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Biomass and carbon stock in mangrove forests of the Mamanguape River estuary, Brazil

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Abstract: The purpose of this study was (1) to quantify above-ground biomass (AGB), below-ground biomass (BGB), and carbon stocks; and (2) to evaluate the variation of these attributes along the Mamanguape River estuary, Paraíba, Brazil. Eighteen plots were demarcated in six study sites. In each plot, we measured circumference at breast height (CBH, 1.3 m above substrate) and the height of all living individuals ≥1 m tall. The data were used in allometric equations to estimate biomass, and the values were converted into carbon stock. Above- and below-ground biomass values showed averages of 136.6 ± 106.5 Mg ha^{-1} and 70.9 ± 38.8 Mg ha^{-1}, respectively. Average carbon stocks were estimated at 60.1 ± 46.9 MgC ha^{-1} for AGB, 27.7 ± 15.1 MgC ha^{-1} for BGB and 87.8 ± 61.4 MgC ha^{-1} for total biomass (AGB + BGB). The variables analyzed showed significant differences among the study sites, with no pattern along the estuary. The results revealed that the mangroves analyzed play an important role as a carbon sink. Considering the estimates in this study, the destruction of the mangrove vegetation in the Mamanguape River estuary would result in CO_2 emissions equivalent to 0.41 Tg. Maintaining and increasing blue carbon stocks requires sustainable management, with increased efforts to conserve and restore degraded areas in the mangrove and in the Mamanguape River basin.

Key words: blue carbon, climate change, mangrove forests, mangrove species, selective logging.

Biomassa e estoque de carbono em florestas de mangue do estuário do Rio Mamanguape, Brasil. Resumo: Os objetivos deste estudo foram (1) quantificar a biomassa aérea (BA), a biomassa subterrânea (BS) e o estoque de carbono; e (2) avaliar a variação destes atributos ao longo do estuário do Rio Mamanguape, Paraíba, Brasil. Dezoito parcelas foram instaladas em seis sítios de estudo. Em cada parcela, medimos o diâmetro à altura do peito (DAP, 1,3 m acima do substrato) e a altura de todos os indivíduos vivos ≥1 m de altura. Os dados foram usados em equações alométricas para estimar a biomassa e os valores foram convertidos em estoque de carbono. As biomassas aérea e subterrânea apresentaram médias de 136,6 ± 106,5 Mg ha^{-1} e 70,9 ± 38,8 Mg ha^{-1}, respectivamente. Os estoques médios de carbono foram estimados em 60,1 ± 46,9 MgC ha^{-1} para a BA, em 27,7 ± 15,1 MgC ha^{-1} para a BS e 87,8 ± 61,4 MgC ha^{-1} para a biomassa total (BA + BS). As variáveis analisadas apresentaram diferenças significativas entre os locais de estudo, não havendo padrão ao longo do estuário. Os resultados revelaram que o manguezal analisado tem um papel importante como sumidouro de carbono. Considerando as estimativas deste estudo, a destruição da vegetação de manguezal no estuário do Rio Mamanguape resultaria em emissões de CO_2 equivalentes a 0,41 Tg. A manutenção e o incremento dos estoques de carbono azul requerem a gestão sustentável, com aumento dos esforços de conservação e restauração das áreas degradadas no manguezal e na bacia hidrográfica do Rio Mamanguape.

Palavras-chave: carbono azul, mudança climática, florestas de mangue, espécies de mangue, corte seletivo.

Introduction

The mangrove is a coastal ecosystem that provides various environmental services, such as maintaining marine biodiversity, providing habitat for economically important species, protecting coastlines, and retaining anthropogenic contaminants (Lacerda 1997, Barbier 2006, Mumby 2006, Adame *et al*. 2010, Lee *et al.* 2014). In recent decades, one of the environmental services of mangroves that has attracted the most attention from the scientific community is their greater capacity (four times more) to store carbon than terrestrial forest ecosystems (Donato *et al*. 2011, Mcleod *et al*. 2011). However, mangroves have high rates of deforestation and conversion to other uses that compromise their structure and reduce their carbon storage (Valiela *et al*. 2001, Ferreira & Lacerda 2016, Atwood *et al*. 2017, Diniz *et al.* 2019, Pham *et al.* 2019). In Brazil, the potential loss of carbon from mangroves has been estimated at 0.05 Tg C yr^{-1}, ranking the country as the fourth largest emitter of carbon dioxide globally (Atwood *et al.* 2017).

Like tidal salt marshes and seagrass meadows, mangroves are considered a blue carbon ecosystem because they produce more net organic carbon than they lose through ecosystem respiration (Production/Respiration >1), which makes it possible to store carbon in organic form (Alongi 2023). Mangroves are therefore significant carbon sinks and a promising nature-based solution for climate change mitigation when restored or conserved (Kauffman *et al*. 2018a, Kandasamy *et al.* 2021, Zimmer *et al.* 2022, Alongi 2023, Lovelock *et al.* 2024, Xu *et al.* 2024, Ju *et al.* 2025, Machite & Adams 2025).

On a global scale, the total carbon stock in mangroves corresponds to a range of 6.2-11.7 Pg C (Alongi 2020, Kauffman *et al*. 2020, Ouyang & Lee 2020). In Brazil, the total carbon stock in this ecosystem (~0.44 Pg C) places the country in second place in terms of global carbon stock, just behind Indonesia (1.27 Pg C) (Beloto *et al.* 2023).

In mangrove forests, carbon is stored in the soil, in above-ground biomass (AGB), below-ground biomass (BGB), and dead organic matter (Mcleod *et al.* 2011). The above- and below-ground biomasses are important carbon pools in mangroves (Kauffman & Donato 2012, Howard *et al.* 2014, Rovai *et al*. 2022). However, the carbon storage capacity of these compartments can vary widely according to latitude, geomorphology, hydrology, climate, and anthropogenic disturbances (Castañeda-Moya *et al*. 2013, Estrada & Soares 2017, Magris *et al*. 2020, Rovai *et al.* 2022, Beloto *et al*. 2023). For example, Beloto *et al.* (2023) showed that above- and below-ground carbon stocks in Brazilian mangroves followed a latitudinal trend, with the highest values found at lower latitudes. Some studies have also identified trends in biomass and carbon stocks along the estuarine gradient, with higher values recorded at sites under less marine influence (Saintilan 1997, Kauffman *et al.* 2011, Wang *et al*. 2014). In addition, mangrove forests impacted by anthropogenic actions have lower carbon stocks (Schaeffer-Novelli *et al.* 2018).

Although Brazil has one of the largest mangrove areas in the world (Bunting *et al.* 2018), there are regional data gaps regarding above- and below-ground biomass and carbon stocks in these compartments and in the ecosystem as a whole (Rovai *et al.* 2022, Beloto *et al.* 2023). In the state of Paraíba, northeastern Brazil, there is a scarcity of studies on this subject (Rovai *et al*. 2022, Beloto *et al.* 2023), highlighting the need for more research to demonstrate the contribution and role of regional factors in mangrove carbon stocks.

The Mamanguape River estuary is located in the state of Paraíba, northeastern Brazil (Fig. 1) and is one of the main environments for the occurrence and reproduction of the marine manatee *Trichechus manatus* (threatened with extinction) and other species of ecological importance (ICMBio 2014). The mangrove forests of this estuary cover approximately 4,620 ha (Freires *et al*. 2023) and are made up of *Avicennia germinans* (L.) Stearn., *Avicennia schaueriana* Stapft and Leechm, *Laguncularia racemosa* (L.) Gaertn., and *Rhizophora mangle* L. The mangroves of the Mamanguape River estuary provide various fishing resources for the riverside communities (Mourão & Nordi 2003). A total of 68 species are used, including fish, crustaceans, and mollusks, highlighting the importance of the mangroves for the communities that live around them (Rocha *et al*. 2008). However, anthropogenic pressure is high and has caused the destruction and

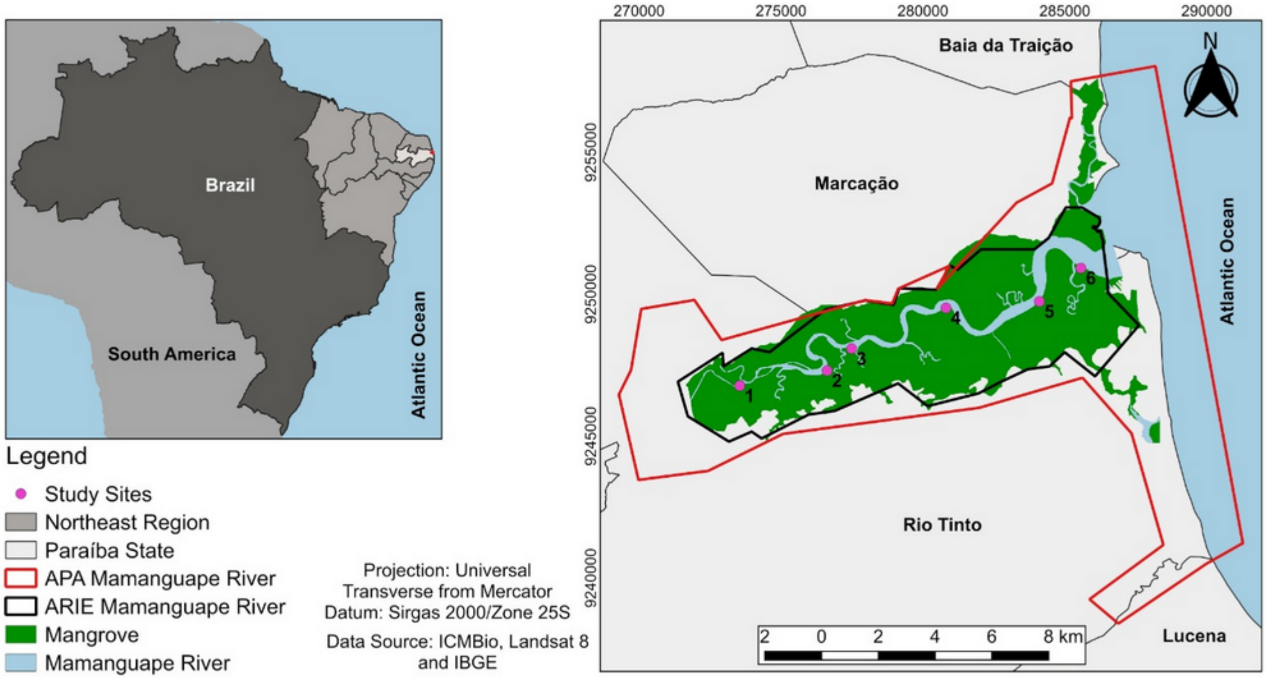

Figure 1. Study sites analyzed in the mangroves of the Mamanguape River estuary. In particular, the Barra do Rio Mamanguape Environmental Protection Area (APA) and the Area of Relevant Ecological Interest (ARIE) Manguezais da Foz do Rio Mamanguape. Prepared by Jerferson Lima.

degradation of the ecosystem. The main threats include severe changes in water circulation, the installation of shrimp ponds, occupation by cattle grazing, and selective logging (Freires *et al*. 2023). These threats to the ecosystem have resulted in significant biomass losses and increased carbon dioxide emissions.

As far as we know, there is no published data in the literature on the biomass and carbon stock of the mangrove forests of the Mamanguape River estuary. Therefore, the objectives of this study were the following: (1) to quantify AGB, BGB, and carbon stocks and (2) to evaluate the variation of these attributes along the estuary. This study contributes information to guide conservation and maintenance strategies for the ecological functions and benefits of the mangrove analyzed.

Material and Methods

Study area: The Mamanguape River estuary is part of two conservation units (Fig. 1): the Area of Relevant Ecological Interest (ARIE) Manguezais da Foz do Rio Mamanguape (created in 1985) and the Barra do Rio Mamanguape Environmental Protection Area (APA) (created in 1993). The region's climate is tropical and rainy (Am, according to the Köeppen classification) and the rainy season is concentrated between February and August. Annual rainfall varies from 1600 to 1900 mm and the average annual temperature is between 24º and 26°C (Alvares *et al*. 2013). The tidal regime in the Mamanguape River estuary is semi-diurnal and the amplitude is consistent with the mesotidal class, with average heights of syzygy and quadrature reaching 2.18 and 1.04 m, respectively.

Biomass and carbon stock: Six study sites were established along the Mamanguape River estuary (Fig. 1), spaced an average of 3.5 km apart. At each study site, three plots were marked out parallel to the body of water (5 m from the shore), 10 m apart. The area of the 18 plots varied between 100 and 400 m^2, and was determined according to tree density (including at least 30 live trees within each plot) (Schaeffer-Novelli & Cintron 1986). Within each plot, the circumference at breast height (CBH) and the height of living individuals ≥ 1 m in height were measured. Identification was carried out to the species level. CBH was measured with a tape measure and height with a telescopic stick with centimeter marks (CRAIN CMR, model: 90182). The occurrence of cut trees was recorded. Data were collected between August 2019 and February 2020 and seasonal variation was not assessed.

From the CBH, the diameter at breast height (DBH) was calculated according to the formula: DBH = CBH / π. Subsequently, the average height, average DBH, basal area, stem density, dominance, and relative density were calculated according to Schaeffer-Novelli & Cintrón (1986). The dominance and relative density of the species for each site were calculated from the sum of the basal area values and the density of individuals in the plots, respectively.

AGB and BGB were estimated non-destructively using allometric equations (Table I). The carbon content of the trees was estimated by multiplying the AGB and BGB values by 0.44 (Rodrigues *et al.* 2014) and 0.39 (Kauffman & Donato 2011), respectively. The total carbon stock of the vegetation was estimated by adding the AGB and BGB carbon values. The total carbon stock was converted into CO_2 equivalents by multiplying by a factor 3.67 (Kauffman & Donato 2011).

Sediment variables: Abiotic variables were sampled in March 2020. A porewater sample was collected from each plot at a depth of 50 cm using a PVC tube, hose, and syringe. The salinity of the water was estimated in the laboratory using a refractometer.

A soil sample (30 cm deep) was taken from each plot to estimate the percentage of organic matter and grain size. Organic matter was determined using the calcination method. Aliquots of 2 g of the < 2 mm fraction of the soil were dried (80°C) to obtain dry weight. The samples then remained in a muffle furnace at 550°C for 2 hours. Subsequently, the percentage of organic matter was calculated based on the initial and final weights of the samples (accuracy of 0.0001 g).

For the particle size analysis, the soil was dried (80°C) and sieved to separate the < 2 mm fraction. In aliquots of 30 g of soil, 250 mL of distilled water and 10 mL of 1 M NaOH were added. The sample volume was topped up to 1 L and then stirred manually and left to stand overnight. The sand fraction and the fine fraction (silt+clay) were separated under running water using a 63-µm sieve and the retained fraction (sand) was then dried at 80°C.

Statistical analysis. Data were square root transformed for comparison among study sites. Vegetation and sediment variables were compared using the ANOVA one-way and Tukey's post-hoc test. A canonical correspondence analysis (CCA) was carried out using the data on height, stem density, AGB+BGB, and sediment variables (interstitial salinity, silt+clay, and percentage of organic matter). The same analysis was carried out with data on the relative density of species and sediment variables. All statistical analyses were carried out in the R environment (R Core Team, 2024).

Results

The basal area was lower at S4 and higher at sites S1 and S6 (Table II; Fig. 2). For height, diameter and density, the differences among study sites were not statistically significant due to the high variability among plots. Anthropic actions were observed, such as the use of a net to catch the crab *Ucides cordatus*. Furthermore, selective logging was recorded in all plots (relative frequency of 100%) at sites 3, 4 and 5 and in two plots (relative frequency of 67%) at sites 1, 2 and 6.

Four species were recorded in this study: *Avicennia germinans*, *Avicennia schaueriana*, *Laguncularia racemosa*, and *Rhizophora mangle*. The species showed trends in their distribution along the estuary (Fig. 3). *Avicennia germinans* was restricted to the upper estuary (less marine influence). *Laguncularia racemosa* showed a wide distribution with a tendency to reduce its contribution in terms of dominance and relative density towards the ocean. *Avicennia schaueriana* and *Rhizophora mangle* also showed a wide distribution along the estuary, but with a tendency to increase in dominance and relative density towards the lower estuary (greater marine influence).

Table I. Allometric equations for estimating above-ground biomass (AGB) and below-ground biomass (BGB) of mangrove species

Species	Equation	R^2	Reference
AGB			
Avicennia germinans	$AGB = 0.14\ D^{2.4}$	0.97	Fromard *et al*. (1998)
Avicennia schaueriana	$AGB = 123.8716\ D^{2.5282}$	0.99	Estrada *et al*. (2014)
Laguncularia racemosa	$AGB = 0.1442\ D^{2.325}$	0.96	Medeiros & Sampaio (2008)
Rhizophora mangle	$AGB = 0.2938\ D^{2.384}$	0.92	Medeiros & Sampaio (2008)
BGB			
All species	$BGB = 0.199\ \rho^{0.899}\ D^{2.22}$	0.95	Komiyama *et al*. (2005)

Notes: D = diameter at breast height (cm) and ρ = wood density (g cm^{-3}). Wood density for trees was 0.64 for *A. germinans* (Virgulino-Júnior *et al.* 2020), 0.73 for *A. schaueriana*, 0.93 for *L. racemosa*, and 0.93 for *R. mangle* (Medeiros & Sampaio, 2008).

Table II. Summary of one-way ANOVA for vegetation and soil variables analyzed at the study sites in the mangrove of the Mamanguape River estuary. *Statistically significant p-values (p≤0.05).

	F-statistic	P
Vegetation		
Height	0.6304	0.68048
Diameter	0.6605	0.66018
Basal area	4.2069	0.01928*
Density	1.3775	0.30299
Above-ground biomass	4.0210	0.02240*
Below-ground biomass	3.7315	0.02862*
Above-ground biomass carbon	4.0210	0.02240*
Below-ground biomass carbon	3.7315	0.02862*
Soil		
Porewater salinity	12.735	0.000187*
Organic matter	29.605	0.000002*
Sand	14.329	0.000105*
Silt + clay	20.194	0.000018*

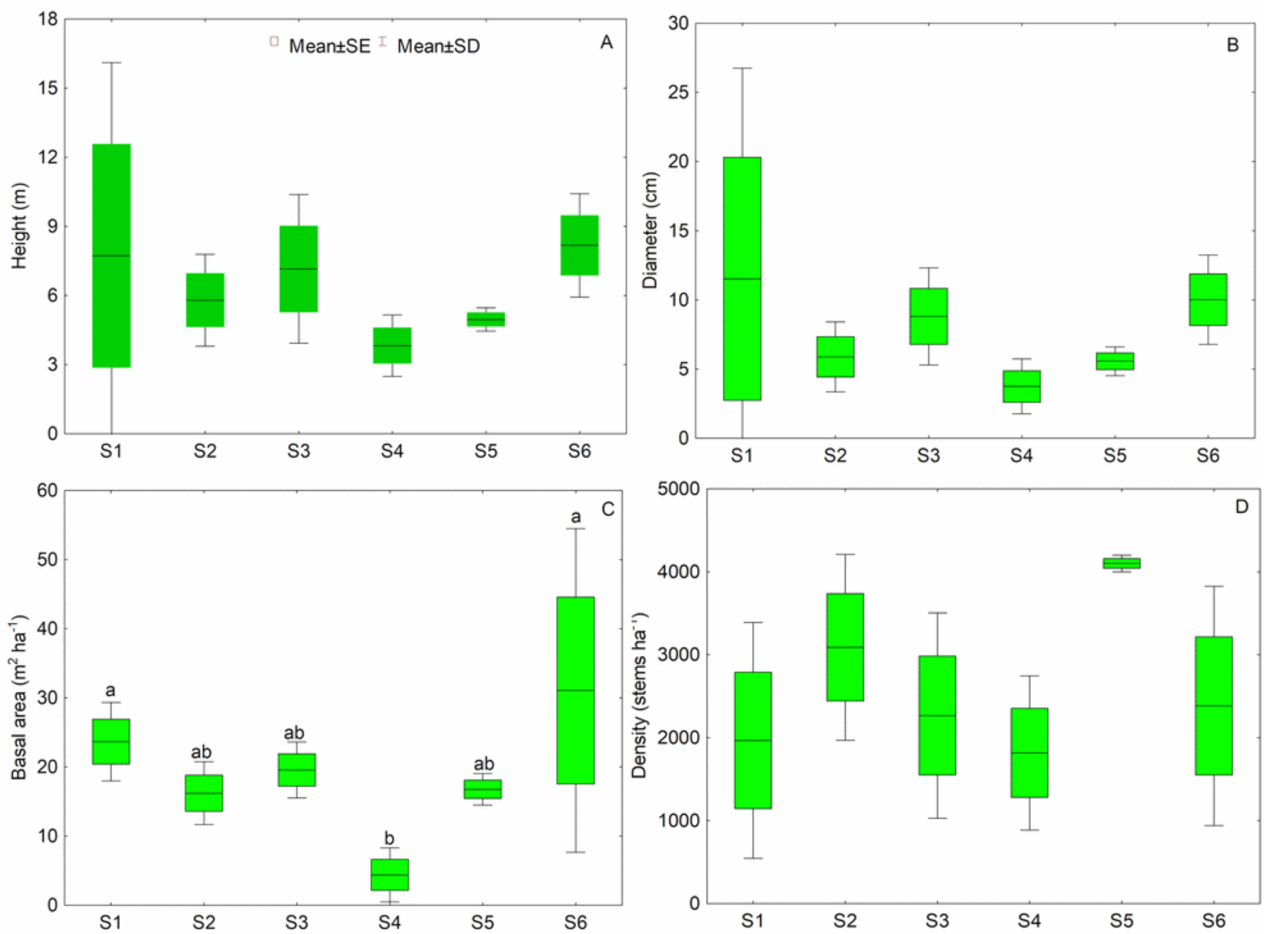

Figure 2. Structural parameters in the sites (S) analyzed in the mangrove of the Mamanguape River estuary. Different lowercase letters indicate significant differences among sites (p ≤ 0.05).

The average AGB values of the study sites ranged from 24.7 to 200.1 Mg ha^{-1} (mean 136.6 ± 106.5 Mg ha^{-1}), while for BGB these values ranged from 13.2 to 79.3 Mg ha^{-1} (mean 70.9 ± 38.8 Mg ha^{-1}) (Figs. 4a-4b). The average AGB/BGB ratio was 1.8. The carbon stocks of AGB and BGB ranged from 10.9 to 88.1 MgC ha^{-1} (mean 60.1 ± 46.9 MgC ha^{-1}) and from 5.2 to 30.9 MgC ha^{-1} (mean 27.7 ± 15.1 MgC ha^{-1}), respectively (Figs. 4c-4d). Above-ground and below-ground biomass and carbon stock were significantly higher at site S6 and lower at site S4 (Table II; Fig. 4).

The average total biomass carbon stock (AGB + BGB) of the Mamanguape River estuary mangrove was estimated at 87.8 ± 61.4 MgC ha^{-1} (322.0 MgCO$_2$ ha^{-1}). Considering the total mangrove area of the Mamanguape River estuary (4,620 ha) and the average carbon stock per hectare (87.8 MgC ha^{-1}), the calculations indicated that the mangrove biomass stores around 405,636 MgC, equivalent to 0.41 Tg CO_2.

Porewater salinity was highest at sites S4 and S5 and lowest at S1 to S3 (Fig. 5). The highest percentages of organic matter were recorded in S2 and the lowest in sites S1, S5 and S6. The sediments were predominantly composed of fine sediments, except at S6 with more than 80% sand. The sand fraction was more abundant at site S6, with lower percentages at sites S1 to S4 (Fig. 5). The opposite results were recorded for the fine fraction (silt + clay).

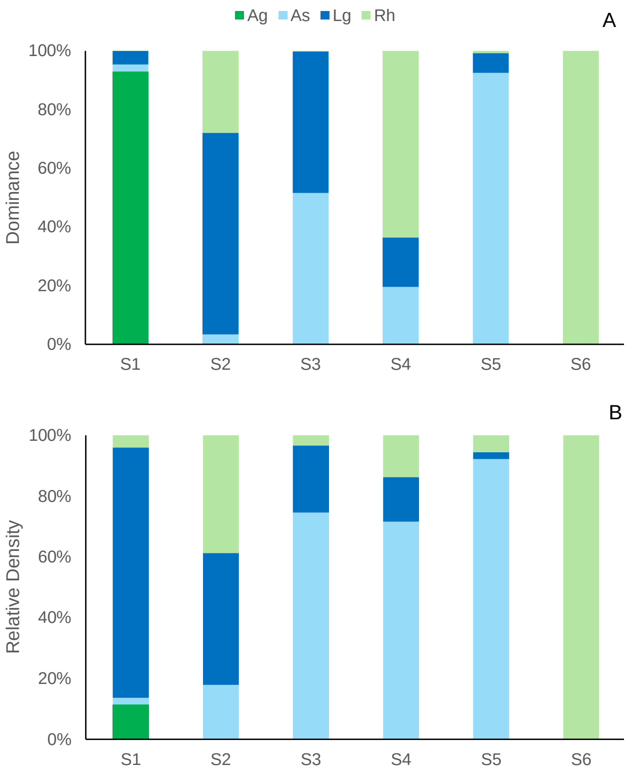

Figure 3 (opposite column). A. Dominance (basal area) and B. relative density of species in the sites (S) analyzed in the mangrove of the Mamanguape River estuary. Ag: *Avicennia germinans*, As: *Avicennia schaueriana*, Lg: *Laguncularia racemosa* and Rh: *Rhizophora mangle*.

CCA indicated that height, stem density, and total biomass (AGB+BGB) were not related to sediment variables (999 permutations, F = 1.219, p = 0.284) and total inertia was 0.02 (0.3% constrained). However, the CCA showed that the relative density of species was related to the sediment variables (permutations test: 999 permutations, F = 3.705, $p < 0.001$) and the total inertia was 1.82 (80.6% constrained). The first two axes explained 96% of the total variance accumulated in the mean calculated for the four species in terms of sediment variables (Fig. 6). The ordination diagram showed that the highest relative densities of *Avicennia germinans* and *Laguncularia racemosa* were associated with the lowest interstitial salinity (Fig. 6). In contrast, the highest relative density of *Avicennia schaueriana* was associated with muddier soils with a higher percentage of organic matter, while *Rhizophora mangle* was associated with sandier soils (Fig. 6).

Discussion

The results showed significant differences among the study sites for basal area, AGB, BGB, and carbon stock. However, no pattern in vegetation structure was identified along the estuary. Differences among study sites may be attributed to variation in regulatory factors (e.g., salinity), resources (e.g., nutrients), and hydroperiod (e.g., flood frequency and river water supply) that control the structure and functioning of mangrove forests (Twilley & Rivera-Monroy 2005). However, there was a lack of association among height, stem density, total biomass, and sediment variables (interstitial salinity, organic matter, and silt+clay).

Studies have shown that height, basal area, biomass, and carbon stock tend to decrease downstream (Soto & Jimenez 1982, Saintilan, 1997, Silva *et al*. 2005; Kauffman *et al*. 2011, Martins *et al*. 2011, Wang *et al*. 2014, Calegario *et al*. 2015, Castillo *et al*. 2018, Rodríguez-Reales *et al*. 2025). These studies suggest that lower values of these variables in locations with greater marine influence are associated with higher salinity values. In the present study, contrary to expectations, salinity values were higher in locations further from the ocean (S4 to S6), where vegetation, in general, did not exhibit less structural development. The higher salinity

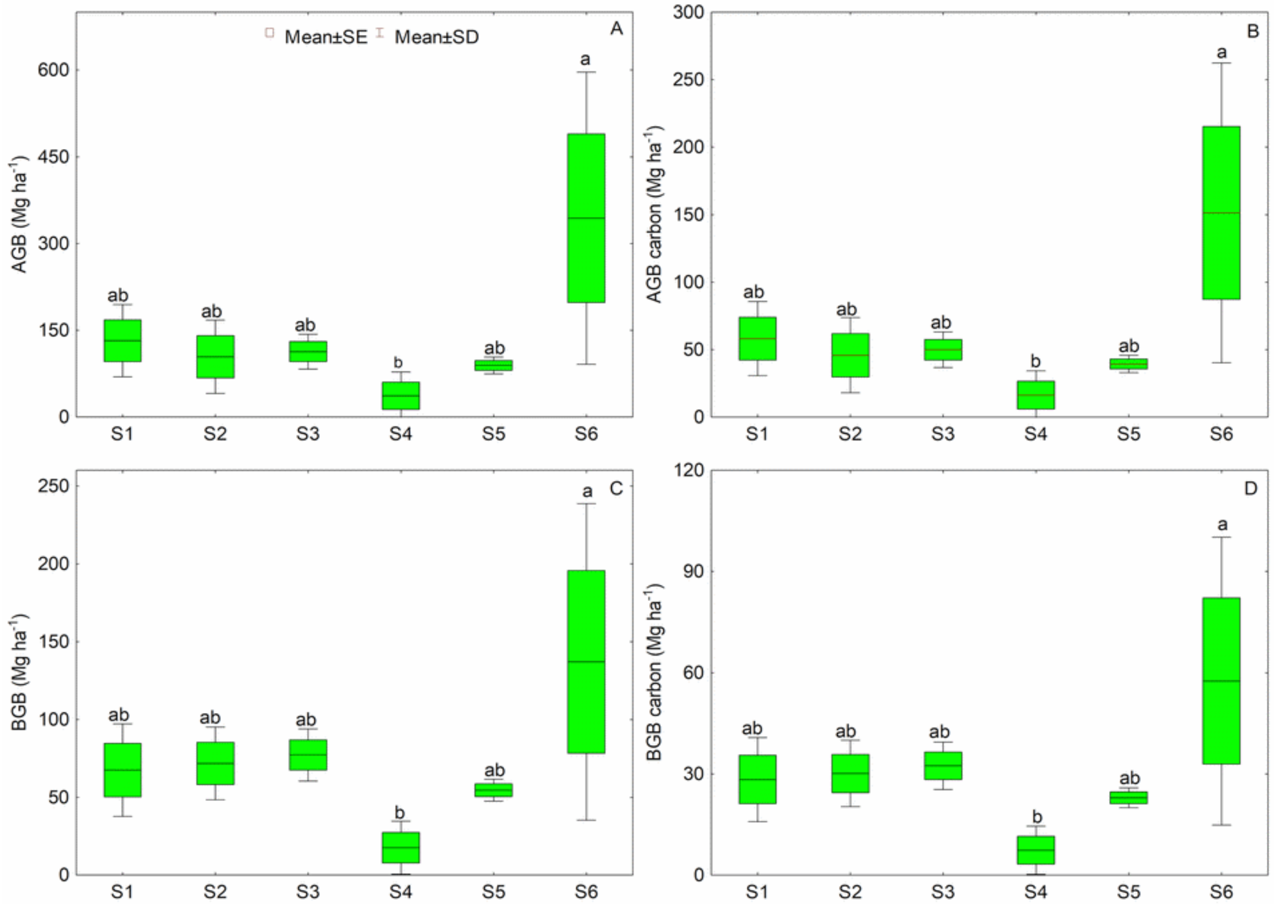

Figure 4. Biomass and carbon stock at the sites (S) analyzed in the mangrove of the Mamanguape River estuary. A. above-ground biomass (AGB), B. below-ground biomass (BGB), C. carbon in above-ground biomass and D. carbon in below-ground biomass. Different lowercase letters indicate significant differences among sites ($p \leq 0.05$).

at sites S4 to S6 is probably related to the lower frequency of substrate flooding due to the higher elevation of the terrain. Other factors can also influence the structure and functioning of mangrove forests when salinity is below the critical value of 65 (Cintron *et al.* 1978), such as forest age, nutrient concentration, percentage of organic matter, and anthropogenic disturbances. For example, higher nutrient concentrations in the sediment result in better structural development of mangrove forests (Chen & Twilley 1999) and higher net primary productivity (Castañeda-Moya *et al*. 2013). Costa *et al.* (2015) also observed that mangroves showed higher values of height and basal area associated with higher percentages of soil organic matter, with no trends along the salinity gradient.

The forests analyzed in this study are secondary and anthropic actions interfere with their structural development and the carbon stock in the biomass along the estuary. Considering all the plots analyzed, 88% included cut trunks and this anthropogenic action was also observed in the areas surrounding the sampling units. Logging can cause changes in the structure and functioning of ecosystems. Mangrove forests subjected to this disturbance exhibit reduced values for height, diameter, basal area, and/or density (Paludo & Klonowski 1999, Walters 2005, Souza & Sampaio 2001, Alongi & Carvalho 2008, Costa *et al.* 2021), with a consequent decrease in biomass and carbon stock.

Intense selective logging in the mangroves of the Mamanguape River estuary has been documented since the 1920s. The establishment of the former Rio Tinto Textile Company in 1924 resulted in excessive logging to obtain firewood for ovens and factory buildings (ICMBio 2014, Brissac 2019). The Rio Tinto Textile Company was shut down in 1983 and there was a reduction in logging for industrial activity. However, the riverside communities (indigenous and non-indigenous) also exploited the mangroves for firewood, charcoal, and timber for building houses, boats, and stakes for yam plantations;

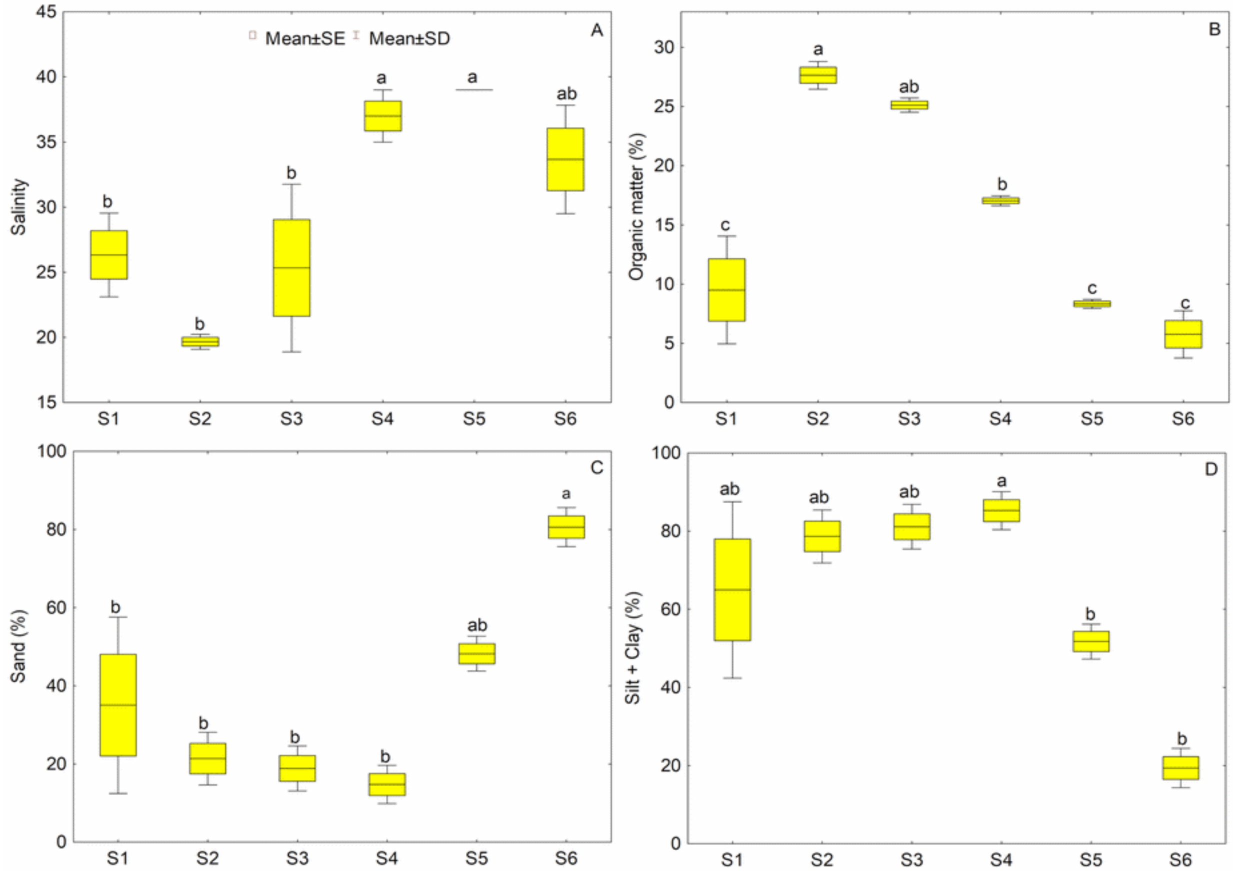

Figure 5. Sediment variables at the sites (S) analyzed in the mangrove swamp of the Mamanguape River estuary. Different lowercase letters indicate significant differences among sites ($p \leq 0.05$).

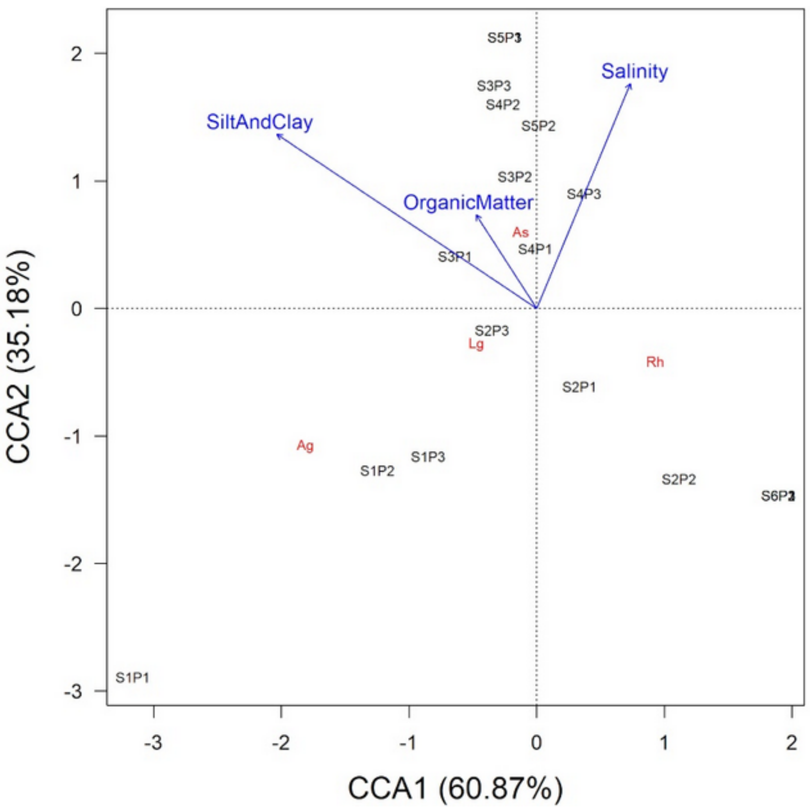

Figure 6 (previous page). Ordination diagram of the first two axes of the canonical correspondence analysis for the relative density data and sediment variables in the study sites in the mangrove of the Rio Mamanguape estuary. Environmental variables are represented by vectors. Ag: *Avicennia germinans*, As: *Avicennia schaueriana*, Lg: *Laguncularia racemosa*, and Rh: *Rhizophora mangle*.

and extracting the bark of the trees for tannin (Paludo & Klonowski 1999). Logging took place intensively throughout the mangrove area without technical criteria, with approximately 44,095 trees being removed between June 1989 and June 1990 (Paludo & Klonowski 1999). Currently, there has been a reduction in the extraction of wood from the mangrove due to the substitution of materials for building houses (masonry) and the intensification of conservation enforcement actions. However, selective logging is still recorded (Costa *et al.* 2021, Freires *et al.* 2023), despite the ecosystem being part of two Conservation Units.

This study showed that there were trends in the distribution of species along the estuarine gradient. *Avicennia germinans* and *Laguncularia racemosa* showed greater contributions in the upper estuary, while *Avicennia schaueriana* and *Rhizophora mangle* showed greater densities in environments under greater marine influence. Similar patterns have been observed in other Brazilian mangroves (Silva *et al.* 2005, Petri *et al*. 2011, Estrada *et al.* 2013, Costa *et al.* 2015, Calegario *et al.* 2015). However, some studies have reported *Laguncularia racemosa* dominating sites with greater marine influence (Chen & Twilley 1999, Bernini & Rezende 2010, Chagas *et al*. 2015). The zonation of mangrove species along the estuarine gradient may be related to interspecific differences in competitive abilities in relation to salt tolerance, nutrient uptake, and flood tolerance (Cintrón *et al.* 1978, Castañeda-Moya *et al*. 2013).

In addition to influencing structural development and carbon storage in mangrove biomass, anthropogenic actions also have the potential to alter species composition. Studies suggest that selective logging results in changes in abundance, as some species may be exploited more than others (Eusebio *et al*. 1987, Pinzón *et al*. 2003, Walters 2005, Chagas *et al*. 2015, Costa *et al.* 2021). In the Mamanguape River estuary, selective logging mainly affects *Laguncularia racemosa* and *Rhizophora mangle* (Paludo & Klonowski 1999). However, more recently, Costa *et al.* (2021) demonstrated that selective logging caused a change in the relative density of species in the upper estuary of the Mamanguape River, where *Avicennia germinans* was replaced by *Laguncularia racemosa* in some of the sites analyzed. In addition, due to its opportunistic characteristics (Saenger 2002, Tomlinson 2016), *Laguncularia racemosa* has been associated with forests altered by anthropogenic disturbances (Soares 1999, Bernini & Rezende 2010). Within this context, we assume that anthropic actions influence the distribution of the species along the estuary analyzed.

The anthropogenic disturbances that affect carbon storage and species distribution are not restricted to selective logging, as the mangroves of the Mamanguape River estuary are in an alarming state of conservation. The amount of fresh water discharged into the mangrove plays an important role, as it determines the salinity of the soil and water in the ecosystem and the availability of nutrients for plant growth (Woodroffe 1992). The mangroves analyzed show signs of stress and widespread death in various places throughout the estuary due to the reduction in fresh water. This has been attributed to changes in the use and occupation of the watershed and climate change (Freires *et al.* 2023).

Due to the increasing demand for water upstream, the amount of freshwater reaching the mangrove is reduced in many mangroves, which can cause a loss of the ecosystem's coverage area and a change in the composition of mangrove species (Gnanappazham & Selvam 2014). Changes in the Mamanguape River basin are related to its history of intense deforestation, the high demand for fresh water for irrigation of sugarcane (dominant in the landscape) and other crops, and the degradation of springs. In addition, the lower reaches of the Mamanguape River have undergone various drainage and dyke construction works, which have resulted in drastic hydrological changes in the mangrove forest. We therefore assume that the various anthropogenic interventions may have caused a reduction in the tidal prism in the Mamanguape River estuary.

According to Lewis & Brown (2014), the decrease in the tidal prism results in the closure of tidal channels and eventual overgrowth of mangroves. This further reduces the tidal prism and therefore the tidal flow, and eventually leads to the eradication of mangrove forests due to hypersalinity or excessive flooding from heavy rains that cannot drain from the system (Lewis & Brown 2014). In the mangroves of the Mamanguape River estuary, the progressive formation of several hypersaline plains on the banks of the river, tributaries, and tidal channels has been recorded, with the consequent death of mangrove plants (Freires *et al*. 2023), probably due to the reduction of the tidal prism. High tree mortality has also occurred due to the obstruction of channels that prevent the flow of tides in internal areas of the mangrove. In these places, so-called “ghost forests” have been formed, with or without the collapse of the soil surface. According to Krauss *et al*. (2018) tree mortality reduces root renewal, with a consequent decrease in the apparent density of the soil, which results in its compaction and subsidence. These sites tend to have an accumulation of tidal water, where stagnation and an increase in water temperature prevent the establishment of mangrove plants (Krauss et al., 2018).

Climate change is reducing potential blue carbon sinks around the world (Richards *et al.* 2020). Research has shown the influence of precipitation on the primary productivity of coastal wetlands, as plant productivity increases where there are higher precipitation rates, which lead to a reduction in porewater salinity (Gabler *et al.* 2017, Osland *et al.* 2018, Duke *et al*. 2019). Changes in climate affect carbon storage in mangroves due to changes in precipitation patterns, temperature increases, and sea level rise (Gonneea *et al.* 2004). In the mangroves of the Mamanguape River estuary, there has already been a downward trend in rainfall and an increase in air temperature in recent decades (Freires *et al.* 2023). These changes have accelerated the degradation of the ecosystem, as observed in other mangroves (Gnanappazham & Selvam 2014, Ward *et al*. 2016, Friess *et al.* 2022).

The fresh water that reaches the mangroves comes from surface runoff, precipitation, and groundwater infiltration. As mentioned earlier, the high demand for water for sugarcane cultivation, deforestation in the watershed, and the decrease in rainfall have reduced the amount of fresh water for the mangroves of the Mamanguape River estuary. However, we believe that the situation could get even worse, as groundwater consumption for sugarcane cultivation has increased in recent years due to the scarcity of surface water. Increased groundwater infiltration results in increased mangrove productivity because it reduces salinity levels (Mazda & Ikeda 2006, Hayes *et al*. 2019). In addition, access to groundwater also increases nutrient availability, which leads to higher primary productivity of mangrove species (Hayes *et al*. 2019). Therefore, the increasing use of groundwater for irrigation of sugarcane plantations is expected to increase interstitial salinity and result in further changes in species composition, reduction in structural parameters (height, diameter and basal area), and loss of biomass and carbon stocks in the mangrove forests of the Mamanguape River estuary.

Our estimate of AGB (136.6 Mg ha^{-1}) is at the lower end of the global average range, with values varying from 8.0 Mg ha^{-1} (Kauffman *et al.* 2011) to 573.0 Mg ha^{-1} (Kauffman & Cole 2010). The AGB/BGB ratio was 1.8 and this value is within the range of 1.0 to 4.4 documented for mangroves worldwide (Miao *et al.* 1998, Komiyama *et al.* 2008, Ragavan *et al*. 2021, Singh *et al*. 2023).

The carbon stock in the AGB recorded in the study area (60.1 MgC ha^{-1}) was lower than those found in Amazonian mangroves (145.0 MgC ha^{-1}) (Kauffman *et al.* 2018a), other mangrove forests in northeastern Brazil (70.0 MgC ha^{-1}) (Kauffman *et al.* 2018b), and mangrove forests in southeastern Brazil (75.3 MgC ha^{-1}) (Rovai *et al.* 2021). The carbon stock in the BGB recorded (27.7 MgC ha^{-1}) was also lower when compared to mangrove forests in Guaratiba (104.4 MgC ha^{-1}) (Santos *et al.* 2017) and mangroves in the Cananéia-Iguape estuarine system (82.0 MgC ha^{-1}) (Rovai *et al.* 2021), both in southeastern Brazil. Considering the latitudinal trends observed in Brazilian mangroves (Beloto *et al.* 2024), it was expected that the biomass carbon stocks in the mangroves of the Mamanguape River estuary would be higher than in the mangroves of southeastern Brazil. However, differences among mangroves also occur due to variations in the availability of fresh water and nutrients, composition, age of the forest, and anthropogenic influence (Lugo & Snedaker 1974, Schaeffer-Novelli *et al.* 1990, Saenger & Snedaker 1993, Boillon *et al.* 2008, Alongi 2014).

Our biomass and carbon stock estimates were carried out for fringe forests (high frequency of tidal inundation) according to Lugo & Snedaker (1974) and Schaeffer-Novelli *et al*. (2000). The average carbon stock in AGB in the study area (60.1 MgC ha^{-1}) was lower than the global average for fringe forests (81.8 MgC ha^{-1}) (Estrada & Soares 2017), but was higher when compared to fringe forests drastically altered by anthropogenic disturbances in Araçá Bay, São Paulo, Brazil (32.4 MgC ha^{-1}) (Schaeffer-Novelli *et al.* 2018).

Fringe forests exhibit greater biomass and carbon stock when compared to basin forests and shrub forests (Estrada & Soares 2017, Rovai *et al.* 2021). Thus, the total carbon stock in the mangrove trees of the Mamanguape River estuary (405,636 MgC) may be lower than we estimated because we did not sample basin forests. Even so, our data are useful as potential carbon stock values that can be reached or surpassed after restoring degraded areas in the mangrove analyzed.

Considering the estimates from this study, the destruction of mangrove biomass in the Mamanguape River estuary would result in CO_2 emissions equivalent to 0.41 Tg. This ecosystem lost 2.1% of its coverage area between 1985 and 2020 (Freires *et al.* 2023), which corresponded to the emission of approximately 31,262 MgC, equivalent to 0.03 Tg CO_2. We assume that emissions could be even higher if we take into account mangrove areas that are showing signs of stress and mortality.

The results revealed that the mangroves analyzed play an important role as a carbon sink. However, the biomass and carbon stock values recorded were lower than other Brazilian mangroves, probably due to the variation of natural factors (e.g., availability of fresh water and nutrients) and to intense anthropogenic disturbance related to selective logging, changes in the Mamanguape River basin, and climate change. Our study has some limitations that may have influenced the biomass and carbon stock values. As mentioned previously, sampling was restricted to fringe forest and therefore the values may have been overestimated. Furthermore, there were limitations in quantifying the impact of selective logging on carbon stocks. Therefore, we suggest future studies to fill these gaps. Despite this, the study raised warnings and made important contributions to planning the sustainable management of mangroves, especially in the face of climate change. Maintaining and increasing blue carbon stocks requires sustainable management, with increased efforts to conserve and restore degraded areas in the mangroves and the Mamanguape River basin. In addition, government agencies should step up control and monitoring of groundwater use in the watershed to prevent an increase in salinity in the estuarine region, which could affect the mangrove and result in higher CO_2 emissions. Conserving this ecosystem can provide benefits for traditional communities and contribute to increasing climate resilience (Zeng *et al.* 2021).

Ethical statement

This research did not involve animals subject to regulation and did not require approval by an Ethics Committee.

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