Comissão 1.2 - Levantamento e classificação do solo

GENESIS, CHARACTERIZATION, AND CLASSIFICATION OF MANGROVE SOILS IN THE SUBAÉ RIVER BASIN, BAHIA, BRAZIL

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ABSTRACT

Preservation of mangroves, a very significant ecosystem from a social, economic, and environmental viewpoint, requires knowledge on soil composition, genesis, morphology, and classification. These aspects are of paramount importance to understand the dynamics of sustainability and preservation of this natural resource. In this study mangrove soils in the Subaé river basin were described and classified and inorganic waste concentrations evaluated. Seven pedons of mangrove soil were chosen, five under fluvial influence and two under marine influence and analyzed for morphology. Samples of horizons and layers were collected for physical and chemical analyses, including heavy metals (Pb, Cd, Mn, Zn, and Fe). The moist soils were suboxidic, with Eh values below 350 mV. The pH level of the pedons under fluvial influence ranged from moderately acid to alkaline, while the pH in pedons under marine influence was around 7.0 throughout the profile. The concentration of cations in the sorting complex for all pedons, independent of fluvial or marine influence, indicated the following order: Na^+>Mg^{2+}>Ca^{2+}>K^+. Mangrove soils from the Subaé river basin under fluvial and marine influence had different morphological, physical, and chemical characteristics. The highest

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Pb and Cd concentrations were found in the pedons under fluvial influence, perhaps due to their closeness to the mining company Plumbum, while the concentrations in pedon P7 were lowest, due to greater distance from the factory. For containing at least one metal above the reference levels established by the National Oceanic and Atmospheric Administration (United States Environmental Protection Agency), the pedons were classified as potentially toxic. The soils were classified as *Gleissolos Tiomórficos Órticos (sálicos) sódico neofluvissólico* in according to the Brazilian Soil Classification System, indicating potential toxicity and very poor drainage, except for pedon P7, which was classified in the same subgroup as the others, but different in that the metal concentrations met acceptable standards.

Keywords: pedogenesis, hydromorphism, heavy metals.

RESUMO: *GÊNESE, CARACTERIZAÇÃO E CLASSIFICAÇÃO DE SOLOS DE MANGUE NA BACIA DO RIO SUBAÉ, BAHIA, BRASIL*

A preservação de manguezais, ecossistema de elevada importância social, econômica e ambiental, requer conhecimento da composição, gênese, morfologia e classificação de seus solos, aspectos de fundamental importância para o entendimento da dinâmica e conservação sustentável desse recurso natural. Dessa forma, buscaram-se caracterizar e classificar solos de manguezais na bacia do Subaé e avaliar as concentrações dos poluentes inorgânicos. Foram escolhidos sete pedons representativos de manguezais, cinco sob influência fluvial e dois sob influência marítima, cujos perfis foram analisados quanto à morfologia e coletadas amostras de horizontes e camadas para posterior análise física e química, inclusive de metais pesados (Pb, Cd, Mn, Zn e Fe). Os solos em condições úmidas apresentaram-se subóxidos, com valores de Eh <350 mV. O pH dos pedons sob influência fluvial variaram de moderadamente ácido a alcalinos, enquanto os pedons sob influência marítima apresentaram valores em torno de 7,0 no longo de todo o perfil. A concentração de cátions no complexo sortivo para todos os pedons, independentemente da influência fluvial ou marítima, indicou a seguinte ordem: Na^{+}>Mg^{2+}>Ca^{2+}>K^{+}. Os solos dos manguezais da bacia do rio Subaé apresentaram características morfológicas, físicas e químicas distintas quando sob influência fluvial e marítima. As maiores concentrações de Pb e Cd foram identificadas nos pedons sob influência fluvial, possivelmente pela proximidade à Plumbum Mineração, e as menores concentrações encontravam-se no pedon P7, em razão da maior distância da fábrica. Por apresentar pelo menos um metal acima dos valores de referência indicados pela National Oceanic and Atmospheric (EPA), os pedons foram classificados como potencialmente tóxicos. Os solos foram classificados como Gleissolos Tiomórficos Órticos (sálicos) sódico neofluvissólicos de acordo com o Sistema Brasileiro de Classificação, apresentando-se potencialmente tóxicos, muito mal-drenados, exceto o pedon 7, que foi enquadrado no mesmo subgrupo dos demais, mas diferenciado deles por apresentar concentração de metal dentro dos limites tolerados.

Palavras-chave: pedogênese, hidromorfismo, metais pesados.

INTRODUCTION

Urban contamination levels with lead (Pb) in the municipality of Santo Amaro, in the State of Bahia, Brazil, is believed to be the highest in the world. This has deleterious effects on human health, in view of the incidence of diseases caused by this metal on the population and damage to the environment, with impacts on the Subaé river basin and its estuary. The mining-metallurgy complex built in 1960, 2.5 km northwest away from the town, for lead (Pb) alloy production, did not only pollute the atmosphere, but left a liability of about 500,000 Mg of slag (21 % Cd and up to 3 % Pb), which resulted in the contamination of the Subaé river, due to waste basin overflow. Studies detected the presence of heavy metals in the mangroves of the municipalities of Santo Amaro and São Francisco do Conde, causing social, economic, and health impacts, because residents may be eating contaminated fish (Garcia et al., 2007; Santos et al., 2010).

Mangroves are ecosystems of tropical and subtropical areas, characterized by soils periodically flooded by tides, poor in oxygen, rich in organic matter, dominated by typical plant species adapted to flooding and salinity variations (Schaeffer-Novelli, 1999). In spite of the increased awareness of their value and significance, mangroves are threatened worldwide by the risk of disappearing, due to economic and social pressure. The presence of toxic and persistent pollutants, such as heavy metals and organic contaminants, resulting from uncontrolled industrialization and urbanization in coastal regions, have damaged the mangrove ecosystem. High concentrations of organic compounds, fine particles from soil and wetlands, and the anoxic environment are some of the factors that intensify the tendency to accumulate pollutants in mangroves (Tam, 2006; Tang et al., 2008).

The investigation of the genesis, morphology, and classification of mangrove soils is of paramount importance to understand the dynamics and sustainable management of their resources and soil conservation, and the best basis underlying the management of soil and land use (FAO, 1981). Mangroves are formed when there is a great exposition of the source material, to intemperate agents mainly associated with river and/or sea water. This study assumes that the rock diversity under the influence of intemperate agents and processes of removal and transportation of products formed, as well as the addition of material from neighboring areas of mangroves contribute to the generation of several soil categories. Furthermore, pollutants and contaminants from anthropogenic activities may be accumulated at concentrations that hamper the ecosystem functions. This study characterized and classified mangrove soils in the Subaé river basin and assessed inorganic pollutant concentrations.

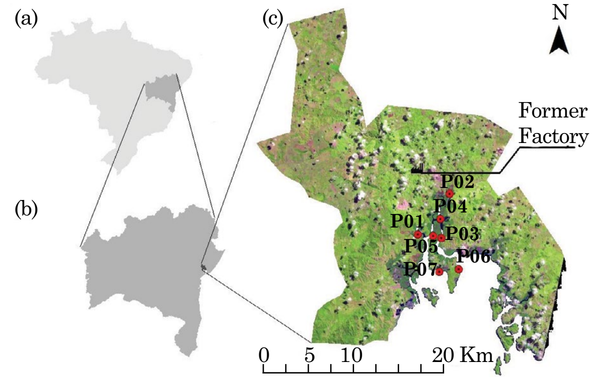

Figure 1. Location of the estuarine zone of the Subaé river, Bahia, Brazil. (a) Location of Santo Amaro, Bahia; (b) Study area in Santo Amaro; and (c) Location of the pedons.

MATERIAL AND METHODS

Study area

The mangroves under study are located in the Subaé river basin, Bahia, Brazil, covering the municipalities of Santo Amaro and São Francisco do Conde (Figure 1). The Subaé river basin is a part of the river basin complex "Recôncavo Norte", located in northeastern Bahia, with a total area of 18,015 km². This area is drained, aside from the Subaé river, by the rivers: Subaúma, Catu, Sauípe, Pojuca, Jacuípe, Joanes, Açu and the secondary rivers from "Baía de Todos os Santos" (BTS) and the Inhambupe river (Inema, 2014).

The regional climate is Af, according to Köppen's classification, i.e., tropical humid to sub-humid and dry to sub-humid, with annual means of 25.4 ºC and 1,000 to 1,700 mm rainfall (Anjos, 2003). Around ⅔ of the territory of Santo Amaro have a smooth wavy relief, consisting of inland plains, and marine and fluvial-marine lowlands. There are two predominant relief forms in this region: coastal lowland (altitude up to 100 m) and plains of the "Recôncavo" (altitudes between 100 and 200 m) (Brasil, 1999).

The study region is located in the Northeastern face of the craton of São Francisco ("Bacia Sedimentar do Recôncavo") which dates back to the Meso-Cenozoic age, delimited by a subparallel system of common faults. The geological formation of this area consists of rocks of the following groups: Santo Amaro, Ilhas, and Brotas, as well as marsh and mangrove deposits (CPRM, 2012).

In the Brazilian mangrove areas, there is a predominance of Vertisols, Argisols, Neosols, in addition to Gleysols (Brasil, 1981). The plant species found in the study area were: *Rhizophora mangle* (red mangrove, RM), *Laguncularia racemosa* (white mangrove, WM), and *Avicennia schaueriana* (black mangrove, MP).

Sampling

Based on aerial photography data, the closeness to the factory, field observation, tide tables, and information provided by local fishermen, seven pedons (P) were selected and sampled, of which six pedons represented the fluvial lowland of the Subaé river (P1 to P5) in higher areas and 2 of them in lower areas, closer to the sea (P6 and P7) (Figure 1). Five of these pedons (P1, P3, P4, P5, and P6) are found ON the Cajaíba island, which divides the Subaé river into two branches near its mouth, in an environment that is more untouched by anthropic actions (P7) than the mangroves along the river banks on the continent; and one pedon in the neighboring area of the former Plumbum Mining (P2).

The sites for vertical cuts of soils were defined by following the tide table: when the tide is low, some fluvial dams are formed on the river banks, which enabled the morphological description of profiles and the sampling process, carried out according to Santos et al. (2005). After describing the profiles, horizon and layer samples were collected, stored in plastic bags, and maintained in a cold chamber at 4 ºC, for subsequent chemical and physical analyses.

Analytical procedures

Field

The oxi-reduction potential (Eh) and pH level of all pedon horizons and layers were measured in the field. The Eh readings (Hanna HI 8424) were obtained by using a platinum electrode and corrected by adding potential of the calomelane reference electrode (+244 mV) and the pH levels were measured with a glass electrode, which was previously calibrated with standard pH solutions at 4.0 and 7.0, after balancing samples and electrodes.

Laboratory

Disturbed samples were air-dried, crumbled, and ground with a soil hammer mill, using a 2 mm sieve, to obtain air-dried fine soil.

For granulometric determination, soluble salts were previously removed with 60 % ethylic alcohol and organic matter by hydrogen peroxide. The pipette method was used with some modifications: 20 g of sample was dispersed in 100 mL of water and 10 mL of 1 mol L^{-1} sodium hexametaphosphate (Embrapa, 2011). After contact for one night, the samples were shaken for 16 h at 30 rpm in a Wagner agitator, model TE-161, following the other procedures of the method.

The samples were assessed with regard to the following chemical properties: electrical conductivity (EC) in the saturation extract; pH in water (1:2.5 soil:solution ratio); exchangeable Ca^{2+}, Mg^{2+} and Al^{3+}, through titration after extraction with a 1 mol L^{-1} KCl solution; Na and K by flame photometry, following extraction through Mehlich-1; H+Al extracted through 0.5 mol L^{-1} calcium acetate at pH 7.0, and determined with 0.025 mol L^{-1} NaOH. Based on these data, we calculated the sum of bases (S), cation exchange capacity (T), and base saturation (V). The P content was determined by photocolorimetry. All determinations were carried out as described by Embrapa (2011).

Organic carbon was determined by the dry method (muffle) for classification according to Embrapa (2013). The sulfur content was determined by sample digestion with HCl 1:1, and then calculated by gravimetry after precipitation with $BaCl_2$ (Embrapa, 2011). In order to assess the existence of thionic sulfur in the soil, a 0.01 m soil layer, at field capacity, was incubated at room temperature for eight weeks. Soils with ΔpH [pH(KCl) - pH(H_2O)] values lower than 0.5 units after incubation were considered thionic (Embrapa, 2013).

Metals were extracted and determined by method 3050B (USEPA, 1996), by which 0.5 g of the dry soil fraction was ground in an agate mortar and digested in 10 mL of a HNO_3:H_2O deionized solution, at a 1:1 proportion, with addition of 10 mL H_2O_2 for organic matter oxidation, in a digestion block heated to 95 ± 5 °C for about 2 h. Samples were cooled for 15 min, then 5 mL of a HNO_3 solution was added again. To complete digestion, 5 mL of concentrated HCl and 10 mL of deionized H_2O were also added. After digestion, the samples were cooled, filtered, completed to 50 mL and the metals Pb, Cd, Mn, Zn, and Fe determined with an anatomic absorption spectrophotometer (model AAS Varian AA 220 FS).

Soil classification

Based on the morphological description and the analytical results, pedons were classified according to the Brazilian System of Soil Classification (SiBCS) (Embrapa, 2013), the U.S. Soil Taxonomy (USDA, 2010), and the World Reference Base for Soil Resources (FAO, 2006).

RESULTS AND DISCUSSION

Soil genesis, morphology, and physics

The results of morphological and physical analyses of pedons located on a plain relief, directly exposed to tides, under fluvial (P1 to P5) and marine (P6 and P7) influence, from fluvial-maritime sediments, deposited on a sediment rocky mineral (shale), are shown in table 1.

The seven pedons are poorly drained, due to constant flooding by the tide, and, under anaerobiose conditions, they favor the waterlogging process, which affects the removal, translocation, and transformation processes of Fe compounds, resulting in bluish and greenish colors, with red or yellowish mottles in horizons and layers (Table 1).

Generally, Gleysols have a massive structure, identified in all horizons and layers of the pedons under study (Table 1). Although the consistency was not measured in the field, the flooding condition resulted in very or extremely hard soils when dry. The transition between horizons was flat and diffuse (P1, P2, P3, P4, P6, and P7) or gradual (P5), showing sedimentation with layers consisting of material with similar composition and homogenized by the action of organisms.

In mangroves, there is a constant sedimentation of fine dust (silt and clay) brought by tidal variation, which may be explained by the low-energy environment (Cintrón and Schaeffer-Novelli, 1983). Texture varied from medium to very clayey, with a predominance of the finer over the sandy fraction (Table 1). Also, irregular variation of texture between the soil horizons and layers, in all pedons, indicates major changes in the environmental conditions of the system (Ferreira et al., 2007a).

Clay in the pedons ranged from 2.4 to 93.5 %, showing wide texture variability, to, is a characteristic of mangrove soils (Barrêdo et al., 2008). In most horizons and layers from P1 to P5, the pedons influenced by the river, there is a prevalence of the clay fraction, while in the pedons influenced by the sea, P6 and P7, silt and clay are predominant.

Table 1. Morphological and physical properties of pedons from mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil

H(1)	Depth	Color		Structure	Transition	Textural class(2)	Sand	Silt	Clay
		Hue	Mottle						
	m						g kg^{-1}		
P1 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.08	Gley 1- 10 GY 4/1	7. 5 YR 5/6	Massive	Flat and diffuse	Very clayey	16	196	788
2Agn	0.08-0.20	Gley 1- 10 GY 4/1	7.5 YR 5/6	Massive	Flat and diffuse	Very clayey	29	192	778
3Agn	0.20-0.34	Gley 1- 10 GY 4/1	7.5 YR 5/6	Massive	Flat and diffuse	Very clayey	39	122	839
4Agn	0.34-0.55	Gley 1- 10 GY 4/1	-	Massive	Flat and diffuse	Very clayey	66	102	832
P2 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.20	Gley 1 10Y 2.5/1	10YR 4/6	Massive	Flat and diffuse	Medium	459	208	333
2Agn	0.20-0.32	Gley 1 10Y 2.5/1	-	Massive	Flat and diffuse	Medium	476	213	311
3Agn	0.32-0.61	Gley 1 10Y 3/1	-	Massive	Flat and diffuse	Medium	494	185	321
4Agn	0.61-0.83	Gley 1 10Y 4/1	-	Massive	Flat and diffuse	Medium	383	295	322
5Agn	0.83-1.02+	-	-	Massive	-	Clayey	308	271	421
P3 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.05	Gley 1 5G 4/1	2.5YR 4/8	Massive	Flat and diffuse	Medium	477	254	270
2Agn	0.05-0.25	Gley 1 5G 4/1	-	Massive	Flat and diffuse	Medium	609	86	305
3Agn	0.25-0.49	Gley 1 5GY 4/1	10 YR 3/6	Massive	Flat and diffuse	Clayey	486	124	390
4Agn	0.49-0.71+	Gley 1 5G 4/1	-	Massive	-	Clayey	439	209	352
P4 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.07	Gley 1 5G 3/1	Gley 1 5G 2.5 /1 and 7.5 YR 4/6	Massive	Flat and clear	Medium	666	78	255
2Agnj	0.07-0.18	Gley 2 10B 3/1	10B 4/1	Massive	Flat and clear	Medium	378	419	203
3Agnj	0.18-0.41	Gley 1 5G 5/1	Gley 2 10GB 4/1 and Gley 1 5G 6/2	Massive	Flat and clear	Sandy	910	3	88
4Agnj	0.41-0.60	Gley 1 5G 4/1	-	Massive	Wavy and abrupt	Medium	688	63	249
4Crgnj	0.60-0.70	Gley 1 10GY 3/1	2.5 YR 2.5/4	-	-	Medium	648	109	244
P5 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.15	Gley 1 5G 4/1	5YR 4/6	Massive	Flat and gradual.	Very clayey	26	150	824
2Agn	0.15-0.26	Gley 2 10B 4/1	5YR 4/6	Massive	Flat and gradual	Very clayey	27	233	740
3Agn	0.26-0.43	Gley 2 10B 3/1	-	Massive	Irregular and abrupt	Very clayey	27	38	935
4Agn	0.43-0.60	Gley 2 5PB 5/1	-	Massive	Irregular and abrupt	Medium	269	677	54
4Crgn	0.60-0.70+	Gley 1 5G 5/2	-	Massive	-	Clayey	211	238	551
P6 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.15	Gley 1 5GY 3/1	7YR 3/3	Massive	Flat and diffuse	Medium	439	458	103
2Agn	0.15-0.33	Gley 1 10Y 3/1	-	Massive	Flat and diffuse	Silty	86	828	86
3Agn	0.33-0.48	Gley 1 5G 3/1	-	Massive	Flat and clear	Very clayey	119	272	609
4Agn	0.48-0.60	Gley 1 5G 4/1	-	Massive	-	Very clayey	315	27	659
P7 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, very poorly drained									
Agn	0.00-0.09	Gley 1 10Y 3/1	7YR 3/3	Massive	Flat and diffuse	Medium	321	637	42
2Agn	0.09-0.17	Gley 1 10Y 4/1	-	Massive	Flat and diffuse	Medium	291	686	24
2Crgn	0.17-0.28	Gley 1 10Y 4/1	-	Massive	Flat and abrupt	Silty	100	836	64

(1) H: horizont; (2) Classification according to Embrapa (2013).

Pedons formed under fluvial influence

Of the pedons under fluvial influence, P1 was shallowest (0.55 m), perhaps because it is located on the edge of the mangrove of the sampled region. All horizons and layers had a 1 10GY Gley color, which indicates a flooded environment and oxidation process promoted by roots and soil microorganisms. Along P1, a more homogenous texture distribution was observed when compared to the other pedons, which may be related to the fact of being in a zone with lower fluvial influence, on the riverbank (continent); therefore, in a more protected environment (Table 1).

The deepest pedon was P2 (1.02 m), due to its location at a higher position, so that it is not completely flooded for a long time. The layers and horizons of this pedon had a 1 10Y Gley color in the whole profile, due to its continuous drying cycles, as well as the presence of very fine to thick roots, up to the horizon 5 Agn. The horizon textures of this pedon were medium, and the last was the most clayey, possibly indicating accumulation of particulate material in the aforementioned horizons (Table 1).

The pedons P3, P4, and P5 have similar depths (around 0.70 m), with colors varying from 1 5G 4/1 Gley to 2 10B 4/1 Gley and a texture ranging from medium (P3 and P4) to very clayey (P5), indicating pedons formed in accumulation and storage regions, respectively. In P4, a horizon (4 Agnj) with shell deposition was found, attributed to two possible causes: presence of oysters that use the stem and roots of the plant species *Rhizophora mangle* (predominating in the area) as habitat and fall on the ground and are incorporated with time; or as a shell disposal area for the fishermen, still on site, as a result of shellfishing (information provided by local fishermen).

The sequence of Ag horizons or layers was identified in P1, P2, and P3 and the Agr sequence in P4 and P5, with material discontinuity (fluvial nature), evidenced by stratifications, with an irregular texture variation (Table 1) and in-depth organic C content (Table 2), found in all pedons, indicating fluvial sediment storage (FAO, 2006). In these soils, there are moderate A horizons and the Cr layer of P4 and P5 corresponds to a soft rocky mineral, derived from blue-greenish shales of the island group, also called "green rust" (van Breemen, 1988).

Pedons formed under marine influence

Pedons formed under marine were shallower than those formed under fluvial influence (Table 1), which is related to a longer submersion time and the location in a marine estuary, favoring greater particle removal. This behavior is very clear in P7, located in the southern part of the island, in the mouth of "Baía de Todos os Santos", where parental material is almost exposed, in addition to sparse or almost absent presence of vegetation.

Dark brown mottles (7YR 3/3) of horizons A1 of P6 and P7 occur due to oxidation of reduced Fe forms in microenvironments created by roots and soil biota (Ferreira et al., 2007a,b). The texture of these pedons ranged from medium in the surface to very clayey, indicating an alternation of different materials deposited over time (Table 1). In P7, high silt percentage may be related to the greater particle deposition in the area, the scarce presence or absence of vegetation, and presence of soft rock at a depth of 0.17 m. The sequence of Ag horizons or layers was identified in P6 and Ag-Crg in P7, for the same reasons as explained for pedons under fluvial influence.

Chemical properties

The results of chemical analyses of pedons under fluvial (P1 to P5) and marine (P6 and P7) influence are shown in figure 2 and tables 2 and 3. Of the seven pedons, four had only an A horizon (P1, P2, P3, and P6) and three had an A horizon and a C layer (P4, P5, and P7). All pedons are formed by a glei horizon, or a reductive environment, due to tidal movements that maintain the soil waterlogged most of the time.

The thiomorphic nature of profiles or layers is determined by the ΔpH value after soil incubation, and soils with ΔpH values >0.5 are identified this way, observed for most of the layers, except for the horizons Agn and 4Agn of P5 and 2 Agn and 2 Crgn of P7. The results for the thiomorphic nature are according to the total S content, higher than the minimum content required (0.75 %) to characterize the presence of sulphide materials (Oliveira et al., 1992), ranging from 3.3 (2Agnj of P6) to 4.0 % (Agnj of P3) (Table 2), which is normal for mangrove soils (Ferreira, 2006; Souza Jr. et al., 2007).

Organic C contents in pedons formed under fluvial influence (P1, P2, P3, P4, and P5) ranged from 46.8 in the 4 Agn horizon to 54.2 g kg^{-1} of Agn in P4, with higher nominal values than those of soils formed under tidal influence (44.5 in the 2C layer of P7 at 49.0 g kg^{-1} in the 3 Agn and Agn horizons of P6) (Table 3). However, for both environments, pedons were classified as orthic, because the organic C content was below 80 g kg^{-1}.

In all pedons, percentage of sodium saturation (PST) values (Table 3) (47 % in the 2 Agnj horizon of P4 at 69 % in the Agn horizon of P1) exceeded the threshold values that classify a soil as sodic (PST≥6), which results in clay dispersion and, probably, in soil organic matter dispersion. High Na^+ levels in all pedons, associated with high pH levels, contribute to the halomorphism processes. Excessive salts in the layers or horizons whose EC values ranged from 20 dS m^{-1} (2 Agn of P5) to 57 dS m^{-1} (3 Agn of P6) led to the classification of pedons as salic, since these values are much higher than the threshold values to classify soils as salic (EC≥7 dS m^{-1}) (Embrapa, 2013) (Table 3). The salic nature hinders water absorption by terrestrial plants, but is less relevant for mangrove plants that are adapted to EC levels exceeding those of the classification.

Sorption complex of pedons is dominated by cations $Na^+>Mg^{2+}>Ca^{2+}>K^+$ and, in almost all horizons and layers, the Mg^{2+} content was higher than Ca^{2+}, which is common in estuarine environments, and may be attributed to pedogenetic processes, such as soluble salt addition, mainly by seawater intrusion and fluvial deposition in a drainage region of fertile soils, as the Vertisols in the region.

Most of the pedons had T values between 25 (2 Agnj and 3 Agnj of P4) and 111 cmol$_c$ kg^{-1} (3Agn of P6). Cation exchange capacity (T) values between 22.47 and 45.36 cmol$_c$ kg^{-1}, in mangrove soils of the Iriri river in "Canal da Bertioga" (Santos, São Paulo, Brazil) (Prada-Gamero et al., 2004). These values are high due to a great contribution of

Table 2. Values for sulfur (S), $pH(H_2O)$, and $pH_{incubation}$ of mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil

Horizont	Depth	S	$pH(H_2O)$	pH incubation level[1]					
				0[2] day	15 days	30 days	45 days	60 days	ΔpH[3]
	m	%							
P1 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico,* potentially toxic, very poorly drained									
Agn	0.00-0.08	3.6	6.7	6.3	6.3	6.6	6.8	4.9	1.4
2Abgnj	0.08-0.20	3.6	6.4	7.1	4.0	3.3	3.1	2.5	4.6
3Abgnj	0.20-0.34	3.5	6.2	7.1	3.1	3.1	2.9	2.6	4.5
4Abgnj	0.34-0.55	3.7	6.1	8.1	4.2	3.9	3.3	3.1	5.0
P2 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agnj	0.00-0.20	3.8	5.8	6.3	5.0	3.7	2.7	3.0	3.3
2Agnj	0.20-0.32	3.6	6.0	6.1	3.1	2.4	1.7	2.2	3.9
3Agnj	0.32-0.61	3.8	5.9	7.0	3.0	2.2	2.1	2.3	4.7
4Agn	0.61-0.83	3.6	6.5	7.5	-	-	-	-	-
5Agn	0.83-1.02+	3.8	7.0	7.5	-	-	-	-	-
P3 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico,* potentially toxic, very poorly drained									
Agnj	0.00-0.05	4.0	6.0	7.0	3.7	2.9	2.6	2.4	4.6
2Agnj	0.05-0.25	3.9	4.7	6.1	3.4	3.1	3.0	2.9	3.2
3Agnj	0.25-0.49	3.8	5.8	7.0	3.0	2.4	2.4	2.3	4.7
4Agnj	0.49-0.71+	3.7	6.4	7.5	3.4	2.5	2.6	2.3	5.2
P4 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.07	3.8	6.4	6.6	5.8	5.4	4.7	4.2	2.4
2Agnj	0.07-0.18	3.8	4.7	6.6	3.1	2.4	1.7	2.3	4.3
3Agnj	0.18-0.41	3.9	5.8	6.9	3.5	2.4	2.2	2.2	4.7
4Agnj	0.41-0.60	3.9	4.9	7.0	3.0	2.4	2.2	2.4	4.6
4Crgnj	0.60-0.70	3.7	3.6	6.9	2.8	2.5	2.0	2.3	4.6
P5 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agn	0.00-0.15	3.8	6.6	6.2	6.5	6.3	6.4	6.4	-0.2
2Agnj	0.15-0.26	3.8	5.5	6.3	3.4	2.9	2.7	2.7	3.6
3Agnj	0.26-0.43	3.4	5.4	6.7	3.0	2.8	2.6	2.4	4.3
4Agn	0.43-0.60	3.7	7.4	7.1	7.0	6.6	6.4	7.3	-0.2
4Crgn	0.60-0.70+	3.7	7.6	7.8	7.5	6.4	7.3	7.4	0.4
P6 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained									
Agnj	0.00-0.15	3.3	5.8	7.2	4.0	3.1	3.2	3.0	4.2
2Agnj	0.15-0.33	3.4	6.5	7.1	3.6	3.4	3.7	3.0	4.1
3Agnj	0.33-0.48	3.3	5.5	7.3	3.1	3.0	1.7	2.3	5.0
4Agn	0.48-0.60	3.3	5.3	7.2	-	-	-	-	-
P7 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, very poorly drained									
Agnj	0.00-0.09	3.9	7.3	7.3	6.6	5.7	5.9	2.9	4.4
2Agn	0.09-0.17	3.8	7.2	7.4	6.7	6.4	7.0	7.1	0.3
2Crgn	0.17-0.28	3.6	7.0	7.1	6.6	6.6	7.0	7.0	0.1

(1) 60-day incubation. (2) pH value on site, humid sample. (3) Difference between pH level in the beginning (0) and the end (60 days).

organic matter content and a predominance of the Na^+, Mg^{2+}, Ca^{2+}, and K^+.

Although being located in an environment with high deposition of organic and mineral compounds, the studied pedons showed low P availability, with contents from 4.9 (4 Agn of P1) to 7.1 mg kg^{-1} (Agn of P7), compared to the contents in Gleysols (19 to 35 mg kg^{-1}) in "Canal da Bertioga" (Prada-Gamero et al., 2004). The Al content in all pedons was close to zero and the acidity in the environment was due to H, as shown by an evaluation of the difference between potential acidity and exchangeable acidity.

Table 3. Chemical properties of mangrove pedons of the Subaé river basin, Santo Amaro, Bahia, Brazil

Horizon	Depth	EC	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	Na^{+}	K^{+}	SB	T	V	PST	P	OC
	m	dS m^{-1}	cmol$_c$ kg^{-1}								%		mg kg^{-1}	g kg^{-1}
P1 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.08	40	3.0	14.0	0.2	3.0	51.2	3.6	71.7	75	96	69	5.3	48.2
2Agn	0.08-0.20	38	3.8	15.6	0.2	4.8	52.3	3.3	74.8	80	94	66	5.5	47.5
3Agn	0.20-0.34	36	3.6	16.9	0.2	5.6	55.5	3.4	79.4	85	93	65	5.7	48.3
4Agn	0.34-0.55	42	4.5	15.5	0.2	7.1	49.0	4.0	73.1	80	91	61	4.9	50.4
P2 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.20	35	2.1	7.6	0.1	5.4	14.9	1.2	25.9	31	83	48	5.2	50.9
2Agn	0.20-0.32	35	4.5	4.3	0.1	5.3	19.2	1.2	29.2	35	85	56	5.1	53.8
3Agn	0.32-0.61	33	3.2	6.7	0.1	4.6	16.4	1.2	27.5	32	86	51	5.2	51.8
4Agn	0.61-0.83	31	2.5	10.0	0.1	1.4	18.1	1.9	32.6	34	96	53	5.2	49.7
5Agn	0.83-1.02+	22	3.7	9.6	0.0	1.8	16.0	2.0	31.3	33	95	48	5.4	54.0
P3 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.05	36	2.7	8.4	0.0	1.9	22.4	1.4	34.8	37	95	61	5.1	51.8
2Agn	0.05-0.25	43	2.5	8.0	0.0	8.8	27.7	1.1	39.4	48	82	58	5.0	52.8
3Agn	0.25-0.49	44	3.3	10.8	0.0	7.1	35.2	1.6	50.8	58	88	61	4.9	53.6
4Agn	0.49-0.71+	38	3.5	11.3	0.1	5.3	39.5	2.0	56.2	61	91	64	5.4	52.1
P4 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.07	31	1.5	5.3	0.0	2.6	18.1	1.1	26.0	29	91	63	5.1	52.5
2Agnj	0.07-0.18	27	1.6	4.2	0.7	6.1	11.7	1.1	18.7	25	75	47	5.1	53.5
3Agnj	0.18-0.41	30	2.2	4.6	0.0	4.3	12.8	1.2	20.8	25	83	51	5.3	54.1
4Agnj	0.41-0.60	29	2.3	7.4	0.5	6.7	19.2	2.2	31.0	38	82	51	5.1	53.1
4Crgnj	0.60-0.70	29	7.8	4.6	3.3	12.3	51.2	1.1	64.7	77	84	66	5.1	50.4
P5 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.15	28	2.9	14.1	0.1	3.6	56.5	3.4	76.9	81	96	70	5.2	54.2
2Agn	0.15-0.26	20	3.5	14.7	0.2	7.2	42.7	4.8	65.7	73	90	59	5.4	50.8
3Agn	0.26-0.43	38	5.1	13.0	0.3	11.1	59.7	4.8	82.7	94	88	64	5.3	49.5
4Agn	0.43-0.60	44	8.6	9.8	0.1	0.9	43.7	2.2	64.3	65	99	67	5.6	46.8
4Crgn	0.60-0.70+	33	4.9	10.1	0.1	1.0	20.3	3.3	38.5	40	97	51	6.2	50.6
P6 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained														
Agn	0.00-0.15	36	3.4	11.3	0.1	6.3	38.4	3.1	56.1	62	90	62	5.7	46.0
2Agn	0.15-0.33	46	6.3	16.2	0.1	5.6	58.7	4.2	85.4	91	94	64	5.1	48.4
3Agn	0.33-0.48	41	5.4	19.6	0.6	10.9	70.4	4.5	99.9	111	90	64	5.4	49.0
4Agn	0.48-0.60	57	5.5	11.6	0.1	3.7	71.5	5.4	94.0	98	96	73	5.2	48.7
P7 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, very poorly drained														
Agn	0.00-0.09	45	4.5	12.8	0.2	2.2	54.4	3.1	74.9	77	97	71	7.1	49.0
2Agn	0.09-0.17	48	5.5	10.7	0.2	1.9	58.7	3.0	77.7	80	98	74	5.3	48.1
2Crgn	0.17-0.28	42	7.5	15.7	0.2	2.1	67.2	2.8	93.2	95	98	71	5.7	44.5

EC: electrical conductivity; Ca^{2+}, Mg^{2+}, Al^{3+}: extractor 1 mol L^{-1} KCl; P, K, Na: extractor Mehlich-1; SB: sum of bases; T: cation exchange capacity; H+Al: extractor 0.5 mol L^{-1} calcium acetate at pH 7.0; V: base saturation; PST: sodium saturation; OC: organic carbon, determined by the dry method (muffle).

Despite the similar characteristics of the pedons under study, those formed under fluvial influence differed somewhat from those formed under marine influence, as described below.

Pedons formed under fluvial influence

The pH levels of pedons under fluvial influence (P1 to P5), assessed in the field, ranged from moderately acid (pH 6.1-6.5) in the 2A horizon of P1 and P3 to moderately alkaline (pH 7.1-8.1) in the 4A horizon of P2 (Figure 2). Studying mangrove soils under fluvial influence in the Marapanim river (Pará, Brazil), Amazon Coast, Barrêdo et al. (2008) found pH values similar to those obtained in this study. Similarly to observation for physical characteristics, the chemical characteristics of the shallowest (P1) and the deepest pedon (P2) differed from the others under fluvial influence.

The pH of P1 increased in deeper layers, entering the alkaline range (8.14), which was attributed to a higher concentration of Na^{+}, Mg^{2+} and K^{+} than in the other pedons (Table 2). The highest pH values of P2 were registered in the deepest horizons, probably as a result of Mg^{2+}

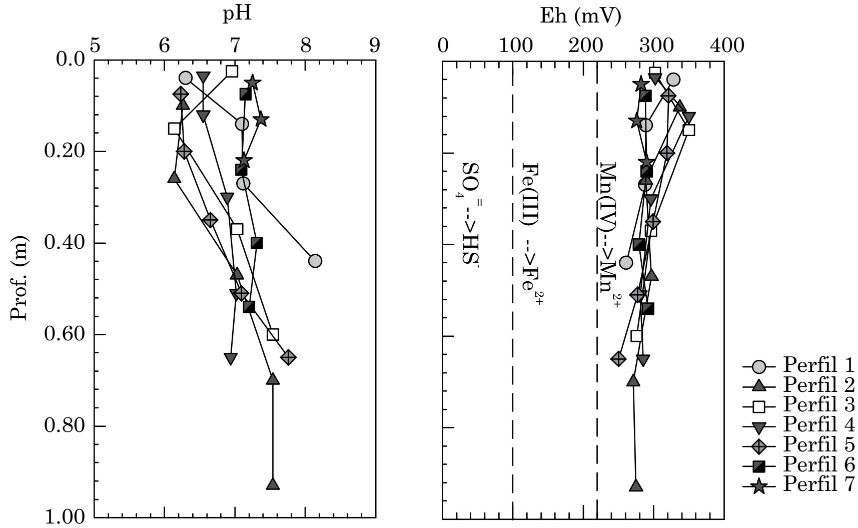

Figure 2. Distribution of pH and Eh in field in deeper layers in the mangrove soil profiles in the Subaé river basin, Santo Amaro, Bahia, Brazil.

accumulation (Table 2), which may have resulted from the closeness to rocks or leaching of the element in the upper layers. Accumulation of Mg^{2+} and simultaneous increase in pH values in deeper layers of pedons under fluvial influence, was not observed only for P4 (Figure 2, Table 2). The pH value in P3, P4, and P5 ranged from 6.2 to 7.5, and tended to increase in deeper layers, which may be explained by Mg^{2+} and Na^+ accumulation in the profile (Figure 2, Table 2).

The Eh values of P1 (328 to 261 mV) and P2 (337 to 271 mV) were higher in the surface horizons and layers and decreased in deeper layers. Lower Eh values in deeper layers are usual in estuarine environments (Ferreira et al., 2007a; Otero et al., 2009). Although this proposition is applicable to all pedons assessed, it was observed that, in P3 and P4, the horizons with highest Eh values were concentrated in the subsurface layers (Figure 2). Water level fluctuation resulted in Eh values from 66 to 74 mV. Eh values in this study ranged from oxic (>300 mV) to suboxic (100-300 mV) (Figure 2), in the reduction range from Mn^{4+} to Mn^{2+}, usually between 200 and 300 mV (Sousa et al., 2009), and do not reach typical values for anoxic environments (Eh <100 mV, pH = 7), as those reported in other studies (Ferreira et al., 2007a,b; Otero et al., 2009, 2010). Ferreira et al. (2007b) also observed a substantial variation in the redox conditions for *Rhizophora* woods in the Cananeia Lagoon System, Brazil, triggering variation in the redox conditions. The suboxic values in this study may be explained by the collection of samples from the edge of mangroves, where according to Price et al. (1988), drainage and, as a consequence, aeration are quicker.

The inverse and significant correlation between pH and Eh (r = -0.705, p<0.001, n = 30) is mainly due to presence of Fe oxides (Figure 3), the most common electron acceptors in saturated soils, whose reduction tends to buffer Eh for several weeks and which, thanks to the proton consumption, cause an increase in the pH level (Curi and Kampf, 2012).

The Crgn horizon observed in P4, which indicates presence of carbonate material (shells), showed a Ca concentration of 7.8 $cmol_c$ kg^{-1} (Table 2), but one of the lowest $pH(H_2O)$ levels (3.6) (Table 3), which may be attributed to the sulfur concentration (3.7 %). Sulfur compounds may contribute to decrease the

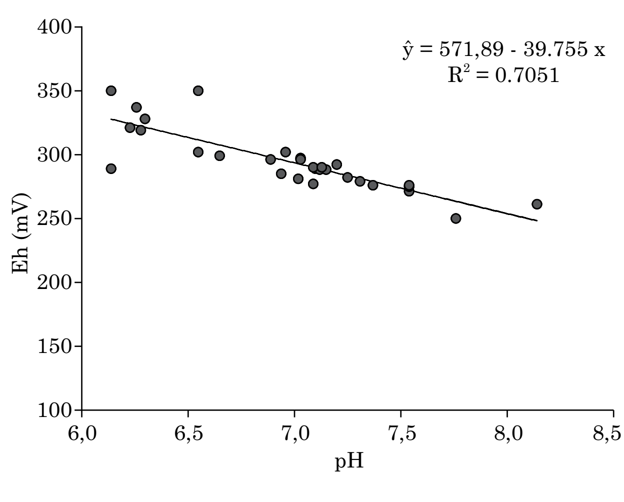

Figure 3. Correlation between Eh and pH in the field of the seven pedons from mangrove soils in the Subaé river basin, Santo Amaro, Bahia, Brazil.

pH levels in the environment, solubilizing some chemical elements (Araújo, 2000).

Pedons formed under marine influence

Pedons under marine influence (P6 and P7) showed pH values around 7.0 along the whole profile (Figure 2), which may be attributed to a higher Ca^{2+} and Mg^{2+} concentration (Table 2). Eh values, mainly on the surface of these soils, were lower than those observed for pedons formed under fluvial influence. These results confirm the inverse relation between pH and Eh already pointed out.

The Eh values of these pedons differed somewhat from those for the pedons under fluvial influence: while the values for pedons under fluvial influence were between 250 and 350 mV, those under marine influence varied from 276 to 292 mV (P6) and 276 to 290 mV (P7). These results may be explained by the fact that pedons formed under marine influence remain submersed for a longer time than those under fluvial influence. There is no tendency to decrease Eh values in deeper layers and the range of Eh values in P6 (13 mV) and P7 (14 mV) is lower than the range for Eh values in the pedons formed under fluvial influence.

Heavy metals

Soils can naturally contain high concentrations of heavy metals derived from weathering of a source material rich in these elements or due to anthropogenic influence, by urbanization and industrialization processes. The environment where mangrove soils are formed, as those assessed in this study with T values between 25 and 100 $cmol_c$ kg^{-1} (Table 2) had a great capacity to retain metals coming from tidal waters, fresh water, rainwater flow, and atmospheric and anthropogenic precipitation. The presence of metals in mangroves is a matter of concern because this environment is the cradle of several animal species used as human food (fish, crabs, oyster, etc.).

The environmental legislation of Brazil contains no specific rules for heavy metal concentrations in coastal environments. To assess the normality level of heavy metal concentrations in pedons under fluvial (P1 to P5) and marine influence (P6 and P7) (Table 4), we used Resolution 420/2009, established by the Brazilian National Environmental Council (Conama, 2009). This institution determines soil quality criteria and values regarding the presence of chemical substances and classifies the metal contents of soils as preventive values (threshold concentration of a certain substance in the soil, at which main soil functions are preserved) and critical values (threshold concentration of a certain substance in the soil potentially hazardous to human health); and the values established by the National Oceanic and Atmospheric Administration (NOAA, 1999), which classify heavy metal content levels in the soil as background, preventive threshold (TEL) and potentially hazardous to the biota of marine sediments (PEL).

Pedons formed under fluvial influence

Lead is among the heavy metals with severe effects on the aquatic environment, because it is, at the same time, toxic, persistent, and bioaccumulative in the food chain (Marins et al., 2002). Among the pedons under study, P1 had the highest contamination degree, with a Pb concentration in all layers above the prevention threshold established by Conama (2009) (Table 4). The lead concentrations in 4 Abgn horizon of P3 also exceeded the prevention threshold. According to the NOAA (1999) classification, all layers and horizons of pedons formed under fluvial influence contained between 1 and 3.5 times higher Pb concentrations than the TEL value. The Pb concentrations in 4 Crgnj (P4) were an exception, for being below the background. In contrast, Pb concentration in 2 Abgn (P1), 111.3 mg kg^{-1}, was very close to the PEL value (112 mg kg^{-1} Pb). The Pb concentrations registered in P1 are a matter of concern, because the pedon is located in an area frequently used by the riparian population to collect shellfish for consumption and sale.

Cadmium is a metal of great mobility within the systems and, therefore, it is hard to establish a distribution characteristic for this metal. Cadmium values in some horizons of pedons under fluvial influence, P1 (2 Abgn), P2 (4 Abgn), P3 (4 Abgn) and P5 (3 Abgn), were equal to or higher than the prevention values established by Conama (2009). Cadmium concentrations in the two pedons under marine influence (P6 and P7) were below the prevention values (Table 4). The greater presence of Cd in pedons under fluvial influence was also confirmed by the NOAA (1999) method. Only the Cd concentrations in 5 Abgn (P2), Crgnj (P4), and Agn (P5) were equal to or lower than the established background values (NOAA, 1999).

The other layers or horizons showed Cd concentrations above the TEL limits and the Abgn layer (P2) showed a Cd concentration level that may cause adverse effects to the biota, i.e. a value above PEL (Table 4). Highest Cd concentrations in pedons under fluvial influence may be associated with external waste disposal, such as contamination by waste disposed during lead mining, in the municipality of Santo Amaro, or, by urban and industrial activities, as in the Godavari Estuary, India (Ray et al., 2006).

The Zn concentrations in the pedons represent no risk for the biota, with values below the prevention values established by Conama (2013) and the TEL values established by NOAA (1999). In all P4 layers, the pedon least affected by heavy metals, the concentrations were lower than the background values (Table 4).

Table 4. Heavy metal concentrations (mean ± standard deviation) in mangrove pedons from the Subaé river basin, Bahia, Brazil and reference values for metals

Horizon	Pb	Cd	Zn	Mn	Fe
	mg kg^{-1}				dag kg^{-1}
P1 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	85.1 ± 5.7	0.9 ± 0.1	73.4 ± 1.0	128.7 ± 5.0	3.6 ± 0.2
2Abgn	111.3 ± 2.1	1.3 ± 0.1	92.4 ± 0.7	141.2 ± 2.5	5.2 ± 0.0
3Abgn	77.9 ± 2.2	1.2 ± 0.1	95.1 ± 3.5	188.4 ± 0.4	4.6 ± 0.5
4Abgn	82.9 ± 3.1	1.2 ± 0.0	86.4 ± 1.0	235.6 ± 7.5	4.5 ± 0.5
P2 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	58.8 ± 1.8	0.6 ± 0.0	55.2 ± 1.3	90.8 ± 2.0	1.7 ± 0.3
2Abgn	45.9 ± 8.1	0.4 ± 0.1	54.5 ± 2.2	75.7 ± 1.5	1.6 ± 0.2
3Abgn	70.0 ± 8.0	0.8 ± 0.1	55.6 ± 4.7	77.8 ± 1.2	1.9 ± 0.3
4Abgn	55.6 ± 5.5	4.8 ± 7.2	51.4 ± 2.6	99.6 ± 3.9	2.4 ± 0.6
5Abgn	45.0 ± 0.8	0.3 ± 0.0	50.4 ± 3.9	42.8 ± 2.1	2.8 ± 0.1
P3 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	36.5 ± 3.4	0.7 ± 0.1	40.4 ± 0.9	82.6 ± 28.6	1.6 ± 0.1
2Abgn	47.4 ± 2.4	0.6 ± 0.1	43.3 ± 1.1	70.5 ± 1.7	2.1 ± 0.0
3Abgn	53.6 ± 2.4	1.2 ± 0.1	57.8 ± 0.9	98.8 ± 1.3	2.6 ± 0.1
4Abgn	72.5 ± 3.8	1.5 ± 0.2	64.5 ± 1.1	138.2 ± 5.4	2.9 ± 0.3
P4 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	32.0 ± 5.2	0.4 ± 0.2	33.7 ± 1.6	64.0 ± 2.9	1.2 ± 0.1
2Abgnj	35.0 ± 1.9	0.4 ± 0.1	19.5 ± 6.4	39.5 ± 0.2	0.7 ± 0.3
3Abgnj	26.2 ± 2.4	0.4 ± 0.0	23.3 ± 1.5	58.3 ± 1.8	1.0 ± 0.1
4Abgnj	26.6 ± 4.4	0.4 ± 0.0	35.3 ± 1.8	76.1 ± 2.4	1.7 ± 0.0
4Crgnj	14.0 ± 3.6	0.2 ± 0.0	30.9 ± 1.0	98.8 ± 3.8	1.7 ± 0.1
P5 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	54.4 ± 0.6	0.3 ± 0.1	73.1 ± 1.4	241.9 ± 0.2	4.0 ± 0.1
2Abgn	65.5 ± 9.8	0.9 ± 0.2	72.0 ± 3.3	120.3 ± 1.1	3.5 ± 0.0
3Abgn	63.8 ± 7.3	1.4 ± 0.0	73.9 ± 1.7	173.4 ± 2.6	4.2 ± 0.0
4Abgn	45.3 ± 5.4	0.7 ± 0.0	48.2 ± 1.2	240.1 ± 1.8	3.4 ± 0.1
4Crgn	49.5 ± 6.9	1.0 ± 0.1	65.6 ± 0.7	205.8 ± 3.1	4.6 ± 0.1
P6 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, potentially toxic, very poorly drained					
Agn	43.7 ± 5.8	0.6 ± 0.1	52.3 ± 1.8	141.4 ± 9.1	2.8 ± 0.1
2Abgn	29.5 ± 1.3	0.4 ± 0.0	62.4 ± 0.7	252.3 ± 4.9	4.5 ± 0.4
3Abgn	6.2 ± 0.6	0.0 ± 0.0	62.2 ± 3.9	280.4 ± 11.1	3.8 ± 0.5
4Abgn	14.7 ± 4.6	0.0 ± 0.0	59.2 ± 0.1	268.7 ± 1.0	3.9 ± 0.0
P7 - *Gleissolo Tiomórfico Órtico (sálico) sódico neofluvissólico*, very poorly drained					
Agn	9.0 ± 4.3	0.4 ± 0.0	68.2 ± 20.2	229.3 ± 86.5	3.4 ± 0.0
2Abgn	11.9 ± 5.0	0.2 ± 0.1	50.7 ± 2.6	271.3 ± 11.0	2.7 ± 0.1
2Crgn	15.3 ± 0.0	0.3 ± 0.1	54.8 ± 2.4	284.3 ± 7.6	2.9 ± 0.1
Conama (2013)					
Prevention	72.0	1.3	300	-	-
NOAA (1999)					
Background	4-17.0	0.1-0.3	7-38	400	0.99-1.8
TEL(1)	30.24	0.6	124.0	-	-
PEL(2)	112.0	4.2	271.0	-	-

(1) TEL: may affect the biological community; (2) PEL: causing some effect on the biological community.

For being significant constituints in many source materials, it is difficult to differentiate Mn and Fe concentrations with anthropogenic origin from the natural ones. The Mn concentrations in pedons under fluvial influence ranged from 39.5 (2 Abgnj of P4) to 240.1 mg kg^{-1} (4 Abgn of P5), which are values below the background established by NOAA (1999).

Iron concentrations ranged from 0.7 (2 Abgnj of P4) to 5.2 dag kg^{-1} (2 Abgn of P1). In all pedons under study, either of fluvial or marine origin, Fe concentrations were above the background threshold values established by NOAA (1999), except for Agn and 2 Abgn (P2) and Agn (P3) layers and all P4 layers, which were below the background concentration (Table 4).

Pedons formed under marine influence

Generally, pedons formed under marine influence had heavy metal content levels lower than those in pedons under fluvial influence. None of the pedons formed under marine influence showed Pb concentration close to the prevention values established by Conama (2009). Lead concentrations in the 3 Abgn and 4 Abgn (P6) layers and in the 2 Abgn and Crgn horizons were lower than the background values and only the Agn (P6) layer showed a value higher than the TEL value (NOAA, 1999).

Cadmium concentrations were lower than the threshold value established as background, although in the Agn and 2 Abgn (Pedon 6) and Agn (Pedon 7) layers they exceeded the background value (Table 4).

Manganese concentrations ranged from 141.4 in the Agn horizon of P6 to 284.3 mg kg^{-1} in the 2 Crgn layer of P7, with an increase in the subsurface (Table 4). These values were below the background established by NOAA (1999). Manganese values in the soils from marine origin were higher than those in pedons formed under fluvial influence (P2, P3, and P4), but similar to P1 and P5 (Table 4).

Soil classification

The morphological, physical, and chemical characteristics determined in the seven pedons, under fluvial (P1 to P5) or marine influence (P6 and P7), enabled the soil classification, according to the SiBCS (Embrapa, 2013), as Gleysol thiomorphic orthic (salic) sodic luvissol. If significant areas with pedons similar to those studied here are mapped, we suggest the inclusion of the salic nature as the third category level of the SiBCS classification of the thiomorphic Gleysols, when EC values exceed 7 dS m^{-1} at 25 °C (Table 2).

Based on the characteristics shown, soils were classified according to the Soil Taxonomy (USDA, 2010) as Entisols (Typic Sufalquents). The pedons P5, under fluvial influence, and P7, under marine influence, were classified as Haplic Sufalquents, since they contain, in some horizons, at a depth between 0.20 and 0.50 m below the surface, less than 80 g kg^{-1} of clay in the fine soil portion, and the others (P1, P2, P3, P4, and P6) are classified as Typic Sufalquents. According to the World Reference Base (WRB) (FAO, 2006), the soils were not classified as Salic Gleyic Fluvisols (Thionic, Sodic), except for pedon P7, which had no salic horizon, and was therefore classified as Gleyic Fluvisol (Thionic, Sodic).

Despite some differential characteristics, such as depth, alternation of layers with an irregular distribution of texture and organic C contents, and presence of contaminants (heavy metals), the classification of the soils for all pedons, whether under fluvial or marine influence, was identical, up to the fourth category level. It was possible to distinguish differences only from the fifth category level.

Gleysols are formed, mainly, due to constant or periodic excessive waterlogging, whether they are stratified or not, which may, many times, induce the classification as intermediate for Fluvic Neosols (Embrapa, 2013). Nevertheless, for the thiomorphic Gleysols there is no definition as intermediate for this class (Fluvic Neosols) at the fourth category level, but, since thiomorphic Gleysols are a striking feature of mangrove soils, it was chosen to classify them at the fifth category, to indicate the fluvial nature, rather than using the texture clustering.

Another interesting characteristic of the soils in the region, with a direct influence on occupation, use and management, is the presence of heavy metal contaminants, which may occur due to natural factors and processes (source material) or through anthropic processes (introduced into the system by harmful actions). All pedons had higher heavy metal concentrations than those established by the environmental authorities (NOAA, 1999; Conama, 2009), except for P7 (Table 4). It is believed that, for this last pedon, the longer distance from the contamination point, compared to the others, may have favored its lower concentration.

In the SiBCS, no clear alternative for heavy metals is included in the classification, but it can be included as a differential characteristic that affects soil use and management for several purposes, also in the fifth category level, based on a chemical property that reflects environmental conditions. In the system WRB (FAO, 2006), the prefix *Toxic* may be used as a formative element for second level units, in some classes, to indicate the presence, in any layer down to 0.50 m from the soil surface, of toxic concentrations of organic or inorganic substances other than the ions Al, Fe, Na, Ca, and Mg.

Based on the classification systems of FAO and the Soil Taxonomy, it was chosen to include the term *potentially toxic* in the sixth category level, related to the SiBCS, for the soil classes under study having heavy metal concentration above the reference values established by the U.S. National Oceanic and Atmospheric Administration (NOAA, 1999). The pedons under fluvial and marine influence were classified as thiomorphic orthic Gleysol (salic) sodic luvissol (potentially toxic, very poorly drained), except for P7, due to the low metal concentration.

CONCLUSIONS

Mangrove soils in the Subaé river basin under fluvial and marine influence have different morphological, physical, and chemical characteristics.

The morphological, physical, and chemical characteristics of the mangrove soils in the Subaé river basin indicated holomorphic, hydromorphic, and sulfate-reducing conditions and waterlogging.

The highest Pb and Cd concentrations were detected in the pedons under fluvial influence, probably due to the closeness to the mining factory Plumbum, and the lowest concentrations were found in pedon P7, due to greater distance from the factory.

All pedons in the soils under study had concentrations of, at least, one heavy metal (Mn, Zn, Pb, Fe, and Cd) above the preventive threshold (TEL), except for pedon P7.

Mangrove soils, whether under fluvial or marine influence, were classified as *Gleissolos Tiomórficos Órticos (sálicos) sódico neofluvissólicos* (potentially toxic, very poorly drained), due to the low metal concentration.

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