TEAM, 2021).

The criteria used by Souza (2022) and Sá (2024) were taken into account when mapping the "Mangrove Forest" feature, considering its dark green tone and color, rough texture, and irregular shape. The mapped data was then validated in the field with the aid of aerial images taken by a DJI Mavic Air 2 drone.

Figure 2 - Mangrove interpretation key

Location	Satellite image (1:10.000 scale)	Mapping
Area 1 -2.91107 -41.26605 Timonha Estuary Barroquinha (Ceará, BR) RGB Composition	 CBERS_4A_WPM_20220722_201_117_L4	
Area 2 -2.97219 -39.80813 Itarema (Ceará, BR) RGB Composition	 CBERS_4A_WPM_20210925_199_117_L4	
Area 3 -5.1017 -36.63455 Piranhas-Açu Estuary, Macau (Rio Grande do Norte, BR) NRG Composition	 CBERS_4A_WPM_20210109_195_119_L4 CBERS_4A_WPM_20210814_195_119_L4	
Area 4 -6.78815 -34.93455 Mamanguape Estuary, Rio Tinto (Paraíba, BR) NRG Composition	 CBERS_4A_WPM_20211030_192_122_L4	
Legend: Salt flats / Apicum; Mangrove forest		

Source: INPE (2021; 2022). Elaborated by the authors (2024).

For spatialization of the mangrove forests of the Timonha River (Ceará, BR), the close proximity to the Ubatuba River with the mixing of the rivers' waters prevents precise delimitation of the relative influence of each river, thus a buffer on the left bank was defined as a criterion based on current legislation, Law Nº 12.651/2012 (New Forest Code), which delimits Áreas de Preservação Permanente (APP), protected areas to preserve natural resources, biodiversity and guarantee environmental stability and human well-being, according to the course of the river (Brasil, 2012).

Three strips were considered along the estuary, with the mouth being the place with the largest buffer area, delimiting 500m, as the width of the river is over 600m, then, where the width of the estuary is between 600 and 200m, the left bank was 200m and finally, where the width was between 200 and 50m, the bank was delimited at 100m.

To analyze the environmental variables (Chart 1) for possible relationships between them, Pearson's correlation was used, according to Silva *et al*. (2022):

Chart 1 - Environmental variables in the study area

VARIABLE	SOURCE	CRITERION
Average annual rainfall	Bagnouls and Gaussen (1953), INMET (2009) and Diniz *et al*. (2016)	Climate normals
Number of dry months in the year		Total Precipitation (P) in mm is equal to or less than twice the Air Temperature (T) in Degrees Celsius. (Dry month = P≤ 2.T)
Mangrove species	Field activities	Identification of flora
Fragments (spatialization of mapped polygon features)	Satellite images	Polygons mapped according to Schaeffer-Novelli, Vale and Cintrón (2015)
Area size (ha)		

Source: The authors (2024).

R software (R CORE TEAM, 2022) and RStudio (R STUDIO TEAM, 2022), with Rtools 4.3.3 (5863-5818) were used to analyze the data.

SPATIALIZATION OF MANGROVES

In the semi-arid Northeast, located in the tropical Equatorial Zone climate (Diniz *et al*., 2016), the estuary with the lowest rates is the Piranhas-Açu complex (RN) (area 3), with normal average annual rainfall of around 500 mm/year and eight dry months (INMET, 2021). The areas of the Timonha River and Itarema (CE) have rainfall of 1000 mm/year and six dry months (FUNCEME, 2023a, 2023b). In the tropical climate of the Eastern Northeast, with a moderate humid subdomain and three dry months, the Mamanguape River area has an Average Annual Precipitation of 1750 mm (Table 1) (Diniz *et al*., 2016).

Four species of true mangrove were recorded in areas 1, 2 and 4 (Figure 3): I) *Rhizophora mangle* Linnaeus (1753); II. *Laguncularia racemosa* C. F. Gaert (1807); III. *Avicennia germinans* Linnaeus (1764); IV. *Avicennia schaueriana* Stapf & Leechm (1939). In area 3, three species of true mangrove were identified: *R. mangle*, *L. racemosa* and *A. schaueriana*. In the four areas under study, one species associated with the mangrove was identified, *Conocarpus erectus* Linnaeus (1753), with five and four species accounted for, as shown in Table 1.

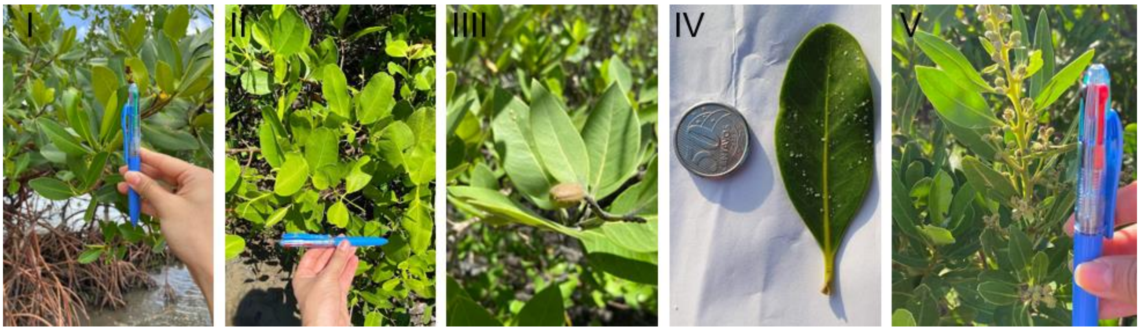
Area 4 in Mamanguape has the largest area of mangrove forest, totaling 4256 hectares spread over 24 polygons (Figure 4). The Timonha River (area 1) mangrove forest covers an area of 2,482 hectares, fragmented into 131 polygons. The Piranhas-Açu (area 3) mangrove forest is the most fragmented, with 1379 polygons and an area of 2396 hectares. The smallest area is found in Itarema (area 2), with 1093 hectares spread over 118 fragments.

Table 1 - Environmental characteristics of the mangroves studied

MANGROVE	CLIMATE[1]	SUB-DOMAIN	CLIMATIC VARIETIES	DRY MONTHS	RAINFALL[2]	MANGROVE FOREST
Timonha (CE) Area 1	Tropical Equatorial Zone Climate	Semiarid	Mild	6	1000 mm/year	I, II, III, IV, V
Itarema (CE) Area 2			Mild	6	1000 mm/year	I, II, III, IV, V
Piranhas-Açu (RN) Area 3			Medium	8	500 mm/year	I, II, IV, V
Mamanguape (PB) Area 4	Tropical Climate of the Eastern Northeast	Humid	Moderate	3	1750 mm/year	I, II, III, IV, V

Fonte: [1]Diniz *et al* (2016); [2]Diniz *et al* (2016), INMET (2021) and FUNCEME (2023a, 2023b). Elaborated by the authors (2024).

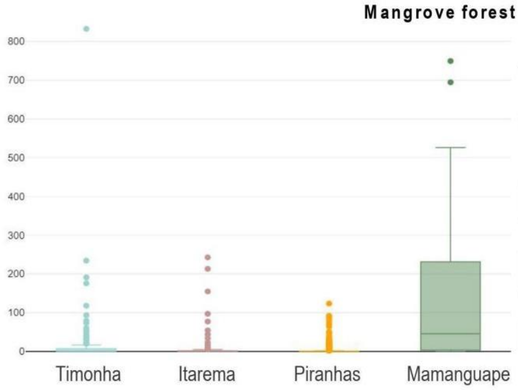
Figure 3 - Mangrove species in the study areas



Species: I. *Rhizophora mangle*; II. *Laguncularia racemosa*; III. *Avicennia germinans*; IV. *Avicennia schaueriana*; V. *Conocarpus erectus*.
Source: The authors (2024).

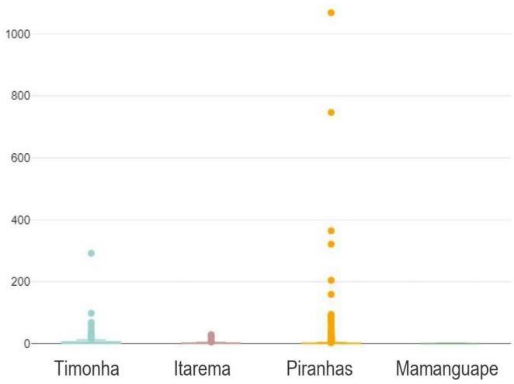
Figure 4 - Spatialization of mangroves

Mangrove forest polygons



Mangrove forest	Timonha	Itarema	Piranhas	Mamanguape
Sample size (n):	131	118	1379	24
Minimum:	0.01	0.001	0.001	0.227
Median:	1.02	0.385	0.118	45.73
Maximum:	832.4	242.65	123.434	749.42
Average:	19.01	9.26	1.73	150.6
Area (ha):	2.482.18	1.093.29	2.396.43	4.256.76

Apicum / Salt flats polygons



Apicum	Timonha	Itarema	Piranhas	Mamanguape
Sample size (n):	96	60	674	6
Minimum:	0.019	0.018	0.01	0.224
Median:	0.899	0.42	0.338	0.41
Maximum:	291.70	29.02	1.068.73	0.637
Average:	9.77	2.71	7.20	0.39
Area (ha):	938.34	146.86	4.858.8	2.39

Source: The authors (2024).

The apicum feature was spatialized quite significantly in the Piranhas-Açu river estuary (RN) to the detriment of the others, with an area of 4.858 ha with 674 polygons, while the smallest extension was identified in the Mamanguape River estuary (PB) in an area of approximately 2.4 ha distributed in 6 polygons.

CORRELATIONS BETWEEN SPATIAL DISTRIBUTION AND CLIMATIC VARIABLES

The pairs of variables showed special configurations, indicating some kind of relationship between them, and it was possible to see a linear relationship between some pairs (Table 2).

Table 2 - Correlation between explanatory variables

	Precipit. Norm.	Dry months	Species	Frag.mf	Area.mf	Frag. apicum	Area. apicum
Precipitation Normals	1.0000						
Dry months	-0.9991	1.0000					
Species	0.6985	-0.7276	1.0000				
Frag.mf	-0.7491	0.7759	-0.9973	1.0000			
Area.mf	0.6984	-0.6746	0.0825	-0.1444	1.0000		
Frag.apicum	-0.7659	0.7970	-0.9929”	0.9986	-0.1587	1.0000	
Area.apicum	-0.7615	0.7921	-0.9836”	0.9903	-0.1193	0.9955	1.0000

Legend: Correlation -1 1 ‘ ’ : disregarded in the analysis; Frag.mf: Mangrove forest fragments; Area.mf: Mangrove forest area; Frag.mf: Apicum fragments; Area.apicum: Apicum area.
Source: The authors (2024).

A strong negative correlation (-0.99) was found between dry months and average annual rainfall, suggesting that lower rainfall is related to an increase in the number of dry months throughout the year. In the northeastern hinterland, rainfall is low and concentrated in a few months during the year.

From this perspective, the distribution of mangrove species and mangrove fragmentation also show a very strong negative correlation (-0.99), where greater fragmentation is associated with a lower distribution of species.

The correlation between the fragmentation of the mangrove forests and the salt flats was very strong (0.99): the greater the area of fragmentation of the mangrove forest feature, the greater the fragmentation and area of the apicum.

The fragmentation of the mangroves associated with the climatological norms for average annual rainfall resulted in a negative correlation (-0.74). This may indicate that less rainfall contributes to greater fragmentation of the mangroves and apicum area.

DISCUSSION

The correlation data shows a linear relationship between the fragmentation of mangrove forests and rainfall climate normals, which are inversely proportional to the dry months during the year and the distribution of species. In the Piranhas-Açu (RN) hypersaline estuary, the fragmentation of mangrove forests into 1379 polygons and the climatological normal with rainfall of approximately 500 mm/year with 8 dry months can be observed. In the estuaries of areas 1 (Timonha) and 2 (Itarema), where annual rainfall is 1000mm with 6 dry months, 131 and 118 polygons were mapped, respectively. The Mamanguape River estuary (PB) has a distribution of mangrove forests among 24 polygons with an average annual rainfall of 1750 mm/year and 3 dry months.

During the fieldwork, four species of true mangrove were identified (*R. mangle, L. racemosa, A. Schaueriana, A. germinans)* and an associated species *(C. erectus*) in areas 1, 2 and 4. In the Piranhas-Açu estuary (RN) - Area 3, A. germinans was not identified; notably, Souza, Silva and Costa (2023), identified all the four species mentioned above in the estuary (*R. mangle, L. racemosa, A. Schaueriana* and *C. erectus).*

The occurrence of *A. germinans* has been observed in estuaries in north-eastern Brazil (Maia; Coutinho, 2012; Maia, 2016; Ximenes *et al.*, 2016) for its ability to survive in high salinity. This relationship to high salinity was found by Costa, Rocha and Cestaro (2014), where the species is distributed from the mouth to upstream in the Apodi-Mossoró river estuary, approximately 40km west of the Piranhas-Açu, but was not found in this estuary during fieldwork, requiring more specific studies to understand the elements that led to the absence of its distribution in area 3, the Piranhas-Açu (RN).

Mangrove fragmentation showed a negative relationship with species distribution (-0.99), but this does not indicate that one variable influences the other or that there is a cause and effect relationship between them as Zar (2009) and Silva *et al*. (2022) point out when applying statistical methods such as Pearson's Correlation.

The distribution of mangrove species can occur for various reasons, in response to the species' physiological limits, with variables related to salinity, air temperature, sea surface temperature, rainfall, aridity, tidal amplitude, ocean currents, the dispersal of propagules (seeds) through hydrocoria and viviparity, as well as anthropogenic actions (Tomlinson, 1986; Schaeffer-Novelli *et al.*, 1990; Osland *et al*, 2007; Lima; Galvani, 2010; Schaeffer-Novelli *et al.*, 2015; Ximenes *et al.*, 2016; Lacerda *et al.*, 2021; Soares *et al.*, 2021; Adame *et al.*, 2021; Madeira *et al.*, 2023).

This set of environmental conditions results in the formation of mangroves. The characteristics of the flat topography and the semi-arid climate of the coastal plains of the northern coast of Rio Grande do Norte mean that given the tidal dynamics, with an amplitude ranging from 0.0 to approximately 2.8 m on the spring tides, they reach vast areas. Where there is daily contact with the tides, the plain is colonized by mangroves, because in the higher places where only the waters of the spring tides reach, salinity becomes a limiting factor for the presence of flora.

Even if species develop mechanisms to eliminate salts, there is a limit to their colonization (Tomlinson, 1986), resulting in extensive areas of salt flats, characterized by features of exposed soil or halophytic herbaceous vegetation (Figure 4). In addition, the average annual rainfall is approximately 500 mm, with rainfall concentrated in four months, and the rivers in the Piranhas-Açu river basin have an intermittent or temporary regime, among other elements that contribute to the formation of these landscapes (Diniz, 2013; Medeiros; Pinheiro, 2018; Medeiros, 2020).

Figure 4 - Hypersaline plains in the Piranhas-Açu river estuary, municipality of Macau (RN)

Source: The authors (2020).

Medeiros and Pinheiro (2018) investigated the effects of insufficient rainfall in the Piranhas-Açu estuary, where the region's semi-arid climate is characterized by low and irregular rainfall, with high rates of potential evapotranspiration, resulting in an annual deficit of 1829.8 mm. Combined with other factors such as the number of dams in the river basin (1,536 dams) and the withdrawal of water for economic activities, the flow of rivers into the estuarine zone is considerably reduced and the source of fresh water becomes almost "null" (Godoy; Lacerda, 2015; Diniz; Vasconcelos, 2016; Medeiros, 2020). In the estuaries of the Brazilian semi-arid region, there is a tendency towards seasonal hypersalinity (Morais; Pinheiro, 2011; Soares *et al.*, 2021). These conditions affect the local vegetation of the mangrove and Caatinga forests around the Piranhas-Açu, decreasing by 41.8% between 2013 and 2015 (Medeiros; Pinheiro, 2018).

In low-energy estuaries, the accumulation of sediments leads to the formation of islands and sandbanks (Morais; Pinheiro, 2011; Godoy; Lacerda, 2014; 2015). This process creates favorable conditions for mangrove colonization, as observed on the islands present in the estuaries of the Timonha, Aracatimirim, and Piranhas-Açu rivers (Morais; Pinheiro, 2011; Godoy; Lacerda, 2014; 2015; Godoy, 2015).

In area 1, between the estuaries of the Timonha River and Ubatuba, Ilha Grande is almost 2,000 ha, and is one of the largest estuarine islands in the Northeast (Choi-Lima, 2017), containing two others, "Ilha do Coronel" and "Ilha dos Preás", with approximately 700ha and 855ha, respectively. Another 11 smaller polygons of mangrove forest were mapped on islands in the course of the Timonha River with areas between 54 and 0.5 ha.

In Aracatimirim, the size of the mangrove forest polygons mapped on islands is smaller, varying between 9 and 0.03 ha out of 14 polygons. On Piranhas-Açu, the largest island is 221 ha in size (west of Macau, it resembles an inverted heart, known as Maracanã Island), and the mangrove forest polygons on the islands total 145, ranging from 78 to 0.001 ha. On Mamanguape, eight islands were mapped containing eight polygons of mangrove forest, ranging from 78 to 0.32 ha.

As an example of mangrove expansion, the data provided by MapBiomas (2022) from the year 1985 (Souza Júnior *et al.*, 2020), indicated that mangrove forests in the Aracatimirim River estuary comprised an area of 24.57 ha; according to the data from this research, the area mapped in 2021 was 324 ha, resulting in a 1218% increase in mangrove areas. In addition to saline intrusion and low river flow, other global factors such as rising sea levels and climate change are driving its expansion (Godoy; Lacerda, 2015; Soares *et al.*, 2021).

Studies by Albuquerque *et al.* (2014a), Albuquerque (2015) and Medeiros (2020) point to the correlation between the development and extent of salt flats and climatic variables, such as water deficit, flat topography, intermittent river hydrography, coastal dynamics, and tidal oscillation. These extreme, hypersaline environments allow only a few herbaceous species to grow, which are adapted to conditions of high salinity, due to the factors mentioned above and the fact that their topography is a little higher so that only the highest tides, syzygial high tides, reach these places, causing evaporation and consequently an accumulation of salts (Schaeffer-Novelli *et al.*, 2015; ICMBio, 2018; Medeiros, 2020).

The salt flats or apicum is of great importance because, with the tendency for sea levels to rise, mangrove forests will migrate to the areas that are now salt flats. Research shows that areas currently occupied by salt flats were once occupied by mangrove forests, indicating that this dynamic occurs periodically over geological time (Albuquerque *et al.*, 2014b; Schaeffer-Novelli *et al.*, 2016; Barbosa *et al.*, 2018; Soares *et al.*, 2021).

Relating climatic variables to the fragmentation of salt flats, in descending order, the Piranhas-Açu estuary has a fragmentation of 674 polygons in an area of 4858 ha, with normal rainfall of 500mm/year and 8 dry months. Timonha has 96 polygons in an area of 938 ha, with an annual rainfall of 1000 mm/year and 6 dry months. Itarema (CE) has 60 polygons in an area of 146 ha, with rainfall of 1000 mm/year and 6 dry months. The Mamanguape river estuary (PB) has six polygons mapped in an area of 2.4 ha with annual rainfall of 1875mm and 3 dry months.

Fragmentation in mangrove forests in the semi-arid region is quite high, with 49% of the fragments being less than 1 ha in Timonha, 71% < 1 ha in area 2, and 82% of fragmentation being less than 1 ha in Piranhas-Açu. In area 4, only 2% of the fragments are smaller than 1 ha. Among the salt flats fragments, 51% in Timonha, 63% in Itarema, 69% in Piranhas-Açu, and 100% in Mamanguape are salt flats polygons of less than 1 ha.

One of the negative impacts caused by fragmentation is the loss of landscape connectivity, altering the ability of species to inhabit the ecosystem (Jaramillo *et al.*, 2023). The changes to the fragments are concentrated on the edges, known as the edge effect (Souza, *et* *al.*, 2023), in more continental areas, at the ecotone from the salt flats to the mainland, and can occur more strongly as a result of anthropogenic activities such as deforestation and changes in land use (Bryan-Brown *et al.*, 2020).

The occupation of the mangroves in the study areas by aquaculture/shrimp farming and solar salt pans is evident. Costa *et al* (2022) studied ecosystem services between different landscape units in the Galinhos-Guamaré estuarine system on the semi-arid coast of Rio Grande do Norte, comparing the provision of services in the estuary/tidal channels, mangrove forest, salt flats, tidal flats, solar saltworks, and shrimp farming. As a result, it was identified that mangrove forest and salt flats areas offer 3.7 and 2.7 times more ecosystem services respectively than shrimp ponds.

In areas 1 and 3, the plains are occupied by solar salt pans, and in all areas there are shrimp farms. In Area 1, due to the climate, the salt pans only operate during the dry months and are not very profitable (Araújo, 2013). In the state of Rio Grande do Norte, the presence of solar salt pans is evident in the estuaries of the northern coast, mainly in areas that used to be mangroves (apicum/salt flats and mangrove forests), reaching 95% of the national production of sea salt, due to local environmental conditions. In the municipality of Macau, Salinor has an area of 4,540.53 ha of evaporator and crystallizer ponds and produces approximately 45% of all Brazilian sea salt (Costa *et al.*, 2013; Diniz, 2013; Soares *et al.*, 2018). According to the Associação Brasileira de Criadores de Camarão, representative entity of the shrimp farming sector in Brazil (ABCC, 2022), shrimp production in the states of Ceará and Rio Grande do Norte was 55.6 tons and 26 tons, respectively, in 2021; they occupy 1st and 2nd place in the national ranking, where Ceará produced 47.1% of all national shrimp and Rio Grande do Norte 21.6%.

Aquaculture and solar saltworks in the municipality of Chaval (CE), in area 1, comprise 323 ha, according to the Secretaria do Meio Ambiente e Mudança do Clima do Ceará, the state agency responsible for the formulation, coordination and execution of public policies related to the environment and climate change in the state of Ceará (Sema, 2022). In the Piranhas-Açu River estuary, the area occupied is quite significant, with 12000 ha of solar salt ponds and 2100 ha of shrimp ponds, giving a total of 14100 ha (Saldanha, 2020). The area occupied by these two types of enterprise is 43 times larger in Piranhas-Açu (area 3) than in Timonha (area 1). In Itarema, area 2, aquaculture/shrimp ponds occupy an area of 555 ha (Sema, 2022), while the occupation in Mamanguape (area 4) by carciniculture is 82 ha (ICMBio, 2014).

Bryan-Brown *et al.* (2020) point to global trends in mangrove fragmentation such as conversion to aquaculture, agriculture, and urban expansion, which are associated with deforestation. Gilani *et al.* (2021) and Grantham *et al.* (2020) also highlight other factors such as road construction, seen in areas 2, 3, and 4, respectively, in Porto dos Barcos (Itarema/CE), Piranhas-Açu (RN) and Mamanguape (PB). As a result, these changes cause environmental imbalances and ecological impacts that affect ecosystem functions (Polidoro *et al.*, 2010; ICMBio, 2018), such as the decline in estuarine fish species (Tran; Fischer, 2017), the release of carbon emissions, loss of biodiversity and water quality (Atwood *et al.*, 2017; Hagger; *et al.*, 2022).

Corte *et al.* (2021) provide evidence that even small mangrove fragments improve biodiversity and ecosystem functions, recognizing their importance in integrating the environment. Li *et al.* (2013), Estoque *et al* (2018) and Gilani *et al* (2021) highlight the establishment of mangrove nature reserves as the most effective way to protect and expand mangroves: the implementation of effective monitoring and the establishment of educational programs and projects, so that the structure and functioning of ecosystems can be perpetuated to provide ecosystem services. In Brazil, even with an advanced legislative framework, the lack of inspection and monitoring of mangroves, especially those that are not located in protected areas, is a limiting factor for the conservation of this ecosystem (Ferreira; Lacerda *et al.*, 2016).

According to Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio, 2018, p. 59), Brazilian environmental agency responsible for proposing, implementing, managing and protecting federal conservation units aimed at biodiversity conservation, 120 out of the existing 2071 Unidades de Conservação (UCs, Conservation Units in English) in Brazil are circumscribed by the mangrove ecosystem, corresponding to an area of 12,114 km², representing 87% of the ecosystem in the whole of Brazil. It should be noted that mangroves are protected nationally by Law Nº 12.651/2012, which delimits them as a APP (Brasil, 2012).

The creation of protected areas requires a series of planning and monitoring measures to analyze and regulate the use of resources in protected areas, aiming for sustainable development in the ecosystems covered by

Sustainable Use UCs (US), and the preservation of environments in Full Protection UCs (PI) (Brasil, 2000). US units aim to balance nature conservation with the sustainable use of some natural resources, while PI units focus on preserving nature, allowing only indirect use of natural resources, and thus have stricter rules and regulations.

At this point, the three UCs involved in this study are part of the US category. Area 1 (estuary of the Timonha River, in the mild semi-arid environment) is located in the APA Delta do Parnaíba and area 4 has two UCs, the ARIE Manguezais da Foz do Rio Mamanguape and the APA da Barra do Rio Mamanguape. This contributes to planning and controlling the use of natural resources in these areas (Paludo; Klonowsky, 1999; ICMBio, 2014).

FINAL CONSIDERATIONS

The data shows a complex interaction between the distribution of mangroves and environmental variables, such as regional climate patterns. The analyses indicate that the fragmentation of mangroves is inversely proportional to the average annual rainfall, suggesting that the climate pattern with low rainfall and a greater number of dry months can lead to a greater division of mangroves, in addition to the extensive areas of apicum, as observed in the Piranhas-Açu river estuary (RN), where the average annual rainfall is approximately 500 mm with a period of 8 dry months.

Furthermore, the statistical correlation between fragmentation and species distribution, although significant, does not imply causality. This highlights the need for a deeper understanding of the underlying mechanisms that govern these ecological relationships, as the presence and distribution of mangrove species are influenced by a series of factors, ranging from the physiological limits of the species to anthropogenic elements, such as changes in land use.

The expansion of mangroves into previously unoccupied areas and the negative impacts caused by fragmentation, such as loss of connectivity and edge effects, highlight the importance of conservation measures and proper management of these ecosystems. The establishment, monitoring, and maintenance of protected areas contribute directly to the sustainable management of mangroves. Thus, a continuous effort to promote the effective conservation of these important coastal ecosystems is essential.

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Ana Caroline Damasceno Souza de Sá: conceptualization, data curation, formal analysis, investigation, methodology and writing – original draft.
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