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Original Article

Silviculture

Mangrove Soil in Physiographic Zones in the Sao Francisco River Estuary

Karen Viviane Santana de Andrade[1], Francisco Sandro Rodrigues Holanda[1],
Tiago de Oliveira Santos[2], Mykael Bezerra Santos Santana[3],
Renisson Neponuceno de Araújo Filho[4]

[1]Departamento de Engenharia Agronômica, Universidade Federal de Sergipe – UFS, Aracaju/SE, Brasil
[2]Programa de Pós-graduação em Ciência do Solo, Departamento de Agronomia,
Universidade Federal Rural de Pernambuco – UFRPE, Recife/PE, Brasil
[3]Natus Engenharia Meio Ambiente e Tecnologias Sustentáveis – ENGENATUS, Aracaju/SE, Brasil
[4]Departamento de Engenharia Florestal, Universidade Federal do Tocantins – UFTO, Gurupi/TO, Brasil

ABSTRACT

Mangrove ecosystem dynamics and diverse human activities have led to a need for studies that give us a better understanding of the peculiarities of their soils. The objective of this study was to evaluate the physical and chemical soil attributes of mangrove forests located in the São Francisco River estuary, related to local ecological conditions. Two stations, divided into three forest types (fringe, basin and transition) were selected and five composite soil samples were collected from each forest type. Soil samples were submitted for chemical and physical analysis. The soil presented a sandy texture, with high organic matter and element content in the following order: $Mg^{2+}>Na^{+}>Ca^{2+}>H^{+}>K^{+}>P>Al^{3+}$ and $Fe^{2+}>Zn^{2+}>Cu^{2+}>Mn^{2+}$, respectively, with variations between the forests and stations. In general, the mangrove forests presented high fertility, especially in the basin forest, provided by vegetation development, showing a zoning trend for species in relation to soil fertility.

Keywords: organic matter, soil elements, mangrove, basin forest.

1. INTRODUCTION

Mangrove ecosystems are complex and highly productive, effective in providing nutrients to adjacent areas and organic debris that serve as a food source for a diversity of living organisms (Zhou et al., 2010).

This ecological system, characteristic of the world's tropical and subtropical coastal regions extends along the Brazilian coast, covering an area of approximately 13,400 km^2 (Spalding et al., 1997). This location enables the sediment carried by water bodies to be retained, allowing the development of plant species, which in turn, act as natural physical barriers and minimize the effect of coastal erosion.

Considering their ecological significance, mangroves are governed by the Law Number 4,771/65, as Permanent Preservation Areas – APPs. However, this ecosystem has suffered degradation, starting during colonization and intensifying due to population growth along the Brazilian coast. Globally, over the last 50 years, approximately one third of mangrove forests have been cleared (Alongi, 2002).

In Brazilian mangroves, the identified woody plants are the red mangrove (*Rhizophora mangle* L.), black mangrove (*Avicennia* sp.) white mangrove (*Laguncularia racemosa* L.) Gaertn., and button mangrove (*Conocarpus erectus*). These woody species have several adaptations that allow the colonization of predominantly muddy soils with attributes that limit the development of other species (Soares et al., 2003).

The physical and chemical attributes of mangrove soils and other factors such as the frequency of high tides, pH, salinity of interstitial water, litter production and decomposition rate, strongly influence mangrove species zoning (Reef et al., 2010). Nutrient levels in mangrove forests generally vary according to the flood tides and the degree of sedimentary water saturation, which can affect the availability of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), indicating good soil fertility (Souza et al., 1996). The levels of organic matter are high, because the environment is humid and the decomposition that occurs via microorganisms in the presence of oxygen are low (Schulz, 2000).

Soil attributes express the level of mangrove preservation or degradation, which is directly related to species distribution and the degree of biological development. Thus, an understanding of soil dynamics is an important tool in terms of ecosystem response to environmental conditions and may contribute to future conservation measures. The objective of this study was to evaluate physical and chemical soil attributes in mangrove forests located in the São Francisco River estuary related to local ecological conditions.

2. MATERIAL AND METHODS

2.1. Study area

This study was carried out in the São Francisco River estuary, Northeastern Brazil, in a tributary named Parapuca river, located in the Municipality of Brejo Grande, Sergipe state (Figure 1).

According to Santos et al. (2014) the São Francisco River estuary occupies a coastal strip 5 km wide and 25 km long, between the mouth of the river and the village of Ponta dos Mangues (municipality of Pacatuba). Part of its Holocene coastal plain is constituted by a string of islands separated from the mainland by tidal channels, with halomorphic soils under the influence of the tides, with typical mangrove vegetation.

The regional climate is classified as mega thermal dry to sub-humid, with an average annual temperature of 25.7 °C and average annual precipitation of 1,201.7 mm, with rainy seasons between March to August (SEPLAN, 2010).

Data collection was conducted at two experimental sites, named Station A (10°30'57" and 48°26'25") and Station B (10°31'13" and 48°26'38"), separated by a river channel. Each station was divided into physiographic zones, according to tidal levels (Lugo & Snedaker, 1974). These included wood fringe forests, defined as forests that grow along a riverbank; basin forest, the inner portion of the forest; and a transition forest zone that borders the mangrove forests and another ecosystem.

The soil of the experimental stations was given the general designation of mangrove soil (EMBRAPA, 2013). Its main characteristics were high salt and organic matter contents, low consistency, anaerobic conditions, dark gray coloration and a texture ranging from clay to sandy (Schaeffer-Novelli, 1995).

Mangrove forests in different physiographic zones were characterized as mixed, in the ripening phase. In Station A, the species *Rhizophora mangle* and

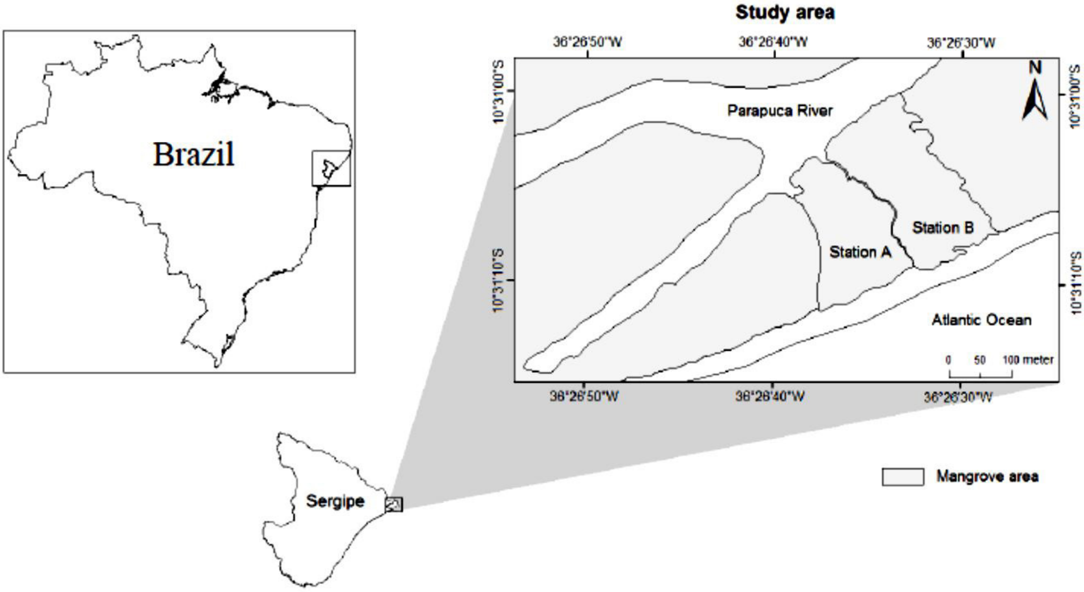

Figure 1. Location of the study area on the Parapuca River.

Laguncularia racemosa and in Station B, the species *Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia* spp., were identified. The species *Rhizophora mangle* was the most prevalent in that area.

2.2. Soil sampling and physical and chemical analysis

0.5 kg soil samples were collected at a 20 cm depth equidistant from one another by 50 m. The soil samples were collected from the two A and B Stations from the fringe, basin and transition forest areas with five repetitions each. Deformed soil samples were air dried at ambient temperature and passed through a 2 mm sieve, to perform physical and chemical analyses.

The physical analysis to determine the granulometric distribution of the soil was performed using the densimeter method (Bouyoucos, 1962) and the texture classification was performed through the textural triangle (Santos et al., 2013).

Soil pH measurements were performed on the saturated water surface at each sampling point, and in water in the laboratory using the SMP and Calcium Chloride methods. The determination of pH in the laboratory was performed as indicated by EMBRAPA (2009).

The chemical analysis was performed on a dried soil sample at 40 °C, to determine calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}), sodium (Na^{+}), potassium (K^{+}), hydrogen (H^{+}) and phosphorus (P) concentrations. Other elements including iron (Fe^{2+}), copper (Cu^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) were extracted using Mehlich^{-1} solution and determined by atomic absorption spectrophotometry (EMBRAPA, 2009).

The exchangeable cations were analyzed according to EMBRAPA (2009), and Al^{3+}, Ca^{2+} and Mg^{2+} KCl were extracted with 1 mol L^{-1}. Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry, and Al^{3+} exchangeable was determined by titration with NaOH 0.025 mol L^{-1} in the presence of bromothymol blue indicator (0.1%). Na^{+} and K^{+} were extracted using Mehlich^{-1} solution and determined by flame emission photometry. Potential acidity (H + Al) was extracted with buffered calcium acetate solution 0.5 mol L^{-1} (pH 7.1-7.2) and determined by titration with NaOH 0.025 mol L^{-1} in the presence of phenolphthalein indicator 10 mg L^{-1}.

Based on the chemical analysis results, the base sum (BS) was calculated with the sum of exchangeable cations. Cation exchange capacity (CEC) was calculated by base sum (BS) and (H + Al), base saturation (V) was calculated as the ratio between SB and CEC, multiplied by 100 and exchangeable sodium percentage (ESP) was the ratio of exchangeable Na^+ and CEC multiplied by 100 (EMBRAPA, 2009).

Available phosphorus (P), extracted using Mehlich^{-1} solution was determined in the presence of the diluted acidic ammonium molybdate solution and ascorbic acid, by colorimetry using a wavelength of 660 nm (EMBRAPA, 2009).

2.3. Statistical analysis

The treatments were arranged in factorial 2 × 3 (stations × forest), with 05 (five) replications. The physical and chemical soil data from the forest at each station was subjected to analysis of variance (ANAVA) and means were compared using the Tukey Test at 5% probability. Simple correlation coefficients were performed to examine the relationship between clay and organic matter of the soil in the fringe, basin and transition areas using the SISVAR computer program (Ferreira, 2011).

3. RESULTS AND DISCUSSION

3.1. Soil texture, organic matter and pH

The average percentage of sand, silt and clay varied between Stations A and B from 59.11 to 80.34%, 14.55 to 30.73% and 6.10 to 10.94%, respectively (Table 1), by area. A homogeneous distribution of soil particles was observed, with coarser soil particles predominating in each of the studied forests, presenting intermediate silt values and lower clay values.

The soil texture of the studied area followed the trend of sand > silt > clay content, and the percentage of sand in the Station A fringe and transition forests was significantly higher compared to Station B, associated with the lower silt percentages (Table 1). Nayar et al. (2007) explained this finding as being a result of the tidal flows in estuarine regions, which lead to silt and clay transportation, helped by the smaller particle size, thus increasing the percentage of sand in the soil.

Comparing the same forest type, the clay fraction showed a different behavior between stations, with higher values observed in the Station A basin forest and in the Station B fringe forest. Comparing forests from the same station, significant differences ($p \leq 0.05$) were observed only in station A, with higher percentages in the basin forest.

Both stations presented similar behavior for soil texture classification, mostly dominated by Sandy loam (moderately coarse), except for the soil of the station A transition forests, which were classified as Loamy sand (coarse). The dominance of coarse soil particles may be related to the accumulation of marine and river sediment. The Parapuca River mouth has been affected because of morphological changes, involving an accelerated erosion process mentioned by Alves et al. (2007). The quantity of coarse canal sediment is influenced by the movement of sandy fractions from the beach, blown inland, due to wind action and high tide events (Bittencourt et al., 1990).

This study found low amounts of clay and high amounts of sand, characterizing a sandy soil, as also observed by Nayar et al. (2007) in Pichavaram, west coast of India; Krishna Prasad & Ramanathan (2008)

Table 1. Mean values of organic matter and soil particles.

Station/Forest	O.M. (g Kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Texture Classification
STATION A					
Fringe	66.18 aA	71.63 aA	22.28 bA	6.09 bAB	Sand loam
Basin	77.92 aA	69.46 aA	19.60 aA	10.94 aA	Sand loam
Transition	53.86 aA	80.34 aA	14.55 bA	5.11 aB	Loamy sand
STATION B					
Fringe	70.76 aA	59.11 bA	30.73 aA	10.23 aA	Sand loam
Basin	64.82 aA	69.18 aA	24.31 aA	6.52 bA	Sand loam
Transition	55.58 aA	67.48 bA	25.95 aA	6.50 aA	Sand loam
CV%	23.85	11.42	27.63	41.67	

O.M: Organic Matter; CV: Coefficient of Variation. Means followed by the same uppercase letters vertically, comparing the averages of the forests in different physiographic zones for the same station, and lowercase letters, comparing the averages between the stations for the same type of wood do not differ significantly by Tukey Test ($p \leq 0.05$).

in Ponggol, Singapore, and Bernini et al. (2006) in Espirito Santo state, Brazil, in contrast with Odum (1972) and Cintrón & Schaeffer-Novelli (1983) who reported high clay concentrations in mangrove soils.

In all sites studied in both stations, high organic matter (OM) content was observed, reaching average values of 77.92 g kg^{-1} (Table 1), even though organic matter (OM) soil content generally varies from 10 to 40 g kg^{-1} in mangrove soils (Cuzzuol & Campos, 2001). This high organic matter content in the soil can be explained by the frequent deposits of litter (Fernandes et al., 2007) and plant debris from watercourses, associated with a low decomposition rate of this material, due to a lack of oxygen in the highly saturated soil.

Organic matter values presented a positive correlation with clay content (Figure 2), as a result of the chemical and physical protection provided by organic matter as reported by Perin et al. (2003), given that the highest organic matter (Table 1) values were also found in the Station A basin forests and in the Station B fringe forest, with the highest clay levels being 10.94 and 10.23, respectively.

The soil pH values ranged from 5.7 to 7.9, indicating a slightly acidic to slightly basic soil tendency, with values near to neutral, which can be considered a standard feature of mangrove soils not subject to disturbance, which tend toward a pH balance promoted by oxidation-reduction reactions (Souza-Júnior et al., 2008). In both stations, pH in water, pH in calcium chloride and pH in SMP, presented a tendency of being below the pH measured *in situ* (Figure 3).

The pH values determined by the calcium chloride method were lower than the valuesfound using the water and SMP methods. This can be explained due to the method of determination of calcium chloride being less affected by the presence of salts (Rossa, 2006), frequently observed in mangrove soil samples due to marine influence or mineralization in humid soil samples packed in plastic bags (Figure 3).

The drop in pH can be related to sample handling in the laboratory leading to oxidation, making the environment more acidic. The same soil behavior was observed with lower pH values determined in the laboratory, when compared to pH *in situ*, probably due to the oxidation of pyrite (FeS_2), which is stable under anaerobic conditions, but which forms sulfuric acid when exposed to air (Roisenberg et al., 2008).

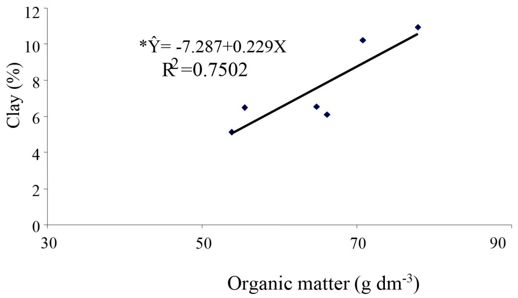

Figure 2. Scatter diagram between the values of organic matter and clay content. *Significant at $P \leq 0.05$.

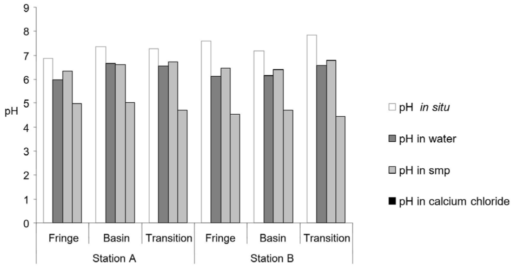

Figure 3. pH values *in situ*, in water, calcium chloride and SMP Stations A and B.

3.2. Elements in mangroves forest soil

$Mg^{2+}>Na^{+}>Ca^{2+}>K^{+}>P>Al^{3+}$ showed a decreasing concentration as follows (Table 2) with no significant differences between the stations studied and the physiographic zones when comparing Ca^{2+}, Mg^{2+}, Al^{3+} and K^{+} concentrations.

P concentrations in the Station A fringe forests were determined, possibly explained by the daily washing generated by tidal movements, differing from the basin forests which showed high levels of these elements (Table 2). This behavior may be related to lower exposure to flooding in the basin forest, which according to Ferreira et al. (2010) makes this environment more vulnerable to accumulating salt due to surface water evaporation. The same behavior was observed in Station B, with no significant difference between the physiographic zones. The Station A basin and transition forests showed sodium values higher than the same physiographic zones in Station B.

In relation to the species *Avicennia* spp. and *Laguncularia racemosa* were found in areas with higher salt concentrations. It can be explained that these

Table 2. Average values of elements of the mangrove soil of Brejo Grande, Sergipe.

Station/Forest	P	Ca^{2+}	Mg^{2+}	Al^{3+}	Na^{+}	K^{+}
	Mg dm^{-3}	------------------------cmol$_c$ dm^{-3}---------------------------				
STATION A						
Fringe	17.42aB	4.29aA	14.10aA	0.01 Aa	7.00 aB	0.73 aA
Basin	30.26 aA	5.25aA	19.10aA	0 aA	23.53 aA	1.06 aA
Transition	23.54aAB	6.18aA	14.02 aA	0.01 aA	17.56 aAB	0.82 aA
STATION B						
Fringe	22.44 aA	6.22aA	11.89 aA	0.03 aA	6.49 aA	0.81 aA
Basin	30.98 aA	5.14aA	14.64 aA	0.03 aA	11.12 bA	0.83 aA
Transition	24.18 aA	4.42aA	12.64 aA	0.02 aA	6.98 bA	0.82 aA
CV%	26.99	41.37	43.20	175.09	60.41	26.81

CV: Coefficient of Variation. Means followed by same upper case letters vertically, comparing the middle of the forest in different physiographic zones for the same station, and lowercase letters, comparing the averages between the stations for the same type of wood do not differ significantly by Tukey Test ($p \leq 0.05$).

species have physiological mechanisms that tolerate salinity (Zamora-Trejos & Cortés, 2009; Umetsu et al., 2011). Additionally, *Rhizophora mangle* showed better adaptation to canals with lower salinity.

The presence of exchangeable mangrove soil cations showed the following descending trend: $Mg^{2+}>Ca^{2+}>K^{+}$, as observed by Alongi et al. (2004), in mangroves in Malaysia. It is known that the chemical characteristics of mangrove soils is related to the contribution of river-sea primary micas (biotite and muscovite) sources of K^{+} and Mg^{2+}, and calcium carbonate and calcium phosphate, from the decomposition of the crustacean carcasses, which are the main source of calcium in that environment.

The nutrient content quantified in mangrove soils is very different from values observed in agricultural land as reported for example, by Sobral et al. (2007), except for Al^{3+} levels, which were below toxicity in the São Francisco River estuary. This can be explained by the soil pH recorded, which was characterized as "almost neutral". This makes this element more soluble, thereby favoring Aluminum leaching and the precipitation of Al^{3+} hydroxides.

As shown in Table 3, the concentrations of micronutrients showed no variation between physiographic zones and stations, except for Manganese (Mn^{2+}) which presented a higher value ($p \leq 0.05$) in Station B (17.71) compared to the Station A transition forest (2.64).

High Fe^{2+} values can be explained by anaerobic condition of mangrove soils favoring greater solubilization in this environment. Similar behavior Fe^{2+} and Mn^{2+} was observed, which increased their concentration under flooding associated with higher organic matter concentrations and the possible presence of less stable chemical forms.

On the other hand, zinc Zn^{2+} presented low concentrations, as a negative response to anaerobic conditions, probably related to the accumulation of CO_2, from the decomposition of organic matter and possible pH fluctuations, which according to Lima et al. (2005) allowed the precipitation of $ZnCO_3$, Zn $(OH)_2$ and ZnS.

In other Brazilian mangrove soils (Cotta et al., 2006; Onofre et al., 2007), heavy metal concentrations (Fe^{2+}, Mn^{2+}, Zn^{2+} and Cu^{2+}) are much higher than their concentration in the São Francisco River estuary (Table 3). The low levels of these elements can be explained by the absence of sewage and industrial residue discharge related to urbanization. Low levels of metals can also be explained by the strong presence of coarse soil sediments, which are predominantly composed of quartz composites, poor in metal concentrations, due to their lower specific surface area.

Micronutrients such as Fe^{2+} and Zn^{2+} tended to be concentrated in the transition forests corroborating with Lacerda (1986) who showed that nutrient concentrations decrease from the transition to the fringe forests, with nutrients entering the mangrove via land-based origins.

In the fringe and basin forests of Stations A and B, a higher H + Al concentration was observed (Table 4). Given that aluminum presented little influence on exchangeable acidity, the increased hydrogen levels may be explained by the dissociation of H^{+} ions from the phenolic groups of organic matter (R-OH), which occurs at pH 6.0, found in the study area (EMBRAPA, 2006).

Table 3. Average micronutrient values in mangrove soils of Brejo Grande, Sergipe state.

Station/Forest	Fe	Cu	Mn	Zn
	---------------------------mg dm^{-3}-----------------------------			
STATION A				
Fringe	257.53 aA	5.55 aA	1.69 aA	36.12 aA
Basin	328.48 aA	5.01 aA	2.74 aA	17.83 aA
Transition	446.61 aA	6.92 aA	2.64 bA	50.69 aA
STATION B				
Fringe	625.05 aA	6.66 aA	7.34 aA	18.70 aA
Basin	458.76 aA	7.65 aA	5.04 aA	38.26 aA
Transition	725.89 aA	6.76 aA	17.71 aA	43.14 aA
CV%	77.51	81.55	153.60	114.05

CV: Coefficient of Variation. Means followed by same uppercase letters vertically, comparing the averages of the forest between different physiographic zones for the same station, and lowercase letters, comparing the averages between the stations for the same type of forest, did not differ significantly by Tukey Test ($p \leq 0.05$).

Table 4. Average values of H + Al, CEC, ESP and V in mangrove soil of Brejo Grande, Sergipe state.

Station/Forest	H + Al	CEC	ESP	V
	--------- cmol$_c$ dm^{-3}--------			%
STATION A				
Fringe	2.58 aA	28.68aB	24.64aB	91.10aA
Basin	2.03 aA	50.94aA	42.80aA	95.60aA
Transition	1.79 aA	40.36aAB	40.74aA	95.14aA
STATION B				
Fringe	2.37 aA	27.74aA	23.46aA	91.64aA
Basin	2.51 aA	34.22bA	28.92bA	91.02bA
Transition	1.69 aA	26.52aA	26.30bA	93.24aA
CV%	32.45	36.65	26.61	3.16

H+Al: Potential Acidity; CEC: Cation Exchange Capacity; ESP: Exchangeable Sodium Percentage; V: Base Saturation; CV: Coefficient of Variation. Means followed by the same uppercase letters vertically, comparing the middle of the forest in different physiographic zones for the same station, and lowercase letters, comparing the averages between the stations for the same type of wood did not differ significantly by Tukey Test ($p \leq 0.05$).

The Station A mangrove forest was more developed than in Station B. Taking into account the physiographic zones, the vegetation of the basin forest was the most developed in both stations. This degree of species development may be related to soil fertility with both stations presenting a higher nutrient concentrations and consequently high SB, CEC, ESP and V values, with finer sediments and higher organic matter content (Havlin et al., 2004).

4. CONCLUSIONS

In mangroves, the proportion of clay, silt and sand influence soil consistency, organic matter, heavy metal content, and consequently species diversity and distribution.

The dominance of coarse particles in the soil may be related to the accumulation of marine and river sediments.

The mangroves of the São Francisco River estuary present micronutrient concentrations in decreasing order of $Fe^{2+}>Zn^{2+}>Cu^{2+}>Mn^{2+}$ and macronutrient concentrations in the soil, in the following decreasing order: $Mg^{2+}>Ca^{2+}>H^{+}> K^{+}>P$.

The high amounts of exchangeable bases (Ca^{2+} and Mg^{2+}) lead to high SB, CEC and V values, giving the soil a eutrophic behavior.

The higher CEC values are probably mainly related to the higher organic matter content in all physiographic zones.

The greater vegetation development regardless of the physiographic zone, but emphasizing the vegetation species in the basin forest, has a strong relation with the greater soil fertility.

There is a trend toward species zoning in relation to soil fertility dominated by *Rhizophora mangle*, which is strongly developed in fertile soils.

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CORRESPONDENCE TO

Francisco Sandro Rodrigues Holanda
Departamento de Engenharia Agronômica,
Universidade Federal de Sergipe – UFS, Avenida
Marechal Rondon, s/n, CEP 49100-000,
São Cristóvão, SE, Brasil
e-mail: fholanda@infonet.com.br

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