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Segmentation of the Apodi-Mossoró river and pedogenetic changes in soils in alluvial environments

Segmentação do rio Apodi-Mossoró e alterações pedogenéticas em solos de ambientes aluviais

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ABSTRACT - The Apodi-Mossoró River Basin is important for the west region of the state of Rio Grande do Norte (RN), Brazil. The rapid increase in population and consequent need for space has resulted in anthropogenic actions, such as the segmentation of the river course within the municipality of Mossoró, RN. The objective of this study was to assess the effects of this segmentation on soils in alluvial environments. Soil collection points were defined in natural and anthropized areas in the Mossoró urban segment; soil profiles were described and collected; and samples of the soil 0-10 and 10-20 cm were collected. The samples were subjected to physical and chemical analyses to determine granulometry, density, aggregates, pH in water, available phosphorus (P), exchangeable bases, potential acidity, total organic carbon, nitrogen, and micronutrients (Cu and Zn). Maps of location and land use and cover were developed. The soil found in the natural area was classified as Neossolo Fluvico Psamitico eutrico, presenting typical physical and chemical characteristics of this soil class, with variable texture and P contents along the soil profile. The soil in the anthropized area was classified as Planossolo Haplico Carbonatico vertissolico, with Ap Horizon presenting a sandy loam texture, since it is a horizon formed due to anthropogenic activity in the environment. All horizons and profiles presented high pH. The evaluated areas formed different groups regarding soil physical and chemical attributes, with overlapping points that can be explained by anthropogenic actions, even in the environment considered natural.

Keywords: Urbanization. Anthropization. Pedology.

RESUMO - A bacia hidrográfica do Rio Apodi-Mossoró é de grande importância para a região Oeste do Estado do Rio Grande do Norte. Com o aumento acelerado da população e a consequente necessidade de espaço geográfico, ações antrópicas como a tricotomização foram necessárias no curso do rio do município de Mossoró/RN. O presente trabalho objetiva compreender os efeitos da tricotomização em solos no ambiente aluvial. Foram definidos pontos de coleta nas áreas natural e antropizada no trecho urbano de Mossoró, descritos e coletados perfis de solo, além da coleta de amostras de solo nas profundidades de 0 – 0,10 m e 0,10 – 0,20 m. Foram realizadas análises físicas e químicas nas amostras, consistindo em: granulometria, densidade do solo, agregados, pH em água, P disponível, bases trocáveis, acidez potencial, carbono orgânico total (COT), nitrogênio (N) e micronutrientes (Cu e Zn). Também foram confeccionados mapas de localização, uso e ocupação dos solos. O solo observado na área natural foi classificado como Neossolo Flúvico Psamítico êutrico, apresentando características físicas e químicas típicas da classe de solo, como textura e teores de P variáveis ao longo do perfil. Na área antropizada, o solo foi classificado como Planossolo Háplico Carbonático vertissólico, com horizonte Ap apresentando textura franco arenosa por se tratar de um horizonte decorrente da atividade antrópica no ambiente. Todos os horizontes e perfis apresentaram pH elevados. As áreas formam grupos distintos em relação aos atributos físicos e químicos, com pontos de sobreposição que podem ser justificados pela atuação do homem mesmo no ambiente considerado natural.

Palavras-chave: Urbanização. Antropização. Pedologia.

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INTRODUCTION

The municipality of Mossoró, Rio Grande do Norte (RN), Brazil, is in the region of the Apodi-Mossoró River Basin, which is the second largest river basin in the state, drains an area of approximately 15,500 km^2, and has a significant importance for the regional economy, mainly for oil extraction and sea salt production activities; land use for irrigated agriculture and fruit production and extensive livestock; and limestone mining (CARVALHO; KELTING; SILVA 2011).

The occupational structure of Mossoró often caused severe floods in areas near the river during rainy periods. Thus, the municipal government carried out works between 1976 and 1986 that altered the course of the Apodi-Mossoró River within the urban area of this municipality (LIMA, 2007), dividing it into segments, a process called segmentation, to reduce flooding in the urban zone (MOURA, 2014). The segmentation project involved deepening of existing channels and opening secondary branches in the river, specifically at points surrounding Santa Luzia, Rincao, and Coroa islands.

The management of urban waters requires to consider not only land use and occupation but also the fluvial evolution of watercourses. Thus, urban planning of occupation along these water courses should consider fluvial dynamics in decision-making processes (BENINI; ROSIN, 2017).

The growth of cities has strong impacts on soils, as materials from buildings forms layers that do not connect with the original material in these areas (LADEIRA, 2012). Environmental impacts from human activities are significant and can result in soil changes, generating several natural and social problems. Probably, anthropogenic actions have caused changes in soil attributes of alluvial environments along the Apodi-Mossoró River.

Human activities make environments subject to changes, including in soils. Soil changes resulting from anthropogenic activities can be morphological, chemical, physical, and mineralogical (TEXEIRA; LIMA, 2016). Natural soils are modified through disposal of solid waste on them, combined with other mechanical processes in urban environments that cause losses of identification horizons (ANTONIO; METTERNICH; TOMMASELLI, 2017).

Intense anthropogenic actions in alluvial environments around the Apodi-Mossoró River may have altered chemical and physical characteristics of soils in these environments. Thus, the objective of this study was to understand anthropogenic effects on soils in alluvial environments caused by the segmentation of the river course within the urban zone of Mossoró, RN, Brazil.

MATERIAL AND METHODS

Study area characterization

The municipality of Mossoró, state of Rio Grande do Norte, Brazil, is in the West Potiguar mesoregion; its territorial area is 2,099.33 Km2, and population of 264,577 in habitants (IBGE,2023). The climate of the region was classified as BSh, dry hot, according to the Köppen classification, with a mean annual temperature of 26.5 °C and irregular rainfall, with mean annual depths lower than 650 mm, concentrated from February to June; Caatinga vegetation is predominant in the region (ALVARES et al., 2013).

The geological formations of the Mossoró region include rocks from the crystalline basement and sediments from the Potiguar Basin and the Barreiras Group (JACOMINE et al., 2015).

Description and collection of soil profiles and samples

The study was conducted in the urban area of Mossoró, which is affected by the segmentation of the Apodi-Mossoró River course that crosses the urban perimeter. Points around the river were defined (Table 1) and trenches were opened in selected locations for morphological description of soil profiles (P1 and P2), following the Field Soil Description and Collection Manual (SANTOS et al., 2015), and soil classification up to the 4th categorical level of the Brazilian Soil Classification System (SANTOS et al., 2018).

Table 1. Location and geological units of soil profiles and random sampling points in the urban area of the Apodi-Mossoró River.

Profile	Latitude	Longitude	Altitude (m)	Geological units
P1	5°11'47"S	37°19'25"W	14	Alluvial deposits
P2	5°11'46"S	37°20'03"W	14	Alluvial deposits
A1	5°11'20"S	37°19'09"W	9	Alluvial deposits
A2	5°11'49"S	37°19'41"W	12	Alluvial deposits
A3	5°12'02"S	37°19'54"W	8	Alluvial deposits
N1	5°11'41.83"S	37°19'43.90"W	11	Alluvial deposits
N2	5°11'48.04"S	37°20'34.63"W	13	Alluvial deposits
N3	5°12'17.09"S	37°20'51.98"W	8	Alluvial deposits

P1: Profile 1; P2: Profile 2; A1, A2, and A3: anthropized areas; N1, N2, and N3: natural areas.

Profile 1 was in the river trichotomized branch and Profile 2 was in the river natural branch. Three points along the natural course (N1, N2, and N3) and three points along the anthropized course of the Apodi-Mossoró River were selected (A1, A2, and A3) for collecting soil samples (Figure 1). Simple soil samples were collected from the 0.0-0.10 and 0.10 -0.20 m layer in each point. The samples were air-dried and sieved through a 2.0 mm mesh sieve to obtain the bulk soil. According to the soil attributes, undisturbed soil samples were collected for soil density analysis using the clod method.

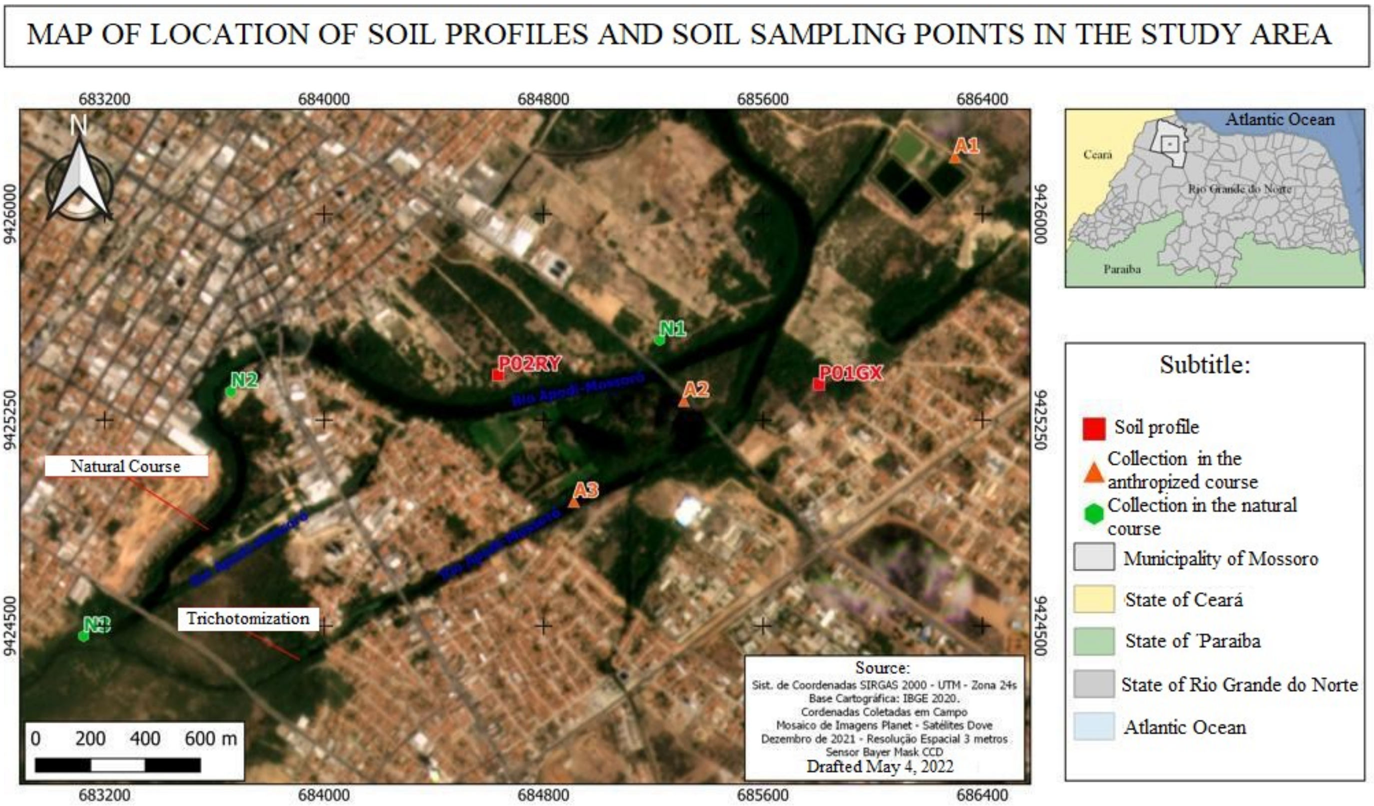


Figure 1. Map of location of soil profiles and soil sampling points in the study area.

Physical analyses

Physical analyses were carried out in triplicate, using the bulk soil. Granulometry was determined using the method proposed by Teixeira et al. (2017). Soil aggregates were analyzed using the wet sieving method. Soil samples were sieved in the field using 4.76 mm and 2.00 mm mesh sieves, taken to the laboratory, placed on a set of sieves (2.0, 1.0, 0.50, and 0.25 mm meshes), immersed in water, and agitated in a mechanical vibration shaker for four minutes.

Chemical analyses

Chemical analyses were carried out in triplicate, using the bulk soil, according to the manual of soil analysis method of the Brazilian Agricultural Research Corporation (Embrapa). The pH in water was measured in a soil-liquid suspension at a ratio of 1:2.5 (TEIXEIRA; CAMPOS; SALDANHA, 2017b); electrical conductivity (EC) was measured in a water extract solution using a conductivity meter (TEIXEIRA; CAMPOS; PIRES, 2017).

Available phosphorus (P) was obtained through Mehlich-1 solution and reduction of molybdate with acid ascorbic and determined by spectrophotometry (TEIXEIRA; CAMPOS; SALDANHA, 2017a). Exchangeable cations, potassium (K^+), and sodium (Na^+) were extracted using Mehlich-1 solution and determined by flame photometry; copper (Cu) and zinc (Zn) were extracted using Mehlich-3 solution and determined by atomic absorption (TEIXEIRA et al., 2017).

Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) were extracted using a 1.0 mol L^{-1} potassium chloride (KCl) solution and determined by atomic absorption spectrometry; and exchangeable aluminum (Al^{+3}) was extracted using a 1.0 mol L^{-1} KCl solution and determined by titration with 0.025 mol L^{-1} sodium hydroxide (NaOH) (TEIXEIRA et al., 2017).

Potential acidity (H+AL) was determined by extraction using a 0.5 mol L^{-1} calcium acetate solution (pH 7.0) and titration with 0.025 mol L^{-1} NaOH (CAMPOS et al., 2017). Calcium carbonate ($CaCO_3$) was extracted using a standard 0.5 mol L^{-1} HCl solution and determined by titration with a standard 0.25 mol L^{-1} NaOH solution (TEIXEIRA; CAMPOS; PÉREZ, 2017).

Total organic carbon (TOC) was determined according to the method proposed by Mendonça and Matos (2017) and adapted from Yeomans and Bremner (1988), through oxidation of organic matter by 0.2 mol L^{-1} dichromate of potassium in a sulfuric acid medium, followed by titration with 0.2 mol L^{-1} ammonium ferrous sulfate.

Nitrogen (N) was determined using the distillation-titration method (Kjeldahl) (BALIEIRO; ALVES, 2017), in which the ammonium (NH_4^+) produced during digestion with sulfuric acid (H_2SO_4) is distilled in a strongly alkaline medium. The condensed NH_4^+ is collected in a boric acid (H_3BO_3) solution and titrated with a hydrochloric acid (HCl) solution.

Cartographic products

Location and land use and cover maps were developed using the open-source GIS software QGIS 3.16 Hannover. A mosaic of Planet satellite images (Dove satellites), with a spatial resolution of three meters, and the cartographic basis of the Brazilian Institute of Geography and Statistics (IBGE, 2020) were used for manual vectorization. Coordinates of sampling points in the study area were collected in the field.

Statistical analysis

Statistical analysis of the evaluated soil profiles consisted of multivariate analysis using the software Statistica 7.0 (STATSOFT, 2004), based on the Pearson's method ($p \leq 0.05$) for variables to ensure that the attributes had minimal correlations for their use in the data matrix. The correlation matrix established a pattern for analytical results for the application of principal component analysis (PCA) (HAIR et al., 2009).

Principal components with eigenvalues higher than 1 were extracted in the factorial analysis; the factor axes were rotated using the Varimax method. A loading factor value of 0.70 was set to consider significant loadings (HAIR et al., 2009).

Two diagrams (Factors 1 and 2) for physical and chemical attributes were generated for PCA. According to these data, a two-dimensional diagram was developed to distinguish the areas and a vector projection diagram was developed to determine the most sensitive soil attributes for the differentiation of the study area (HAIR et al., 2009).

RESULTS AND DISCUSSION

Soil profiles

The soils found in the natural and anthropized alluvial areas had distinct classifications (Table 2).

Table 2. Morphological description of soil profiles evaluated in anthropized and natural areas around the Apodi-Mossoró River.

Horizon	Moist	Structure	Consistency			
cm	color	type	Dry |drought|	Moist	Plasticity	Stickiness
Profile 1 – Planossolo Haplico Carbonatico vertissolico						
Ap (0-7)	5Y 2.5/2	Gs	Sl	Sl	NPl	NPg
Btg1 (7-30)	5Y 2.5/1.0	PR	-	ExF	MPl	MPg
Bg2 (30-66)	5Y 3/1.0	PR	-	ExF	MPl	MPg
Bg3 (66-88+)	5Y 3/1.0	PR	-	ExF	MPl	MPg
Profile 2 – Neossolo Fluvico Psamitico eutrico						
A (0-6)	2.5Y 3/2	BA	Ma	Mfr	LgPl	LgPe
AC (6-15)	2.5Y 3/3	BA	MD	Mfr	LgPl	LgPe
C1 (15-67)	2.5Y 4/2	Gs	Sl	Sl	NPl	NPg
C2 (67-85)	2.5Y 3/3	Mc	MD	Mfr	LgPl	LgPe
C3 (85-94)	2.5Y 4/2	Gs	Sl	Sl	NPl	NPg
C4 (94-112)	2.5Y 3/3	Mc	ExD	Fi	NPl	NPg
C5 (112-121)	2.5Y 4/3	Gs	Sl	Sl	NPl	NPg
C6 (121-134)	2.5Y 5/2	BA	MD	Mfr	MPl	LgPe
C7 (134-149)	2.5Y 3/2	Mc	Sl	Sl	LgPl	LgPe
C8 (149-175)	10YR 2/2 222/2/2	Mc	-	Mfr	Pl	Pe

Gs: single grains; PR: prismatic; BA: angular blocks; Mc: massive; Sl: loose; Ma: soft; MD: very hard; ExD: extremely hard; ExF: extremely firm; Mfr: very friable; Fi: firm; NPl: non-plastic; MPl: very plastic; LgPl: slightly plastic; Pl: plastic; NPg: non-sticky; MPg: very sticky; LgPe: slightly sticky; and Pe: sticky.

The soils in areas along the river course subjected to segmentation were classified as Planossolo Haplico Carbonatico vertissolico (Figure 2a). The soil along the natural course of the Apodi-Mossoró River were classified as Neossolo Fluvico Psamitico eutrico (Figure 2b).

The distinction of soil classes is based on pedogenetic processes occurring in the fluvio-marine area where the Mossoró region is located. Clay illuviation and gleying were the predominant processes identified in the anthropized areas, resulting in the formation of Neossolos Fluvicos only along the riverbanks (natural areas), through the deposition of alluvial sediments.

Figure 2. Planossolo Haplico Carbonatico vertissolico (a); Neossolo Fluvico Psamitico eutrico (b).

This denotes that the segmentation of the river course exposed these areas to continuous flooding for a period, contributing to the gleying process. Accumulation of alluvial sediments was found in anthropized areas, with formation of Ap horizon presenting physical and chemical characteristics different from the underlying horizons.

Regarding the morphological characterization, Profile 1 presented a single-grain structure in the surface horizon (Ap) and prismatic structure in subsurface, which breaks down into angular blocks and less frequently into subangular blocks. This type of hydromorphic environment in semiarid climates is typical of the pedogenetic process of ferrolysis, which causes an abrupt textural change resulting from destruction of silicate clays on the soil surface due to redox cycles of iron and can cause the complete removal of iron oxides, resulting in soil discoloration (KAMPF; CURI., 2015)

Moisture was found throughout Profile 1 in all horizons, except the Ap horizon; Btg1, Btg2, and Btg3 horizons presented high plasticity and stickiness, preventing assessments of dry soil consistency, which is characteristic of Planossolos. Profile 2 presented typical morphological variability of Neossolos Fluvicos, with variations in color, structure, and consistency along the AC and C1 horizons (Table 2).

Regarding the physical characterization, the Ap horizon of Profile 1 presented a sandy loam texture; this horizon is formed from alluvial sediments probably deposited due to the anthropogenic action of segmentation of the river course. It differed from other horizons, which presented sandy clayey loam (Btg1) and clay (Btg2 and Btg3) textures. The textures of the horizons throughout the Profile 2 varied, mainly from sandy loam to sand (Table 3).

The Ap horizon of Profile 1 showed higher soil density than the others horizons, confirming the sandy texture of the recently deposited material due to anthropogenic intervention in the area. The soil density in Profile 2 varied, which can be explained by the genesis of Neossolos Fluvicos, in which fluvial deposits are the essential source material (PINHEIRO et al., 2020).

Table 3. Physical attributes of soil profiles evaluated in anthropized and natural areas around the Apodi-Mossoró River.

	TS	SILT	CLAY	Ds	WMD	GMD
	--------------------------g kg^{-1}	---------------------------		g cm^{-3}	-----------------mm	-----------------
			Planossolo Haplico Carbonatico vertissolico			
Ap	780.3	96.6	123.1	1.3	0.2	1.3
Bg1	502.5	217.4	280.2	1.0	0.6	1.4
Bg2	196.3	240.5	563.2	1.0	0.3	1.4
Bg3	233.6	296.3	470.0	1.0	1.1	1.5
			Neossolo Fluvico Psamitico eutrico			
A	549.2	275.7	175.2	1.1	1.0	1.4
AC	625.0	213.5	161.5	1.4	0.7	1.2
C1	917.0	27.9	55.0	1.4	0.0	0.9
C2	595.6	229.9	174.5	1.4	0.3	0.9
C3	925.0	35.0	40.0	1.6	0.0	0.9
C4	558.6	258.2	183.2	1.4	0.3	0.8
C5	882.3	62.3	55.4	1.4	0.1	0.8
C6	863.5	50.3	86.2	1.4	0.1	0.8
C7	589.1	262.2	174.6	1.3	0.1	1.1
C8	452.3	294.3	253.3	1.1	0.0	0.0

TS: total sand; WMD: weighted mean diameter; GMD: geometric mean diameter; Ds: density.

Aggregate stability can be used to evaluate soil quality under different land uses and managements (SOUZA, 2015); it tends to be higher under higher input of organic matter. Therefore, the organic matter content has a direct and significant correlation with the distribution of larger-sized aggregates (RIBON et al., 2014).

Profile 1 presented geometric mean diameters (GMD) higher than 1 in all horizons and smaller weighted mean diameters (WMD), except for the Btg3 horizon (Table 4). The higher values found for the anthropized area may be due to the added plant material, which contributes to increases in organic matter and, consequently, promotes soil aggregation. Profile 2 presented smaller GMD and WMD, which varied from 0 to higher than 1 throughout the profile. WMD increases as the percentage of coarse aggregates retained on the sieve increases. GMD represents an estimate of the size of the most common aggregate class. Smaller WMD and GMD are a consequence of the breakdown of soil aggregates due to anthropogenic interventions (LOSS et al., 2015).

Overall, both profiles presented variable texture, mainly the anthropized area, which is typical of fluvial environments: alkaline, low Na^+, and rich in P, TOC, and exchangeable bases (Ca^{2+} and Mg^{2+}) (Table 4). Currently, the Apodi-Mossoró River presents a strong eutrophication, therefore, these results are important to explain the contamination potential of water, mainly affecting the areas where the segmentation was carried out. This confirms that the segmentation resulted in land use and occupation of previously non-existent areas, which was the main responsible factor for the environmental contamination.

Soil physical and chemical attributes change by anthropogenic intervention processes, whose effects cause damages to surface water sources in river basins due to sediment runoff, which can directly contribute to eutrophication processes in these systems (MEDEIROS, 2016).

All horizons and profiles presented high pH, which is consistent with the high contents found for cations, mainly Ca^{2+} and Mg^{2+}, and low contents found for H+Al (Table 4). These results may be explained by the flooding process that occurs in these soils, which decreases the redox potential and, consequently, increases pH. Water availability is connected to increases in soil pH (SILVA et al, 2012). Similarly, all profiles and horizons presented low EC and Na^+ levels (Table 4).

High P contents were found in the Ap and Btg1 horizons of Profile P1 (Table 4), which is characteristic of soils with anthropic A horizon (SANTOS et al., 2018). However, P contents varied throughout Profile 2, which is characteristic of Neossolos Fluvicos. According to Medeiros (2016), the use of alluvial soils increases P and N contents, causing decreases in water quality and ecological functioning of aquatic systems, i.e., increasing eutrophication.

TOC contents were higher in the Ap horizon of Profile 1 (Table 4). The profiles presented a high C to N ratio (C/N) (Table 4). Higher C/N in soils is associate with the hydromorphic aspect, which hinders carbon degradation and facilitates N losses by leaching (SANTOS, 2019).

Table 4. Chemical attributes of soil profiles evaluated in the anthropized and natural areas of the Apodi-Mossoró River.

Hor.	pH	EC	TOC	N	C/N	P	Cu	Zn	$CaCo_3$	Na	K	Ca^{2+}	Mg^{2+}	H+Al	BS
	H_2O	dSm^{-1}	---------g kg^{-1}---------			---------mg Kg^{-1}--------				---------------------g Kg^{-1}---------------------					%
Planossolo Haplico Carbonatico vertissolico															
Ap	8.7	0.1	147.2	2.7	54.5	136.1	0.0	0.1	216.0	0.5	0.6	10.0	5.4	0.1	99
Bg1	9.1	0.9	13.5	1.1	12.3	106.7	0.0	0.3	211.6	0.3	0.4	7.1	6.6	0.2	98
Bg2	8.8	0.8	4.0	0.3	12.9	37.5	0.0	0.1	205.3	0.2	0.3	8.1	8.7	0.3	98
Bg3	8.7	0.5	4.5	0.2	18.5	67.7	0.0	0.3	219.7	0.3	0.2	9.4	8.4	0.6	97
Neossolo Fluvico Psamitico eutrico															
A	7.7	0.2	28.1	2.1	13.2	4.5	0.0	0.2	0.0	0.0	1.3	14.8	1.4	0.2	99
AC	7.8	0.2	12.9	0.8	15.3	37.4	0.0	0.4	0.0	0.1	2.0	9.9	2.0	0.2	99
C1	8.2	0.1	3.4	0.1	42.5	12.5	0.0	0.3	0.0	0.2	0.5	3.9	1.2	0.0	100
C2	8.2	0.1	4.6	0.3	15.0	27.2	0.0	0.3	0.0	0.2	1.0	11.1	1.8	0.1	99
C3	8.5	0.0	4.5	0.1	42.8	3.4	0.0	0.2	0.0	0.0	0.2	2.7	1.6	0.0	100
C4	8.2	0.1	4.7	0.3	15.0	52.0	0.0	0.4	0.0	0.1	0.3	12.1	2.1	0.0	100
C5	7.8	0.4	4.7	0.1	58.3	2.9	0.0	0.5	0.0	0.4	0.1	3.5	2.2	0.1	98
C6	8.0	1.6	4.5	0.1	41,0	30.8	0.0	0.5	0.0	0.1	0.1	5.2	3.0	0.1	99
C7	8.9	4.5	3.2	0.2	15.6	10.0	0.1	0.3	0.0	0.2	0.1	8.3	3.2	0.0	100
C8	8.9	3.5	4.4	0.3	15.8	4.2	0.0	0.3	0.0	0.3	0.2	12.2	2.3	0.0	100

Hor: horizon; EC: electrical conductivity; H+Al: acidity potential; Na^+: sodium; K^+: potassium; P: phosphorus; $Ca2^+$: calcium; Mg^{2+}: magnesium; BS: base saturation; TOC: total organic carbon; N: nitrogen; C/N: C to N ratio; Cu: copper; Zn: zinc.

Random soil sampling points evaluated in the anthropized and natural areas of the Apodi-Mossoró river

The soil sampling conducted at random points in the natural and anthropized river course areas indicated changes in the soil physical and chemical characteristics throughout the studied alluvial environment.

The granulometric composition of the anthropized area showed a predominance of the total sand fraction in surface and subsurface layers, as well as in the natural area (Table 5). All areas presented small WMD and GMD close to 1, except in the 0.10-0.20 m soil layer of the natural area, which presented a value close to 2. All means of soil density were close to 1.0 g cm^{-3}.

Table 5. Means of soil physical attributes in random sampling points in the anthropized and natural areas of the Apodi-Mossoró River.

Attributes	A	σ	CV	A	σ	CV	N	σ	CV	N	σ	CV
	0-0.10 m		%	0.10-0.20 m		%	0-0.10 m		%	0.10-0.20 m		%
SAND (g kg^{-1})	454.6	227.1	52	439.2	235.7	54	667.3	273.7	41	662.0	289.0	44
SILT (g kg^{-1})	297.4	66.7	22	255.3	83.3	33	165.0	137.3	83	167.5	147.2	88
CLAY (g kg^{-1})	247.9	174.3	70	305.4	152.4	50	167.6	137.9	82	170.5	142.8	84
WMD (mm)	0.5	0.3	72	0.3	0.2	77	0.2	0.2	151	0.1	0.1	67
GMD (mm)	1.0	0.2	16	1.1	0.2	17	1.9	1.7	91	0.9	0.1	10
Ds (g cm^{-3})	1.1	0.1	11	1.2	0.1	10	1.3	0.1	6	1.4	0.1	10

A: anthropized area; σ: standard deviation; CV: coefficient of variation; N: natural area.

The natural area, i.e., without segmentation, presented higher TOC and P contents than the anthropized area after segmentation (Table 6), differing from the results found for soil profiles. One hypothesis that could explain these results is the absence of actual natural areas, as the riverbanks have been improperly used, for example, for waste dumping, husbandry, and discharge of domestic effluents.

Regarding the soil samples from the anthropized areas, sodium contents in the 0.0-10.0 layer stood out, exceeding 26 $cmol_c$ Kg^{-1}, resulting in an ESP of 25%, classifying this layer as sodic (SANTOS et al., 2018).

Table 6. Means of soil chemical attributes in random sampling points in the anthropized and natural areas of the Apodi-Mossoró River.

Attributes	A	σ	CV	A	σ	CV	N	σ	CV	N	σ	CV
	0-0.10		%	0.10-0.20		%	0-0.10		%	0.10-0.20		%
	m			m			m			m		
pH	7.6	0.8	10	8.0	0.5	7	7.6	0.8	10	7.8	0.5	7
EC (dS m^{-1})	0.2	0.0	16	0.4	0.4	97	0.6	0.9	150	0.5	0.8	159
H+Al ($cmol_c$ kg^{-1})	0.8	0.7	92	0.6	0.3	55	1.0	0.6	61	0.8	0.3	41
Na^+ ($cmol_c$ kg^{-1})	26.6	44.1	166	8.6	12.7	147	3.9	6.5	169	0.1	0.1	115
K^+ ($cmol_c$ kg^{-1})	0.8	0.7	82	0.5	0.1	29	0.5	0.3	60	0.7	0.7	109
Ca^{2+} ($cmol_c$ kg^{-1})	14.8	4.5	30	14.9	5.5	37	8.4	4.6	55	6.9	4.9	71
Mg^{2+} ($cmol_c$ kg^{-1})	10.0	7.4	74	4.8	4.0	83	3.5	2.5	73	4.5	3.5	77
CEC	53.1	54.1	102	29.5	16.6	56	17.2	12.4	72	13.0	8.3	64
BS (%)	97	3	3	97	2	2	92	6	6	92	5	5
ESP (%)	25	36	70	21	25	81	13	21	63	1.0	1.0	106
TOC (g kg^{-1})	18.5	6.5	35	17.2	5.3	31	18.0	9.0	50	11.1	2.5	23
N (g kg^{-1})	1.4	0.4	32	0.8	0.3	38	1.1	0.9	86	0.4	0.3	58
C/N	14.6	7.3	50	22.7	2.8	12	21,0	7.4	35	32.4	19.8	61
P (mg kg^{-1})	24.9	13.1	53	14.4	4.8	33	62.3	48.8	78	48.6	34.4	71
Cu (mg kg^{-1})	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
Zn (mg kg^{-1})	0.3	0.3	92	0.4	0.3	71	0.8	0.6	76	0.5	0.1	29

A: mean in anthropized areas; σ: standard deviation; CV: coefficient of variation; N: mean in natural areas; EC: electrical conductivity; H+: potential acidity Na+: sodium; K: potassium; P: phosphorus; Ca: calcium; Mg: magnesium; T: cation exchange capacity; BS: base saturation; ESP: exchangeable sodium percentage; TOC: total organic carbon; N: nitrogen; C/N: C to N ratio; Cu: copper; Zn: zinc.

Land use and cover

An extensive urban area can be observed around the Apodi-Mossoró River (Figure 3). Additionally, a large area of bare soil was found, reinforcing that these areas are constantly used for disposal of materials or other anthropogenic activities. Araújo et al. (2012) reported that areas with bare soils, corresponding to deforested areas, are mostly in peripheral zones o the Mossoró, specifically between the East-West bridge and the Barrocas dam. Furthermore, the main sources of pollution found along the riverbanks were sewage systems, a brick industry, sand extraction, agricultural activities, waste dumping, and animal rearing.

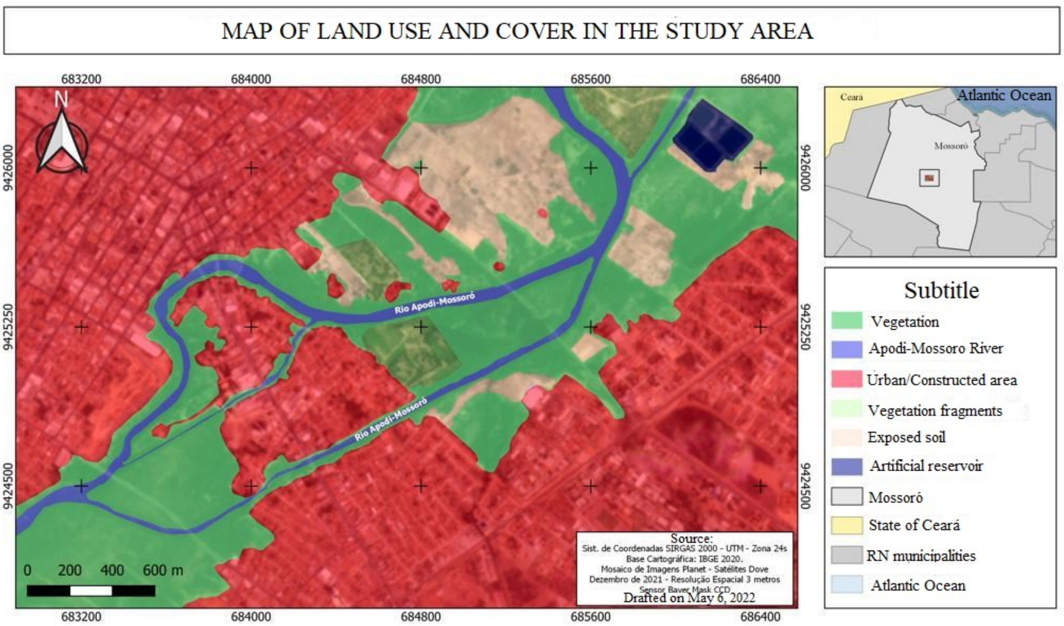
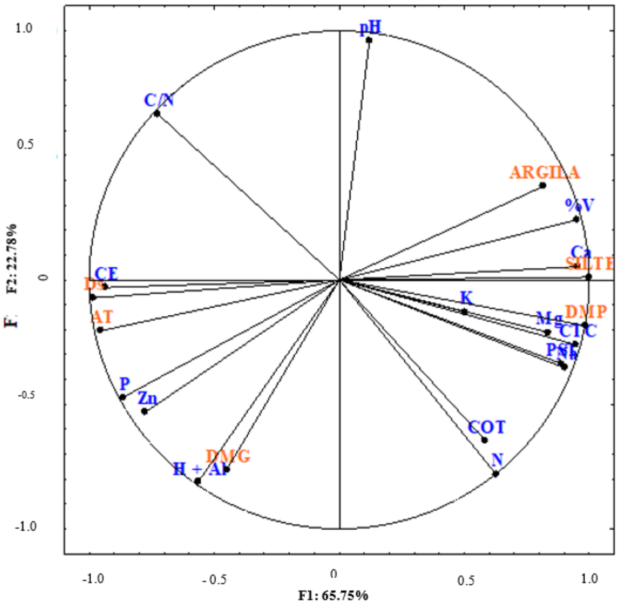


Figure 3. Map of land use and cover in alluvial environments around the Apodi-Mossoró River.

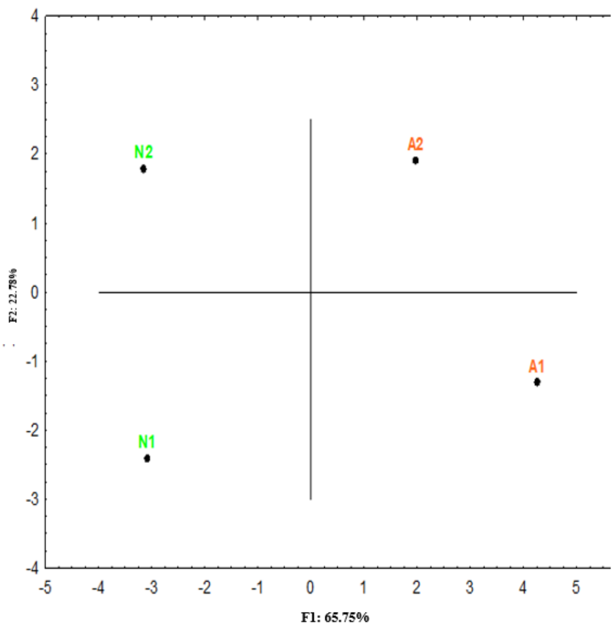
Principal component analysis

Two principal components were generated differentiating the study areas, considering the random samples (Figures 4 and 5) and the horizons of the soil profiles studied (Figures 6 and 7), forming diagrams for sample ordering and projection of vectors that show the physical and chemical soil attributes that most evidenced the distinction of these areas. The vector projection diagrams showed factors 1 and 2 with a cumulative variance of 88.53%.



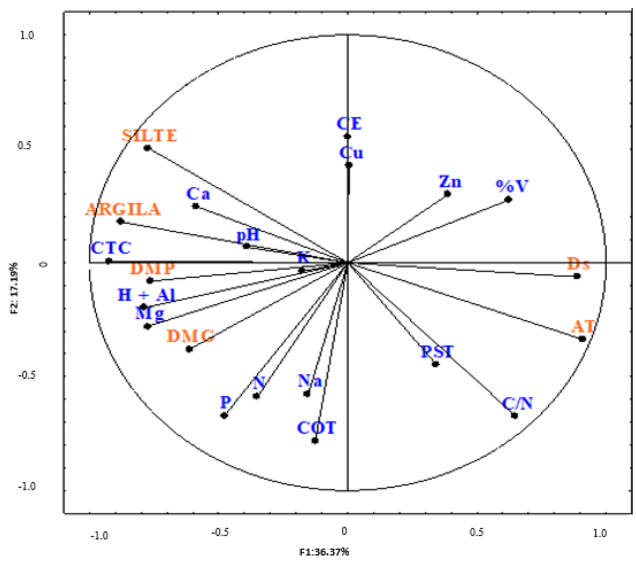
EC: electrical conductivity; H+Al: potential acidity; Na: sodium; K: potassium; P: phosphorus; Ca: calcium; Mg: magnesium; CEC: cation exchange capacity; BS: base saturation (%); ESP: exchangeable sodium percentage; TOC: total organic carbon; N: nitrogen; C/N: C to N ratio; Cu: copper; Zn: zinc; TS: total sand; Ds: soil density; WMD: weighted mean diameter; GMD: geometric mean diameter.

Figure 4. Projection diagram of soil attribute vectors for the different areas studied for Principal Components 1 and 2.



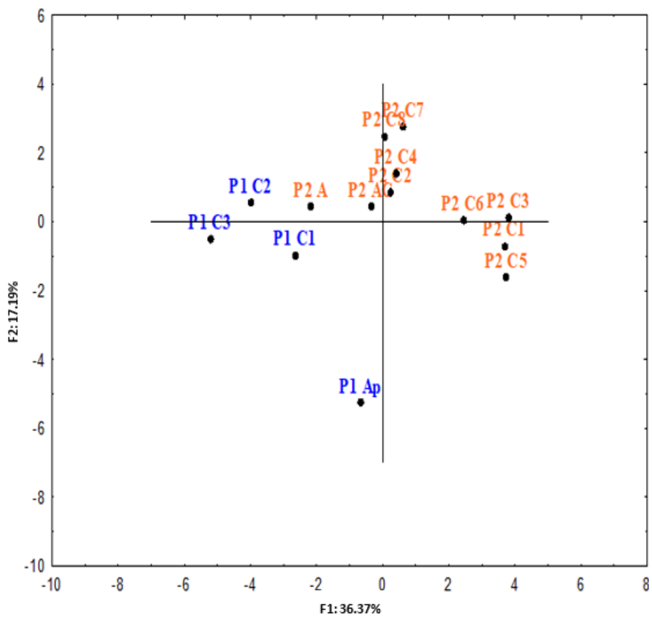
A1: mean of anthropized areas in the 0.0-0.10 m soil layer; A2: mean of anthropized areas in the 0.10-0.20 m soil layer; N1: mean of natural areas in the 0.0-0.10 m layer; N2: mean of natural areas in the 0.10-0.20 m soil layer.

Figure 5. Order diagram of Principal Components (PC) for the different studied areas for PC1 and PC2.



Grade: EC: electrical conductivity; H+Al: potential acidity; Na: sodium; K: potassium; P: phosphorus; Ca: calcium; Mg: magnesium; CEC: cation exchange capacity; BS: base saturation; ESP: exchangeable sodium percentage; TOC: total organic carbon; N: nitrogen; C/N: C to N ratio; Cu: copper; Zn: zinc; TS: total sand; Ds: density of soil; WMD: weighted mean diameter; GMD: geometric mean diameter.

Figure 6. Projection diagram of soil attributes vectors for the evaluated soil profiles for the Principal Components 1 and 2.



P1: Profile 1; P2: Profile 2.

Figure 7. Order diagram of Principal Components (PC) for the evaluated soil profiles for PC1 and PC2.

The natural area (before segmentation) and the anthropized area (after segmentation) formed distinct groups, which tended to be different even between depths (Figure 5). Different factors were significant for distinguishing the areas, despite human activities along the alluvial environment through the intense land use and occupation in the areas adjacent to the river.

Considering the projection vectors of factors 1 and 2 (Figure 4), the attributes WMD, CEC, ESP, Na^+, Mg^{2+}, TOC, and N affected the distinction of the first sampling point in the anthropized area on the surface (A1) from the other areas. The factors that had most affected the 0.10-0.20 m soil layer of the anthropized area were pH, clay, silt, BS, and Ca^{2+}.

Three factors were generated, considering eigenvalues higher than 0.70 a significant; factor 1 contributed with 65.75% for distinguishing the areas, by the effects of the attributes EC, Na^+, P, Ca^{2+}, Mg^{2+}, BS, CEC, ESP, C/N, Zn, TS, silt, clay, WMD, and Ds (Table 7).

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Table 7. Correlation coefficients of principal components (Factors 1, 2, and 3) for soil attributes of the different evaluated areas.

Attributes	F1	F2	F3
pH	0.12	0.96	-0.26
EC	-0.94	-0.03	-0.35
H+Al	-0.57	-0.81	0.14
Na^{+}	0.90	-0.35	0.25
K^{+}	0.50	-0.13	0.86
P	-0.87	-0.47	0.17
Ca^{2+}	0.96	0.05	-0.28
Mg^{2+}	0.84	-0.21	0.51
BS	0.95	0.24	-0.18
CEC	0.95	-0.26	0.19
ESP	0.89	-0.34	-0.32
TOC	0.58	-0.64	-0.49
N	0.63	-0.78	0.01
C/N	-0.73	0.67	0.17
Zn	-0.78	-0.53	-0.34
TS	-0.95	-0.20	0.22
SILT	1.00	0.01	0.02
CLAY	0.82	0.38	-0.44
WMD	0.98	-0.18	0.03
GMD	-0.45	-0.76	-0.47
Ds	-0.99	-0.07	0.15
Eigenvalues	13.81	4.78	2.41
Total variance (%)	65.75	22.78	11.47
Cumulative total variance (%)	65.75	88.53	100.00

[(1)]Factors ≥ 0.70 are significant (MANLY, 1994).

Regarding the natural areas, the attributes that most affected the surface layer (0.0- 0.10 m) were EC, P, Zn, H+Al, Ds, TS, and Ds. The 0.10-0.20 soil layer m was significantly affected by C/N, differing from the other areas.

Considering the projection diagram of vectors (Figure 6) and respective correlation coefficients, the attributes TOC, P, N, and Na^{+} affected the distinction of the Ap horizon from the other horizons. The attributes that most affected the C1 horizon of Profile 1 were GMD, WMD, Mg^{2+}, and H+Al. The C2 and C3 horizons of Profile 1 and the A horizon of Profile 2 were grouped together, with higher effect of CEC, Ca^{2+}, pH, K^{+}, clay, and silt. The C1, C3, C5, and C6 horizons of Profile 2 were grouped together, with higher effect of the attributes TS, Ds, C/N, ESP, BS, and Zn; the C2, C4, C7; and the C8 horizons of Profile 2 were grouped with higher effect of EC and Cu.

Five factors were generated to distinguish the profiles and horizons, explaining 87.72% of the cumulative variance. Factor 1 accounted for 36.37% of the variance; the discriminant variables were Ca^{2+}, CEC, C/N, TS, and silt (Table 8).

Table 8. Correlation coefficients of principal components (Factors 1, 2, 3, 4, and 5) for soil attributes of the evaluated profiles.

Attributes	F1	F2	F3	F4	F5
pH	0.14	0.27	-0.83	-0.25	0.09
EC	0.29	-0.20	-0.77	0.25	0.11
H+Al	0.20	0.02	0.15	-0.94	0.03
Na^{+}	-0.03	0.39	-0.21	-0.19	0.86
K^{+}	0.39	0.17	0.68	0.13	-0.29
P	0.05	0.75	0.00	-0.38	0.23
Ca^{2+}	0.92	0.25	0.16	0.08	-0.09
Mg^{2+}	0.09	0.28	-0.35	-0.87	0.11
BS	-0.05	0.08	-0.23	0.90	-0.20
CEC	0.80	0.37	0.01	-0.44	-0.02
ESP	-0.36	-0.05	0.01	0.03	0.87
TOC	-0.05	0.94	0.11	0.08	0.22
N	0.25	0.86	0.31	0.02	-0.01
C/N	-0.81	0.21	0.16	0.20	0.40
Cu	0.05	-0.13	-0.67	0.10	-0.17
Zn	0.03	-0.70	0.28	0.22	0.44
TOTAL SANDY	-0.72	0.05	0.26	0.61	0.07
SILT	0.94	-0.09	-0.12	-0.25	-0.07
CLAY	0.47	-0.01	-0.32	-0.77	-0.06
WMD	0.51	0.09	0.50	-0.61	-0.15
GMD	0.00	0.36	0.22	-0.71	-0.30
Ds	-0.54	-0.16	0.29	0.68	-0.05
Eigenvalues	8.00	3.78	3.42	2.55	1.54
Total variance (%)	36.37	17.19	15.55	11.61	6.99
Cumulative total variance (%)	36.37	53.56	69.12	80.73	87.72

[(1.0)]Factors ≥|0.70| are significant (MANLY, 1994).

CONCLUSIONS

The segmentation of the Apodi-Mossoró River course minimized the effects of floods, but intensified improper land use and occupation in the areas, causing negative impacts on the alluvial environment, such as accumulation of waste on riverbanks and in the river and contamination of the river waters with domestic sewage.

There are differences between the soils in the natural river course areas and in those in the trichotomized areas, however with some overlapping points, which can be attributed to the intense human activity in the alluvial environment along the Apodi-Mossoró River.

There are evidences of absence of natural areas along the riverbanks, as the results showed higher TOC and P contents in areas considered natural compared to those found in the areas after segmentation.

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