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Carbon stocks in mangroves, tidal salt marshes and subaqueous soils of the semi-arid region, Northeast Brazil

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A B S T R A C T
Due to the climate changes that have occurred in recent years, studies on carbon sequestration and storage have aroused great global interest. The main objective of this study is to quantify the total carbon stocks in the soil (TCstc) in mangrove, tidal salt marsh and subaqueous soils areas in the semi-arid region of Northeast Brazil. Soil samples were collected from ten mangroves, five tidal salt marshes and two subaqueous soils up to 100 cm deep and the stocks of total organic carbon (TOCstc), total mineral carbon (TMCstc) and aboveground biomass were quantified. The TCstc is the sum of the TOCstc plus TMCstc. For mangrove areas, the average aboveground biomass found was 176 Mg ha^{-1}. The average TCstc was 549 Mg ha^{-1} in subaqueous soils areas, 236 Mg ha^{-1} in tidal salt marsh areas and 345 Mg ha^{-1} in mangrove areas. The results showed that the stocks of TOCstc and TMCstc are similar and superior to several regions of the world. Mangrove and subaqueous soils areas have higher TOCstc at 0-20 cm depth, while in tidal salt marsh areas the highest TOCstc values were found at shallower depths. As for TCstc, underwater soils show the highest values, followed by mangrove forests and tidal salt marshes. However, this research reinforces the importance of these ecosystems in the sequestration and storage of carbon in the soil, demonstrating that the inspection of these areas should be intensified to ensure greater protection.
Keywords: blue carbon, soil carbon pools, mineral carbon, tropical wetlands.

Estoques de carbono em manguezais, restingas e solos subaquáticos da região semiárida, Nordeste do Brasil

R E S U M O
Devido as alterações climáticas ocorridas nos últimos anos, estudos sobre o sequestro e estocagem de carbono tem despertado grande interesse global. A pesquisa tem como objetivo principal quantificar os estoques totais de carbono no solo (TCstc) em áreas de mangue, apicum e solos subaquáticos, no semiárido do Nordeste do Brasil. Para isso, foram coletadas amostras de dez mangues, cinco apicuns e solos de ambientes subaquáticos nas seguintes profundidades do solo: 0-10, 10-20, 20-30, 30-50, 50-100 cm., sendo quantificados os estoques de carbono orgânico (TOCstc), carbono mineral (TMCstc) e biomassa vegetal acima do solo. O TCstc é a soma do TOCstc mais TMCstc. Para as áreas de mangues foram observados valores de biomassa vegetal média de 176 Mg ha^{-1}. Os estoques totais médios de carbono para os solos subaquáticos foram de 549 Mg ha^{-1}, já nas áreas de apicuns foram quantificados valores médios de 236 Mg ha^{-1} e nas dos mangues de 345 Mg ha^{-1}. Os resultados mostraram que as estocagens de TOCstc e TMCstc são similares e superiores a diversas regiões do mundo. As áreas de mangues e ambientes subaquáticos possuem maiores TOCstc na profundidade de 0-20 cm, enquanto, nas de apicuns os maiores valores de estoque foram verificados em menores profundidades. Quanto ao TCstc os solos subaquáticos mostram os maiores valores, seguido pelos bosques de mangue e apicuns. Contudo, esta pesquisa reforça a importância desses ecossistemas no sequestro e estoque de carbono no solo, demonstrando que a fiscalização destas áreas deve ser intensificada para a sua maior proteção.
Palavras-chave: carbono azul, carbono no solo, carbono mineral, pântanos tropicais.

Background

Blue Carbon is the name given to the carbon (C) sequestered by the ecosystems of coastal environments (mangroves, tidal marshes and seagrass meadows), which store this C in vegetation and soil. These environments are considered important sinks in the face of climate change mitigation and adaptation, due to their role in the global cycle of C, through its sequestration and redistribution (Howard *et al*., 2014; Cusack *et al*., 2018). Therefore, studies on C sequestration and storage are of great global interest, due to the climate changes that have occurred in recent years and that can play a significant role in offsetting carbon dioxide (CO_2) emissions.

Global greenhouse gas emissions have continued to rise, with historically and continuously unequal contributions resulting from the unsustainable use of energy, land-use change, lifestyles, and consumption and production patterns (IPCC, 2022). Consequently, scientific research has been striving to propose actions aimed at reducing pollutant gas emissions and restoring natural environments to enhance carbon sequestration. In this context, Tiefenbacher *et al*. (2021) state that climate change, along with alterations in soil hydrological regimes, vegetation, or soil management, can further modify organic carbon stocks. Furthermore, Panchal *et al*. (2022) emphasize soil reforestation as a key strategy for carbon sequestration.

It is recognized that C storage in mangrove ecosystems is higher than in other terrestrial forests, both in soil and in plant biomass (Giri *et al*., 2011). Mangroves cover an area of approximately 14 thousand km^2 in Brazil, one of the countries with the largest continuous extension of mangroves in the world and are considered to be significant global C sinks (ICMBIO, 2018; Kauffman, 2018a). Despite that, research related to the quantification of C in the soil and plant biomass in these environments is still incipient, especially on the coast of Northeast Brazil (Portela, 2019).

Studies on the Atlantic Coast southwest of Guyana to Argentina through compilation and systematic synthesis on the organic carbon stock of aboveground and soil biomass, as well as the rate of organic carbon sequestration, analyzes that the region has potent blue carbon hotspots, including the world's largest concentration of mangroves along the equator, as well as the undervaluation in the global estimate of subtropical and temperate salt marshes and seagrass meadows (Hatje *et al*.,2023).

For mangrove environments, most research on blue carbon estimates focuses on humid regions, highlighting a lack of studies in arid and semi-arid regions. Mangroves adapted to these regions, in terms of biogeography and ecology, are subjected to extreme climatic conditions (Rodrigues, 2022; Rodrigues *et al*., 2024; Eid *et al*., 2020). Nóbrega *et al*. (2018) also emphasize the scarcity of studies on soils associated with subaqueous environments, which could provide valuable information for their management and protection. Furthermore, because they are submerged, these environments often lack government oversight.

Regarding the concept of subaqueous soils, the World Reference Base for Soil Resources (WRB, 2015) considers water as the upper boundary of soil in locations where the water column is less than two meters deep. Thus, the system introduces the qualifiers "tidal" and "subaqueous" to distinguish soil orders that are either permanently inundated (subaqueous soils) or only flooded by high and mid tides, remaining exposed during low tide. However, the WRB-FAO system does not yet provide a precise characterization, as it limits tidal environments to a maximum water depth of two meters, while seagrasses are known to occur in deeper waters (Nóbrega *et al*., 2018).

The Brazilian Soil Classification System (SiBCS) (Santos *et al*., 2018) considers the atmosphere as the upper boundary of soil, thereby excluding submerged vegetated environments from its definition of soil. Nevertheless, pedogenetic processes (addition, loss, translocation, and transformation) have been identified in seagrass meadows worldwide, including in Brazil (Nóbrega *et al*., 2018).

Tidal salt marshes are considered hypersaline plains associated with mangrove areas, serving as nutrient reservoirs and supporting various biological cycles of mangrove-associated fauna. They also perform numerous other essential functions for maintaining coastal zones. However, they do not receive the same level of attention as other environments, as they are not designated as Protected Areas due to their sparse or absent vegetation (Rodrigues, 2022; Rodrigues *et al*., 2024; ICMBio, 2018).

Although coastal ecosystems play a crucial role in global climate change mitigation and biodiversity conservation, their degradation and biodiversity loss are progressively compromising their ecological functions. Urbanization, agricultural expansion, and the construction of port and road infrastructure have accelerated their decline. In northeastern Brazil, urban expansion in several coastal cities has converted mangrove areas into urban land. Additionally, industrial and aquaculture expansion has raised concerns about the contamination of mangroves by heavy metals, which can accumulate in these soils, acting as long-term pollutant reservoirs (Biondi & Silva, 2023).

Thus, the objective of this study was to quantify the total C stocks in soils (TCstc) in mangrove, tidal salt marsh and subaqueous soils areas in the extreme east of the Parnaíba Delta Environmental Protection Area - EPA, encompassing the states of Piauí (PI) and Ceará (CE). Total organic C stocks (TOCstc) and total mineral C stocks (TMCstc) were quantified.

The hypothesis of the study is that the mangrove areas, because they have a greater amount of plant biomass above the soil, are the ones that have a higher carbon stock in the soil followed by subaqueous soils, which have a large amount of grasses, and finally tidal salt marshes, which have either no vegetation or sparse vegetation, because research such as Portela (2020) and Kauffman (2018a) show the importance of plant biomass in adding carbon to the soil.

This study is important because it provides information about global estimates of C stocks, contributing to the understanding of global warming, and aims to foster a sustainable development of these areas, since they perform ecosystem services, especially C sequestration.

The important ecosystem service of C storage in these environments and, therefore, the importance of their preservation is highlighted. It is also noteworthy the important ecosystem service of C storage performed by these environments and, therefore, the importance of its preservation and/or conservation.

Methods

Study site

The study area is located within the boundaries of the Parnaíba Delta Environmental Protection Area (APA), which spans the states of Maranhão, Piauí, and Ceará in northeastern Brazil. This conservation unit covers an area of 3,189 km² and is classified as a protected area that allows for the sustainable use of its natural resources without requiring full conservation (ICMBio, 2020). In the present study, soil sampling was conducted in the easternmost portion of the APA, encompassing the municipalities of Luís Correia (PI), Cajueiro da Praia (PI), and Barroquinha (CE).

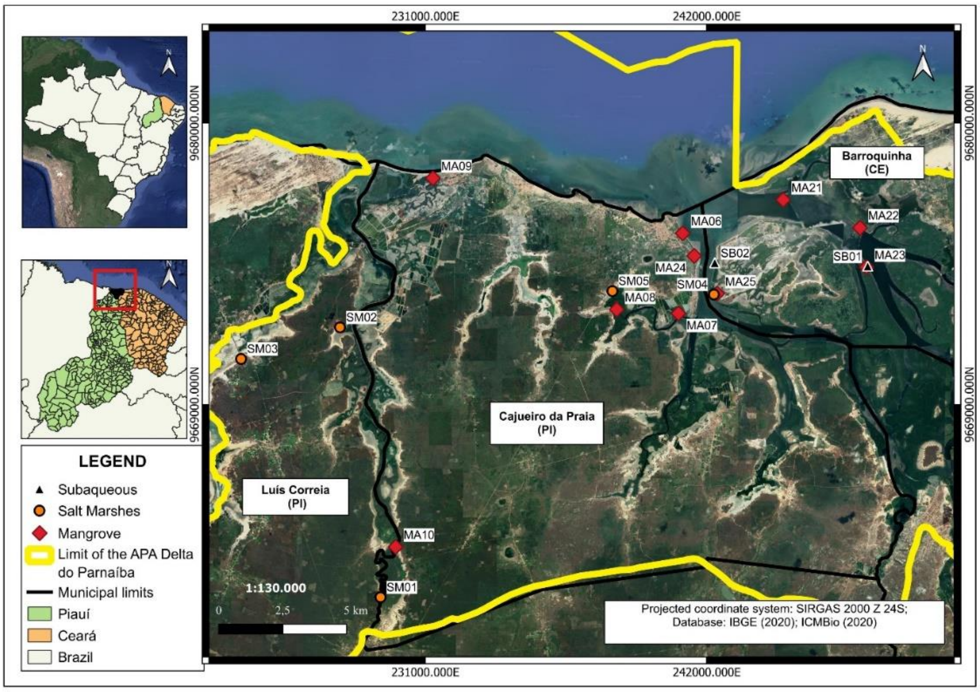

Figure 01. Location of the sampled points for the subaqueous soils, tidal salt marshes and mangroves in the extreme east APA Delta do Parnaíba.

In this region, the rainy season is concentrated in the first half of the year, from January to June, and is subdivided into a pre-rainy season (January) and the main rainy season (Lira, 2016). The municipality of Barroquinha belongs to the Coreaú River Basin and has a Mild Coastal Semi-Arid Tropical climate, with daily temperature variations averaging between 26°C and 28°C. Annual precipitation averages range from 1,000 to 1,300 mm in coastal areas, while in the hinterland, precipitation rates range from approximately 850 to 550 mm, with the rainy season occurring between January and May (Zannela, 2005; Lira, 2016).

The coastline of Piauí is influenced by a humid tropical climate with summer rains (Aw) and an extended humid tropical climate with summer rains continuing into autumn (Aw'), according to Köppen's classification. In the municipalities of Luís Correia and Cajueiro da Praia, which belong to the Parnaíba River Basin, temperatures range from a minimum of 24°C to a maximum of 34°C throughout the year, with rainfall exceeding 240 mm in the wettest months (Cavalcanti, 1996).

Regarding geology, Luís Correia and Cajueiro da Praia are part of the Precambrian crystalline basement, the Paleo-Mesozoic formations of the Parnaíba Sedimentary Basin, the Tertiary sediments of the Barreiras Formation, and Quaternary coastal sediments (Fundação Cepro, 1996; Sousa, 2019). In Barroquinha, the geology is represented exclusively by Tertiary sedimentary formations of the Barreiras Group, which in this area include outcrops of sandstone and conglomerates intercalated with siltstone and claystone, as well as Quaternary deposits such as alluvial and coastal deposits (Lira, 2016).

Regarding soil types, the municipalities contain associations of Gleysols, Argisols, Neosols, and Planosols, the latter being restricted to areas within the Parnaíba Basin (Pfaltzgraff; Torres; Brandão, 2010; Lira, 2016). Gleysols are found in fluvic-marine plains and floodplains, associated with wetland and mangrove vegetation. Argisols and Neosols are typically covered by tablelands vegetation, with Neosols also supporting stabilized dune vegetation that varies from herbaceous to arboreal, adapted to sandy and saline soils. Planosols, on the other hand, support riparian forests and floodplain vegetation, particularly carnauba palms, which are adapted to hydromorphic soils (Pfaltzgraff; Torres; Brandão, 2010; Sousa, 2019).

Field Sampling

The field sampling strategy was defined in advance following the method of Portela (2019), considering areas with high representativity in terms of mangrove forest structure and the absence of vegetation in tidal salt marsh areas. The representativity of mangrove vegetation was assessed through site visits and visual interpretation of the Normalized Difference Vegetation Index (NDVI), obtained from Landsat/OLI 8 imagery. This index allowed for the identification of the density of photosynthetically active vegetation, thereby highlighting potential sampling points. Figure 2 illustrates the low or absent vegetation cover in tidal salt marshes, whereas Figure 3 shows the high vegetation density in mangrove environments.

Figure 02. Different sampling points in tidal salt marsh environments located in the semi-arid region of Northeast Brazil.

Figure 03. Different mangrove forests in the semi-arid region of Northeast Brazil. 1- Red Mangrove (*Rhizophora mangle*). 2- Black Mangrove (*Avicennia sp*.). 3- Button Mangrove (*Conocarpus erectus*). 4- White Mangrove (*Laguncularia racemosa*).

The selection of sampling areas for subaquatic soil environments was based on information provided by local fishermen, as these areas remain completely submerged by seawater for most of the time. Access to these sites is only possible during extremely low tides, as illustrated in Figure 4.

Figure 04. Subaqueous soil environments located in the semi-arid region of Northeast Brazil. 1a- *Spartina maritima*. 1b – Subaqueous environment SB02. 2a- *Halodule sp*. 2b- Subaqueous environment SB01.

The TCstc of ten areas of mangrove (MA), five areas of tidal salt marshes (SM) and two areas of subaqueous soils (SB) up to 100 cm of soil depth were quantified in 200 m² (10 x 20 m) plots according to the method recommended by Kauffman and Donato (2012). Mangrove areas were sampled along the municipalities of Luís Correia, Cajueiro da Praia and Barroquinha, tidal salt marsh areas were sampled in the cities of Cajueiro da Praia and Luís Correia, and subaqueous soils were sampled in the municipality of Barroquinha. Table 01 shows the type of vegetation found at each point and the classification of the soils according to Santos *et al.* (2018) and WRB (2015).

Table 01. Associated vegetation of each point and classification of soils.

POINT	***VEGETATION***	***Classification according to Santos et al. (2018) / WRB (2015)***
SM01	No vegetation	GLEISSOLO SÁLICO Órtico solódico / Salic Gleysol
SM02	No vegetation	GLEISSOLO TIOMÓRFICO Órtico sódico sálico / Thionic Gleysol
SM03	No vegetation	GLEISSOLO TIOMÓRFICO Órtico sódico sálico / Thionic Gleysol
SM04	No vegetation	GLEISSOLO SÁLICO / Salic Gleysol
SM05	No vegetation	GLEISSOLO TIOMÓRFICO / Thionic Gleysol
MA06	*Conocarpus erectus*	GLEISSOLO HÁPLICO / Eutric Gleysol
MA07	*Rhizophora mangle* and *Avicennia sp.*	GLEISSOLO SÁLICO / Salic Gleysol
MA08	*Rhizophora mangle*	ORGANOSSOLO TIOMÓRFICO / Terric Histosol
MA09	*Rhizophora mangle*	GLEISSOLO TIOMÓRFICO / Thionic Gleysol
MA10	*Rhizophora mangle* and *Avicennia sp.*	GLEISSOLO TIOMÓRFICO / Thionic Gleysol
MA21	*Rhizophora mangle*	GLEISSOLO SÁLICO / Salic Gleysol
MA22	*Rhizophora mangle* and *Laguncularia racemose*	GLEISSOLO SÁLICO / Salic Gleysol
MA23	*Rhizophora mangle*	GLEISSOLO SÁLICO / Salic Gleysol
MA24	*Conocarpus erectus*	GLEISSOLO SÁLICO / Salic Gleysol
MA25	*Conocarpus erectus*	GLEISSOLO SÁLICO / Salic Gleysol
SB01	*Halodule sp.*	GLEISSOLO SÁLICO / Salic Gleysol
SB02	*Spartina maritima*	GLEISSOLO SÁLICO / Salic Gleysol

Soil Carbon

To quantify the total C storage, first, the total organic C content (TOC) was determined according to Teixeira *et al*. (2017) and the total mineral C content (TMC) was determined according to the method proposed by Heiri, Lotter and Lemcke (2001).

The TOC was quantified through oxidation with potassium dichromate ($K_2Cr_2O_7$) in an acidic medium added to the soil sample. Only carbon derived from easily oxidizable or decomposable organic materials was quantified via titration with ammonium ferrous sulfate (of the remaining potassium dichromate). For the determination of TMC, the soil samples were heated in a muffle furnace at 550 °C for 4 hours, followed by heating at 950 °C for 2 hours. Calcium carbonate was determined by the difference in weight after combustion at 950 °C and the oven-dried sample at 105 °C.

To quantify the total stock, soil bulk densities were also determined according to Teixeira *et al.* (2017). Thus, it is worth remembering that the soils were collected up to 100 cm deep. For points SM01, SM02, and the first three depths of SM03, a volumetric ring was used. For the remaining points, the volume of the Russian auger was utilized (Figure 05), as the collection with the volumetric ring was unfeasible due to the depth or consistency of the soil.

Figure 05. Soil sampling in tidal salt marshes area using Russian auger.

After determining bulk density, TOC and TMC, the total organic C stocks and the total mineral C stocks were calculated using the equation developed by Veldkamp (1994). The equation is defined as:

$$ECs = (C*D*t)/10 \quad (1)$$

were, ECs - Ecosystem carbon stocks, Mg ha-1; C - Total Carbon Content of the Depth, g kg^{-1} ; D - Depth density, kg dm^{-3}; t - Thickness of the layer considered. TCstc is the sum of TOCstc plus TMCstc.

Aboveground biomass (AGB) was quantified by using the method proposed by Kauffman and Donato (2012), only for mangrove vegetation, due to its robustness represented by height and diameter at breast height (DBH), a specific equation was adopted for each species or genus of mangrove to estimate aboveground biomass, as shown in Table 2.

Table 02. Equations used to determine biomass in different mangroves. Note: DBH is the diameter at breast height in centimeters (cm); H is the tree height in meters (m).

Species	*Equation*	*References*
Laguncularia racemosa	Biom (kg)= 0,1023 x DBH $^{2.5}$	*Fromard et al. (1998)*
Avicennia spp.	Biom (kg)= 0,14 x DBH $^{2.4}$	*Fromard et al. (1998)*
Conocarpus erectus	Biom (kg)= 0,1023 x DBH $^{2.5}$	*Fromard et al. (1998)*
Rizophora mangle	ln (Biom. (kg)) = 14,867663 = 0,5132 ln (basal area ^{2} x H)	*Santos et al. (2017)*

The difference in C stocks between the environments was presented through descriptive statistics, resulting in bar graphs and boxplots, and were tested with analysis of variance and Tukey test of untransformed data.

Results and discussion

The average biomass found among the vegetation was 176 Mg ha^{-1}, a value slightly higher than that quantified by Kauffman (2018a) in mangrove areas of the Brazilian Amazon, with average value of 145 Mg ha^{-1}. The values determined in this study were lower than the average determined by Portela (2019), on the order of 517 Mg ha^{-1}, in mangrove areas of northeastern Brazil. Mangroves have the highest values of aboveground biomass due to the density of vegetation and the large size of the plants. It is worth noting that trees with height variations of 40 m and expressive diameters were found. Portela *et* al. (2020) considers that the mangroves in this region have the largest biomass, being among the largest in Brazil

Points M21 and M23 stand out for having the highest AGB value. These are representative of the *Rhizophora mangle* species. Vegetation contributes to a greater addition of organic material. In the areas of the M24 and M25 mangroves, the lowest biomass and the presence of *Conocarpus erectus* vegetation were observed (Figure 07).

Tidal salt marsh areas were the environment with the lowest TCstc, ranging from 57 Mg ha^{-1} for SM01 to 448 Mg ha^{-1} for SM05, with average value of 236 Mg ha^{-1} (Figure 06). The total stocks observed in tidal salt marsh areas were similar to those quantified by Kauffman *et al.* (2018a), who found average value of 257 Mg ha^{-1} for tidal salt marshes in the Amazon, also similar to the global averages observed by Ward (2020) for tidal salt marshes of 250 Mg ha^{-1}, and higher than those found in shrimp farming areas in Ceará, with average value of 123 Mg ha^{-1} (Kauffman, 2018b). Deforestation and changes in soil management in these areas for the development of the enterprise may have contributed to the low stocks.

For the mangrove areas, a variation from 106 Mg ha^{-1} in MA07 to 592 Mg ha^{-1} in MA23 was observed, with average value of 344 Mg ha^{-1} (Figure 06), which is similar to that found by Kauffman *et a*l. (2018a), 340 Mg ha^{-1} in Amazonian soils, and lower than those reported by Kauffman *et al.* (2018b) for soils in Ceará, with average value of 413 Mg ha^{-1}, Cooray *et al.* (2021) for soils in Sri Lanka, with average value of 404 Mg ha^{-1}, and Kauffman and Bhomia (2017) for Liberia, in West Africa, with value of 901 Mg ha^{-1}.

Subaqueous soils areas had the highest TCstc among the studied environments, with minimum value of 461 Mg ha^{-1} in ME02 and maximum value of 636 Mg ha^{-1} in ME01, with average of 548 Mg ha^{-1} (Figure 06), which are higher than those found in temperate zone areas, ranging from 23.1 to 351.7 Mg ha^{-1} (Röhr *et al.*, 2018). According to the analysis of variance, subaqueous soils areas were statistically different from tidal salt marsh areas at 5% probability level.

Rodrigues (2022) also argues that the proximity to the river, in the case of this study to the river and the sea, and the consequent more frequent flooding, in this case of mangrove and subaquatics soils, contributes to conditions of lack of soil oxygen, supporting greater accumulation of organic carbon than tidal salt marsh. Therefore, this result can evidence the influence of the topography of the tidal profile on the carbon stock in the soil.

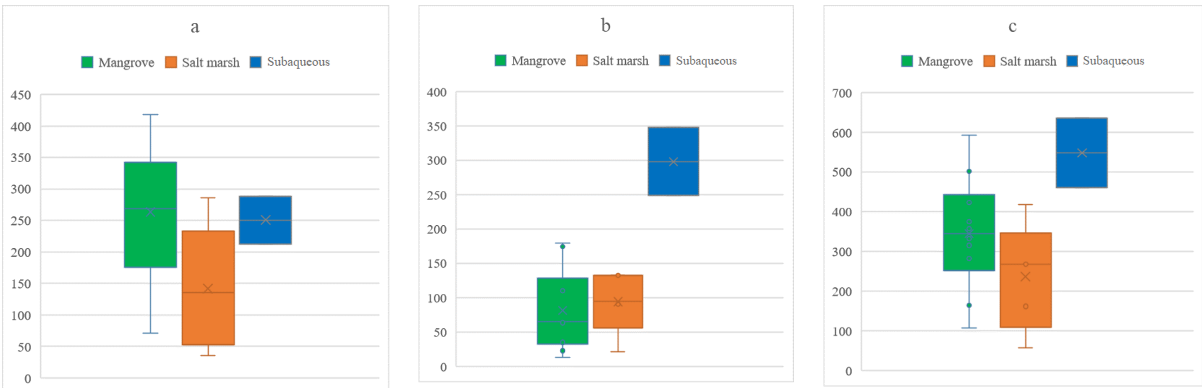

Figure 06. Boxplot of carbon stocks (Mg ha^{-1}) of mangroves, tidal salt marshes and subaqueous soils in Northeast Brazil. (A) Total organic carbon stocks. (B) Total mineral carbon stocks. (C) Total carbon stock in the soil.

Tidal salt marsh areas (Figure 06) showed average TOCstc value of 142 Mg ha^{-1} and average TMCstc value of 95 Mg ha^{-1}, with erratic distribution of C contents in the layers, Zhang et al. (2021) found values of 150 Mg ha^{-1} in the Yellow River Delta, mean values higher than those found in this study. In subaqueous soils areas (Figure 06), the average value of TOCstc was 250 Mg ha^{-1} and the average value of TMCstc was 298 Mg ha^{-1}, showing a balanced distribution among the stock values. In mangrove areas (Figure 06), TOCstc was 263 Mg ha^{-1} and TMCstc was 82 Mg ha^{-1}, with a greater contribution of the organic fraction. A distinct pattern was observed by Adame *et al.* (2013) for the mangrove areas of Mexico, where the authors found a balanced distribution between mineral and organic fractions of the soil. Analysis of variance showed that mangrove areas have higher TOCstc compared to tidal salt marsh areas at 6% probability level, while subaqueous soils areas had the highest TMCstc values compared to the other environments at 1% probability level.

In mangrove and subaqueous soils areas, the highest values of TOCstc were observed at the 0-20 cm depth (Figure 07), possibly due to the higher concentration of plant biomass on the surface in these environments compared to tidal salt marsh areas, since these areas show absence or low presence of vegetation (Table 01). Although there is no vegetation on the surface, in the tidal salt marsh areas, there is an increase in TOC contents in subsurface at points SM02, SM03 and SM05, considerably interfering with the significant increase in TOCstc at 20-100 cm depth. This pattern suggests the occurrence of buried surface horizons, a condition not observed at points SM01 and SM04. Also, the increase of stocks in subsurface may be related to buried paleosurfaces or surface horizons, given the great morphogenetic dynamics of these environments, and soils with this feature receive the qualifier “fluvic” according to WRB (2015) and the character “fluvic” according to Santos *et al*. (2018).

All environments showed an increase in TMCstc in subsurface (Figure 07). Such increase has also been observed in the environments of salt marshes located in Germany by Muller *et al.* (2023) and in mangroves and tidal salt marshes of Mexico by Adame *et al.* (2013). In subsurface, TMCstc should be interpreted with caution, especially in the context of dynamics with carbonate, as the change of TMC in subsurface may reflect succession in younger ecosystems (Muller *et al*., 2023), which would reinforce the occurrence of buried paleosurfaces or surfaces in tidal salt marsh areas. The high values of mineral C stock in the seagrass meadow environment are conditioned by the large presence of shells in the habitat, which contain about 95% calcium carbonate in the form of aragonite and calcite, in their composition (Fagundes; Silva, 2022).

Geomorphic configuration also acts as an important predictor of TMCstc because it controls the frequency and quantity of carbonate deposition, so the accumulation of mineral C would be more favored at more hydrologically exposed sites, with high marine exchange, compared to more hydrodynamically protected sites, with less marine exchange. In addition, the presence of plants in the environment interferes with the concentration of TMC, since plants retain sediments from the water column, increasing mineral sediment deposition compared to areas without vegetation (Mueller *et al*., 2023).

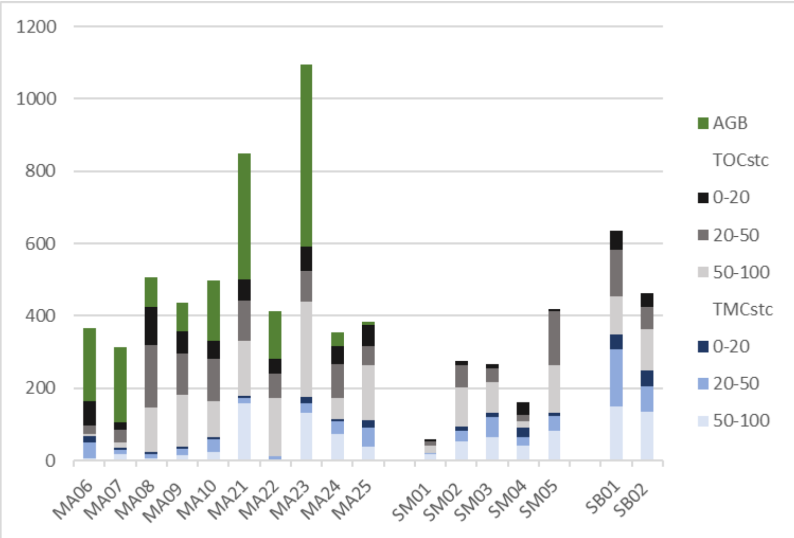

Figure 07. Ecosystem carbon stocks (Mg C ha^{-1}) of mangroves, tidal salt marshes and subaqueous soils in the Brazilian semi-arid region, Piauí and Ceará coast. AGB, aboveground biomass; TOCstc, total organic carbon; TMCstc, total mineral carbon.

Conclusion

The results indicate that the presence of shells in the environment directly interferes with the total soil carbon stocks, as they consist of approximately 95% calcium carbonate in their composition. This directly contributed to the subaqueous environments exhibiting the highest carbon stocks, followed by mangrove forests and tidal salt marshes.

The results do not corroborate the initial hypothesis of the study, since other factors can increase carbon storage. Frequent soil flooding processes and the presence of benthic macrofauna animals and the deposition of their shells can directly influence C storage in the soil.

The carbon stocks in the soils of the studied environments were found to be high and superior to those of several environments worldwide. Highlighting the importance of these environments for the balance of environmental systems and maintenance of ecosystem services provided on local and global scales.

Hypersaline tidal flats demonstrate significant carbon storage even without substantial aboveground vegetation biomass. Therefore, further research should be developed to better investigate these environments and its role in increasing soil carbon stocks.

The law protecting mangrove areas should be revised to include Brazilian tidal salt marshes, as they are not effectively protected, leaving them vulnerable to degradation driven by aquaculture activities, especially shrimp farming, and the increasing alteration of these environments due to the advancement of cities in coastal areas.

Therefore, changes in land use and management directly interfere in C sequestration and storage in these environments, so they need more effective inspections; in addition, in the current context of severe climate change, result like this reinforce the importance of natural areas in climate mitigation.

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