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Papers

Soils of lake environments in the Brazilian Pantanal

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Abstract
The Pantanal comprehends a set of heterogeneous and biodiverse landscapes of esteemed environmental, economic and social value. The study of soils is effective to stratify and to understanding the operation of these environments. The purpose of this study was to characterize and compare soils of lake landscapes of the Pantanal: baías (freshwater lakes), salinas (alkaline lakes) and their respective levees (sandy ridges originally with forest vegetation). For this purpose, we carried out field work with sampling, in triplicate, of superficial soil layers in 12 representative areas of low and high Nhecolândia; analytical determinations of 26 soil attributes were performed, totaling 936 response variables and statistical analyses were performed in order to synthesize the data and present the results. In both landscapes, the fine sand fraction predominates in the soil granulometry. The textural class of the soils varied from very sandy, medium sandy and medium sandy for the baías; very sandy for the levees, with particle density related to the presence of quartz; and very sandy, medium sandy, medium clayey and clayey for the salinas. In the chemical attributes and organic matter, the baías stand out for higher potential acidity (H+Al), slightly high organic matter contents and availability of metal ions, especially Fe; in the levees, higher average remaining phosphorus (Prem) are more evident; while the saline lake soils are related to more alkaline pH values, high base saturation and high Sodium Saturation Indices (ISNa). Salinas landscapes presented the highest data variability and have soil attributes that refer to the action of different environmental processes.

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INTRODUCTION

The Brazilian Pantanal comprises a mosaic of landscapes with distinct pedological characteristics, phytophysiognomies, and flooding gradients. Such landscapes are inserted in the Paraguay River watershed and their territory expands over three Latin American countries: Brazil, Paraguay, and Bolivia. The Pantanal is known for the exuberance of its environments and for its substantial biod iversity, being one of the main wetlands in the world (JUNK et al., 2006).

Due to the ecosystem services indispensable for society and the maintenance of ecological processes, wetlands have been the focus of many scientific studies (JUNK et al., 2014; RIBEIRO et al., 2019). As it consists of a set of large extensions of continuous wetlands, the Pantanal is considered a National Heritage by the 1988 Brazilian Constitution (BRASIL, 1988). Its landscapes comprise environments known for their great economic, cultural, recreational, aesthetic, scientific, and educational relevance (ALHO; SABINO, 2011; JUNK et al., 2006; SCHULZ et al., 2019).

Despite the significant ecological and social relevance provided by intact wetlands to Brazilian society (JUNK et al., 2014), the Pantanal ecosystems are vulnerable to changes promoted by anthropic activities (AB'SABER, 1988; JUNK et al., 2006; OLIVEIRA et al., 2019).

The intermittently flooded plain – where Pantanal is established – is not homogeneous, as it varies depending on the flood and ebb cycles, among other variables (SILVA; ABDON, 1998). Subtle geomorphic variations in the coverage of the plains result in comparatively large differences in the extent of the inundation area (JUNK et al., 2018), influencing the physical, ecological and human dimensions of the Pantanal region (SCHULZ et al., 2019).

Among the "Pantanals", the region called Nhecolândia attracts attention due to the coexistence of hundreds of lakes with different geochemical characteristics, which leads to numerous ecological interactions between the biotic and abiotic elements of the landscape (FURQUIM et al., 2017; MENEZES et al., 2022).

Soils are indeed relevant to landscape stratification. Their attributes provide information about the place and show active pedogenetic processes (RESENDE et al., 2014; SCHAEFER et al., 2016).

The study of the soil's nature investigates its physical, chemical, and biological properties, thus allowing us to understand the past and present of the soil and predict its future (IUSS WORKING GROUP WRB, 2015). Understanding the diversity of landscapes from the pedological point of view is a challenge for scientific research on the Pantanal because the economic dynamics of land use has been intensified at the expense of the integrity of the Pantanal ecosystems.

Pedological studies in the Pantanal environments are still scarce, which indicates the need for soil characterization and identification in the large areas of the floodplain (MENEZES et al., 2022). Carrying out soil characterization in the lake landscapes of Pantanal contributes to the definition of more homogeneous areas and the collection of environmental information on a broader scale. It also enables the individualization of regions with similar characteristics and with the potential to support strategies for the use and monitoring of natural resources, promoting sustainable management and preservation (CUNHA; JUNK, 2009; JUNK et al., 2018; SCHULZ et al., 2019).

This study aimed to characterize and compare the chemical, physical, and organic matter attributes of soils from different lake landscapes in the Pantanal of Nhecolândia: baías (freshwater lakes), salinas (alkaline lakes), and their respective levees (sandy ridges originally with forest vegetation).

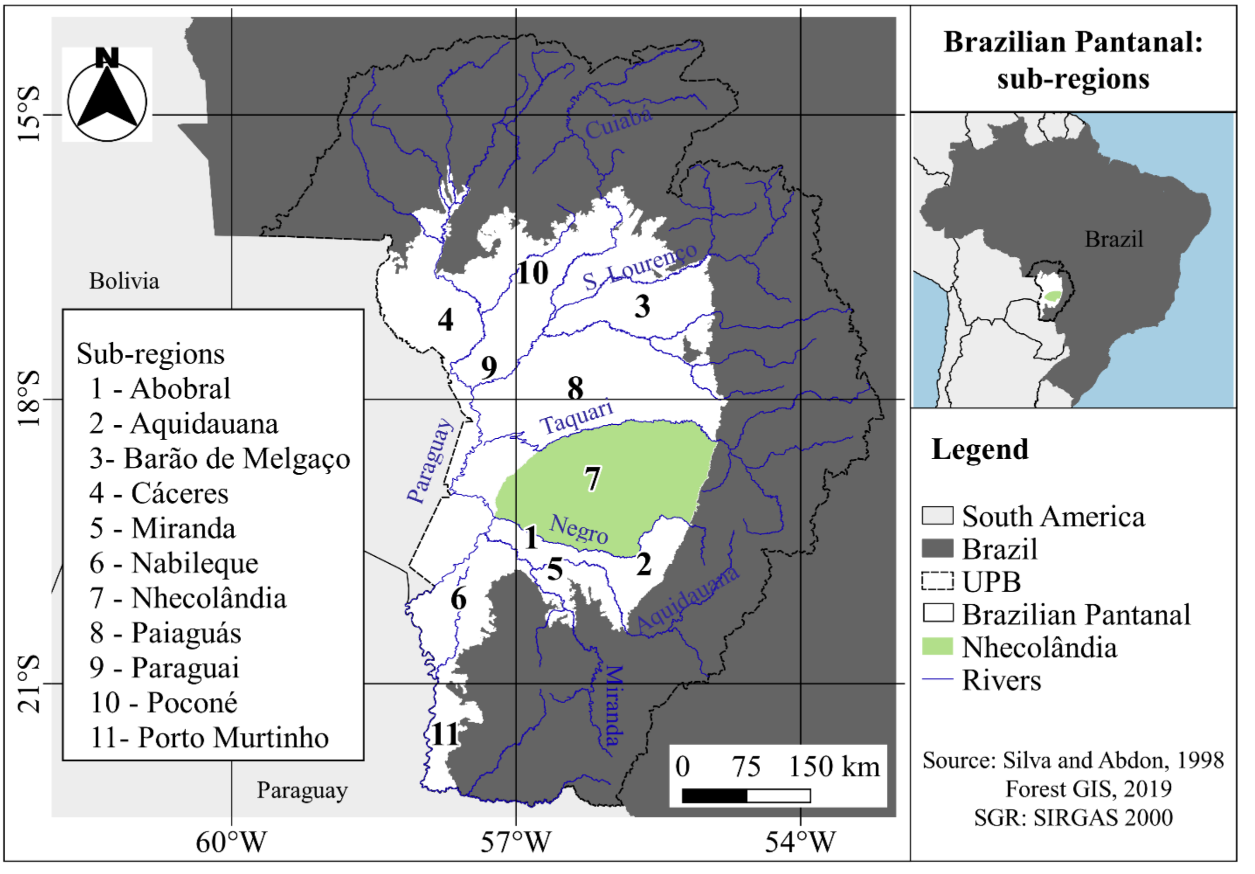
MATERIALS AND METHODS

Area of study

The Pantanal is an active sedimentary basin filled with a thick sequence of Quaternary sediments, whose geomorphic characteristics are relics of paleoclimatic and paleogeographical changes that have been occurring since the Pleistocene (ASSINE; SOARES, 2004). Its lithology is mainly understood by the lithostratigraphic unit called Pantanal Formation, characterized by the presence of ancient alluvial deposits covered by more recent sediments, which constitute the floodplains and form layers on the Paleozoic basement of the Paraguay River basin (BAZZO et al., 2012).

Our area of study is the Nhecolândia region, an area of 26,921 km², corresponding to 19.5% of the total area of Pantanal (SILVA; ABDON, 1998). It borders the Taquari river to the North, the Serra de Maracaju plateau to the East, the Negro river to the South, and the Taquari and Negro rivers' confluence with the Paraguay river to the West (Figure 1).

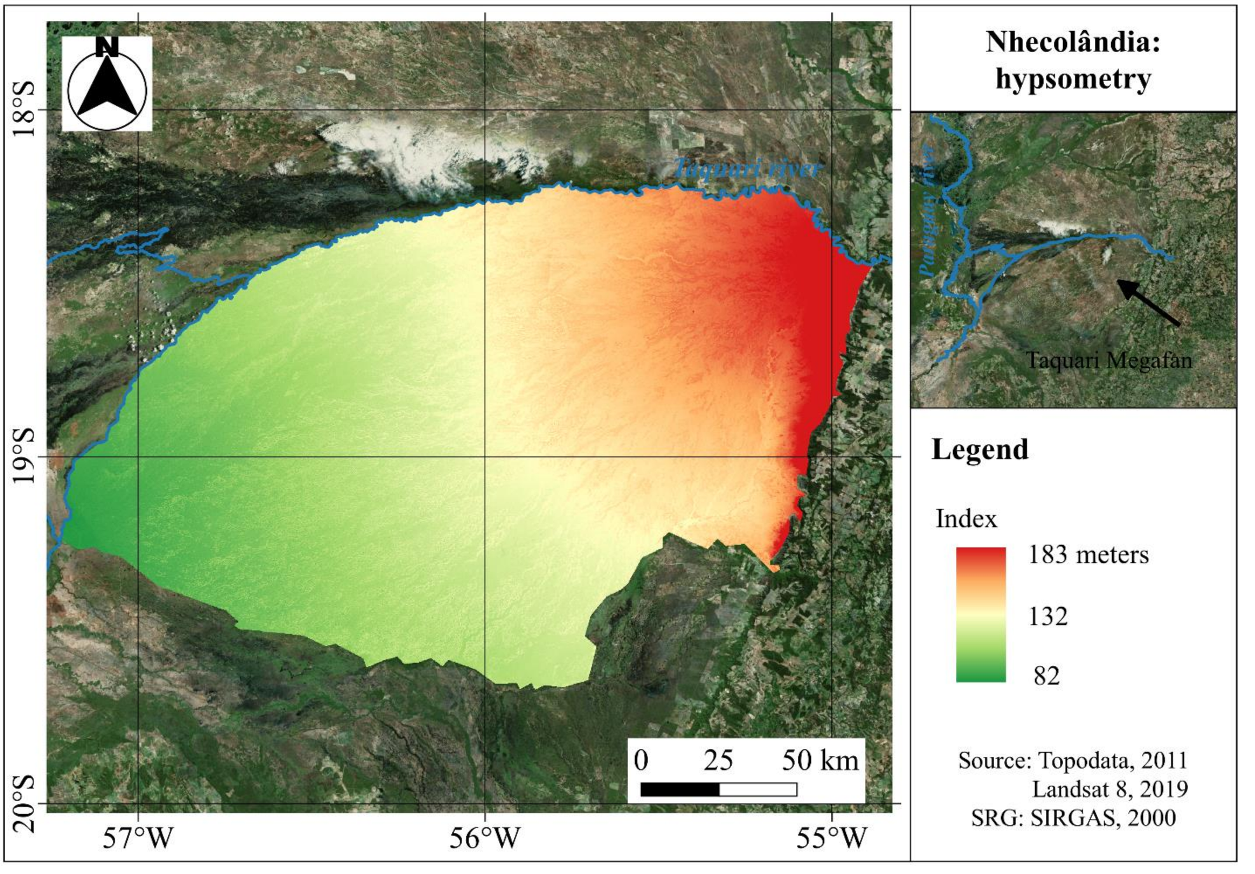
Figure 1 - Nhecolândia region in the Brazilian Pantanal



Source: SILVA; ABDON (1998); FOREST GIS (2019). Elaborated by the authors (2020).

Nhecolândia is located in the Southern portion of the alluvial megafan of the Taquari river, at low hypsometric levels, between 82 and 183 m above sea level (Figure 2). It is constituted by depositional lobes abandoned in two contrasting situations: the upper region is marked by paleosols and old drainage canals, and the lower region concentrates hundreds of small lakes (GUERREIRO et al., 2018).

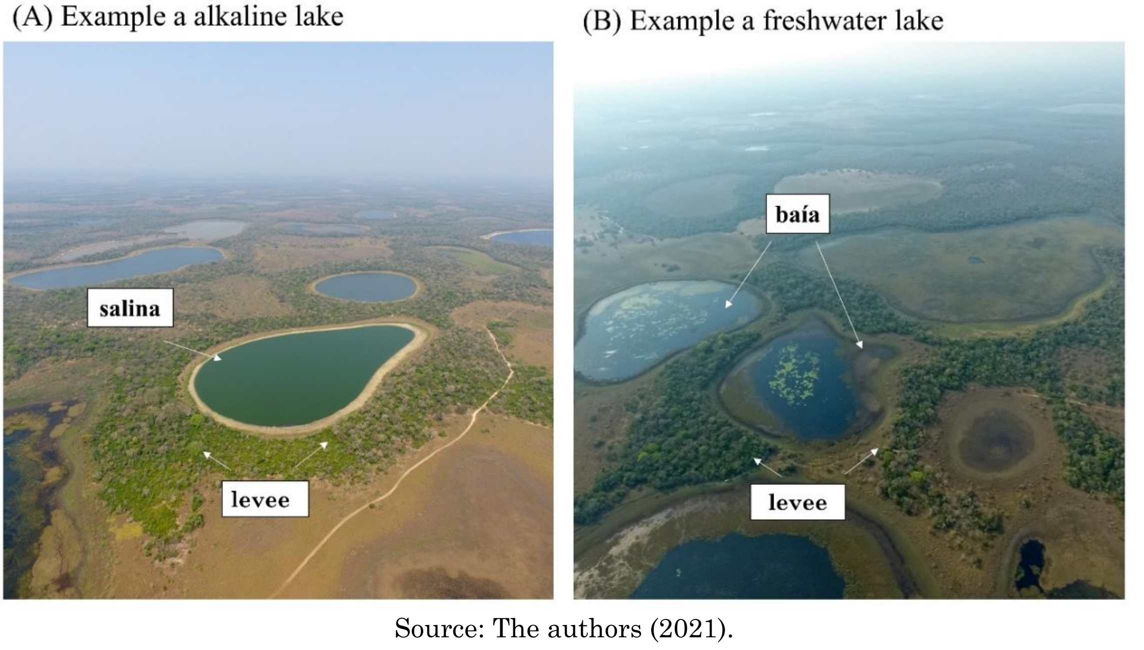
Figure 2 - Hypsometry of the Pantanal of Nhecolândia, MS, Brazil



Source: TOPODATA (2011), and USGS (2019). Elaborated by the authors (2020).

The landscapes of Nhecolândia have typical regional names, such as baías, salinas, and levees (Figure 3). Salinas are usually associated with sandy ridges (called levees), made up of alkaline waters and commonly calcium carbonate and preserved mollusk shells (ASSINE; SOARES, 2004). The pH is basic (~10), and there is high electrical conductivity (500-65,000 μS cm^{-1}). Baías, in contrast, can occur dissociated from levees in the midst of intermittent canals (ebbs and streams), which are periodically connected to the surface drainage network. They can reach depths of ~2 m, have a pH ranging from 5 to 8, low electrical conductivity (750- 2000 μS cm^{-1}), and the presence of macrophytes (GUERREIRO et al., 2018).

Figure 3 - Aerial images of landscapes in the Pantanal of Nhecolândia



Source: The authors (2021).

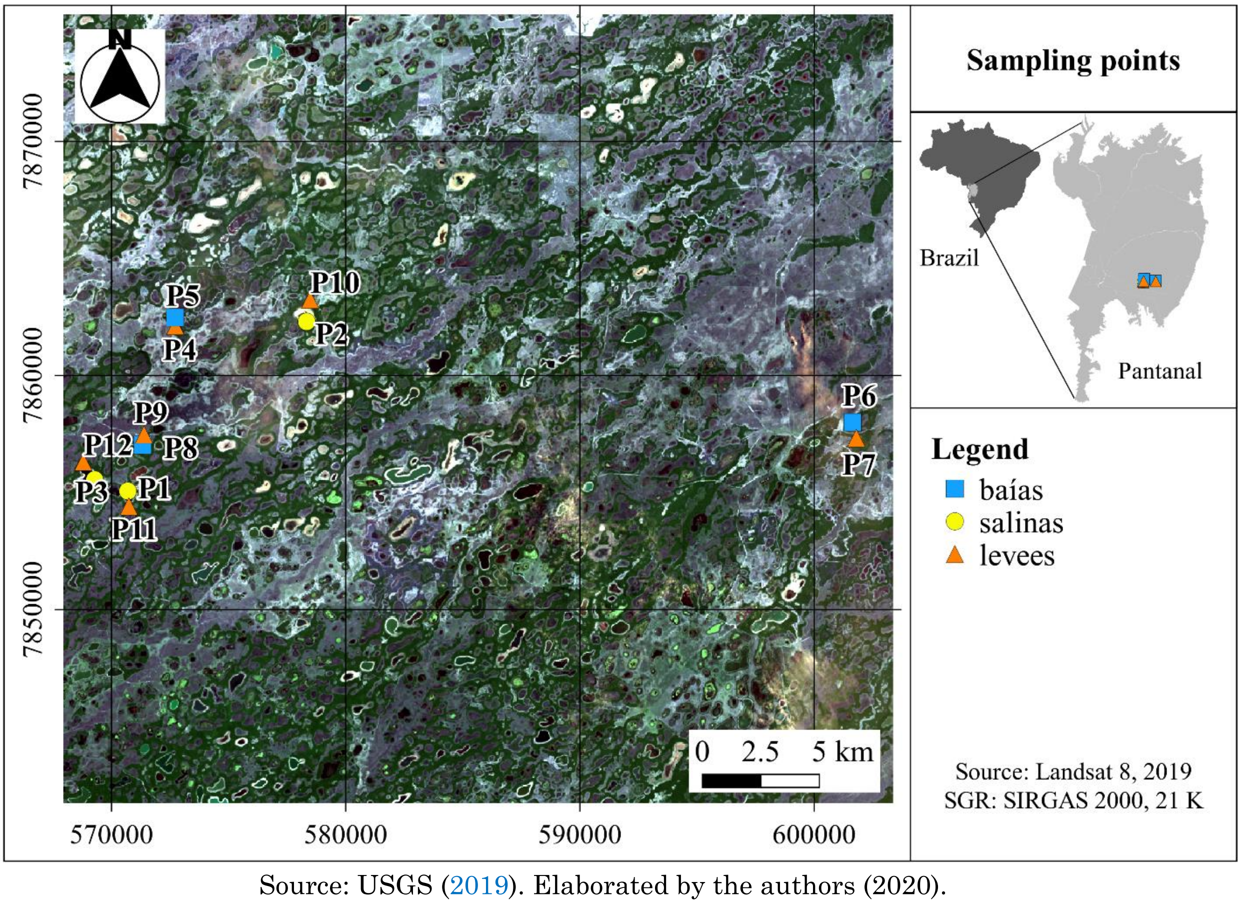
The climate of Nhecolândia fits the Aw type (KÖPPEN; GEIGER, 1928). The average annual air temperature is 25 ºC, with average minimum and maximum temperatures of 18 and 29 ºC, respectively. The rainfall regime has two well-defined periods: a rainy period (October to March), which concentrates around 80% of the total volume of rainfall, and a dry period (April to September), typically with a tropical Savannah climate. The average annual precipitation is 1100 mm. The region's evapotranspiration is greater than the precipitation, totaling an annual water deficit of 289 mm (INMET, 2019).

Nhecolândia comprises vegetation formations constituted by species of Cerrado phytophysiognomies, including floodable fields, cerrados, cerradões, and forests. The forms of vegetation are strongly influenced by the local topography and by the different levels of flooding, hence the presence of arboreal, grassland, and aquatic vegetation stratum (BAZZO et al., 2012).

Sampling Design and Soil Collections

With the images from the Landsat-8 OLI satellite, typical landscapes of the Nhecolândia wetland were selected: baías, baía-associated levees, salinas, and salina-associated levees. In the field, twelve sampling points were established (Figure 4), and soil was collected with a Dutch auger. Soil classes were differentiated according to morphological attributes (color, mottling, texture, presence of nodules and concretions, etc.) and then established representative pedons for collection. Fieldwork was carried out during the ebb period (dry season), when it is possible to prospect for samples on the extensive edges of seasonally flooded environments.

Figure 4 - Sampling points and soil collections



Source: USGS (2019). Elaborated by the authors (2020).

At each point (Figure 4), nine soil samples were collected in the 0-20 cm layer, totaling 108 simple samples, which were subsequently homogenized into 36 composite samples. The collection procedures in the 0-20 cm layer and at different points of the terrain are in line with the recommendations of the soil collection and description manual in the field, for the purposes of analytical characterization of soil attributes variation (SANTOS et al., 2015).

In the laboratory, composite soil samples were air-dried, crushed, and passed through a stainless steel sieve with a 2-mm mesh opening to obtain air-dried fine earth (ADFE). Subsequently, the samples were submitted to chemical, physical, and soil organic matter analyses.

Chemical, Physical, and Soil Organic Matter Characterization

The study determined 26 soil attributes, namely: physical (coarse sand, fine sand, silt, clay, and particle density (PD), chemical (pH H_2O, pH KCl, P, K, Na, Ca^{2+}, Mg^{2+}, Al^{3+}, H+Al, SB (sum of exchangeable bases), t (effective cation exchange capacity – CEC), T (CEC at pH 7), V% (percentage of base saturation), m% (percentage of aluminum saturation), SSI (sodium saturation index), Cu, Mn, Fe, Zn, P-remaining, and soil organic matter. The analysis methods, the International System (SI) units adopted, and the analytical precision are in accordance with the recommendations described by Teixeira et al. (2017).

Statistical Analysis

For descriptive statistics, measurements of central tendency (mean and median), position (quartiles), dispersion (standard deviation and interquartile range), and minimum and maximum values were calculated. For the Principal Components Analysis (PCA), the data were previously standardized, since the variables were in different scales. In the hypothesis test with multivariate data (PERMANOVA), the environments were evaluated using the multiple comparison functions of multivariate groups *pairwise.perm.manova* of the *RVAideMemoire* package. The significance level considered was 5%.

The analyses were performed in the software R 4.1.1 (2022), using packages FactMineR (HUSSON et al., 2020), factoextra 1.0.7 (KASSAMBARA; MUNDT, 2020), dplyr (WICKHAM et al., 2022a), ggplot2 (WICKHAM et al., 2022b), RVAideMemoire (HERVÉ, 2022), and vegan, (OKSANEN et al., 2022) and presented in tables and graphs.

RESULTS AND DISCUSSION

Principal Components Analysis (PCA)

The PCA included the set of 936 response variables (26 soil attributes x 36 composite samples). The first principal component (PC1) represented 49.9% of the total variance of the data, while the second component (PC2) accounted for 20.2%. Therefore, the first two principal components were enough to explain 70% of the total variance of the data (Figure 5). The threshold of 70% of the total explained variance is a common cutoff point for defining the number of PCs to be evaluated (JOLLIFFE; CADIMA, 2016). Therefore, this study considered the first two components.

Regarding PC1, the soil attributes that made the greatest contribution were SB, t, T, Na, Mn, clay, P, and fine sand (Figure 5). These attributes correspond to 54.1% of PC1. Therefore, it is understood that this main component mainly represents these attributes. In PC2, the attributes that contributed most clearly were MO, H+Al, pH KCl, pH H_2O, Zn, SSI, V%, and PD, whose weight of contribution added up to 70.9%.

The PCA graphical representation is presented in the variable correlation matrix and circle (Figure 5).

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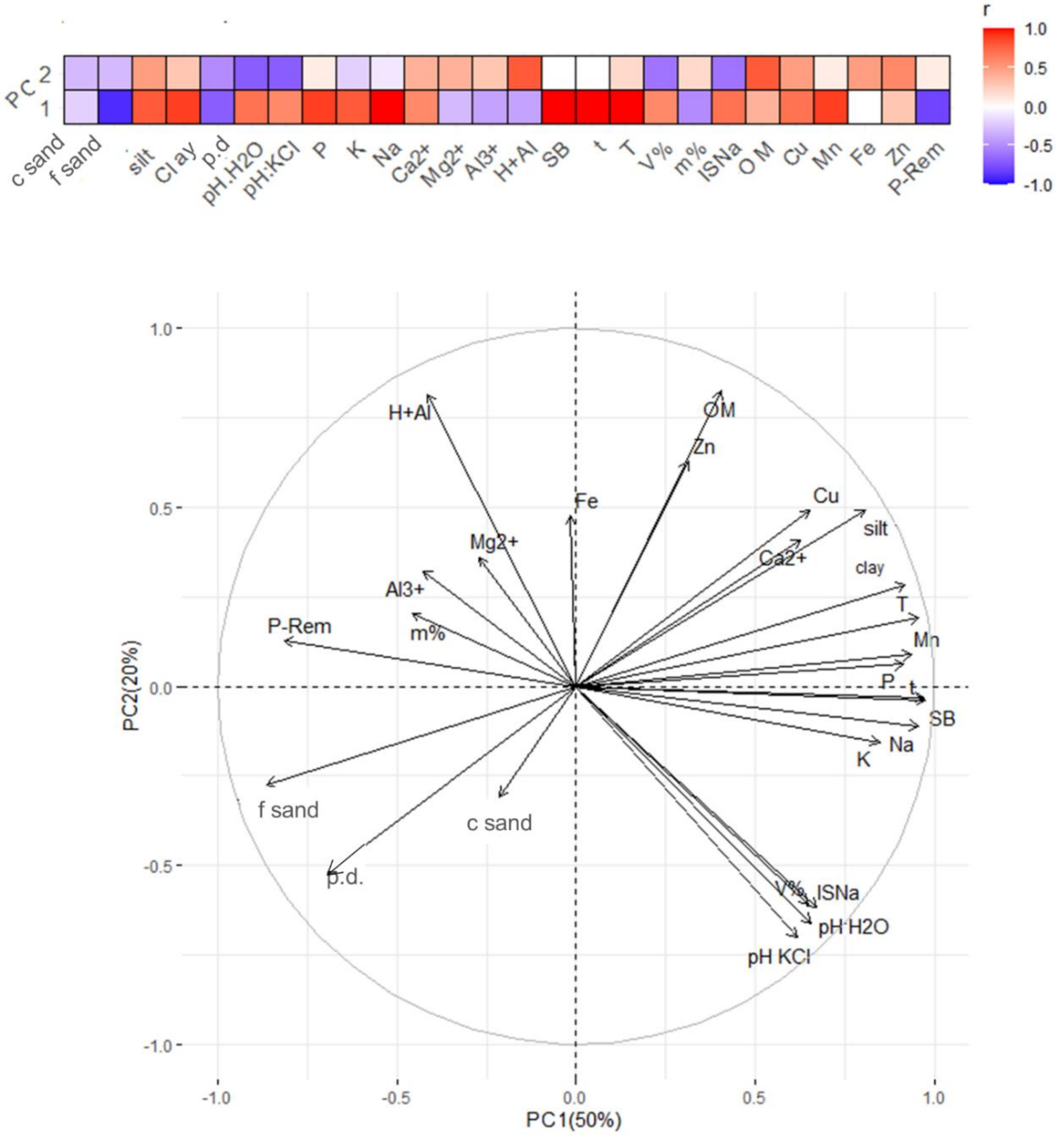
Figure 5 - Matrix and correlation circle of the principal components PC1 and PC2



Source: The authors (2022).

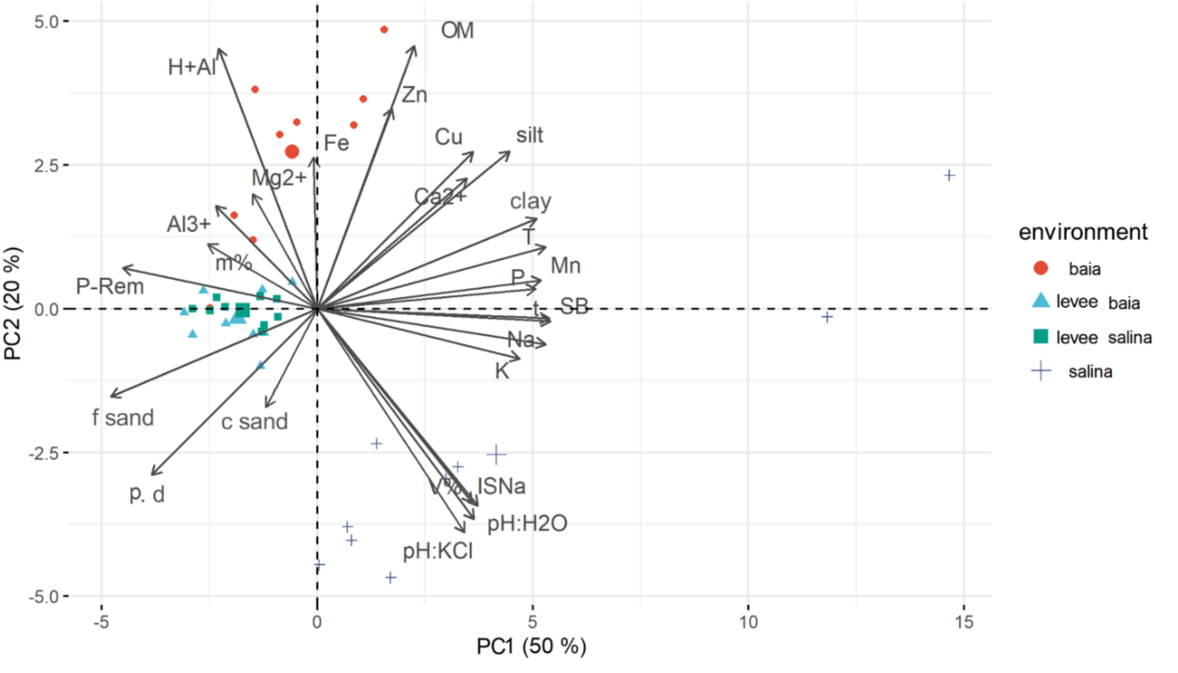
In the variable correlation with the PC1, all the variables that contributed the most (SB, t, T, Na, Mn, clay, P, and fine sand) have a very strong positive correlation with this component (r > 0.90), except fine sand, whose r is -0.86, being negatively correlated with PC1 (Figure 5). PC2, in contrast, is characterized by a positive correlation with the attributes MO, H+Al, and Zn (r 0.82, 0.81, and 0.61, respectively) and a negative correlation with pH KCl, pH H_2O, and SSI (r -0.70, -0.66, and -0.61, respectively).

The correlation circle of the response variables (Figure 5) shows that the attributes pH H_2O, pH KCl, SSI, and V% are highly correlated with each other. It appears that this group of variables is positively correlated with PC1 and oppositely with PC2. Likewise, there is an association between a wide group of variables, such as MO, Zn, K, Na, SB, P, t, T, Mn, clay, and silt. The graph also shows that H+Al has an inverse relationship with pH, V%, and SSI, and fine sand and PD have an inverse relationship with MO, Zn, Cu, Ca, silt, and clay. The variables m%, Al^{3+}, Mg^{2+}, Fe, and coarse sand, showed a low representation quality (see vector length).

The combined representation of the coordinates of the sampling points and response variables (vectors) of PC1 and PC2 is presented in a biplot graph (Figure 6).

The salinas samples are related to the highest values of SSI, pH H_2O, V%, and pH KCl. The baía environment has a positive relationship with the variables H+Al, MO, Zn, Fe, and Cu. In contrast, both levee environments presented a very similar behavior in the PCA, indicating a great similarity of environmental conditions given the evidenced overlaps. They are positively related to the attributes P-rem, sand fractions, and PD (Figure 6).

Figure 6 - Biplot graph representing PC1, PC2, and sample coordinates



Source: The authors (2022).

Permutational Multivariate Analysis of Variance (PERMANOVA)

The use of hypothesis tests with multivariate data aims to obtain inferences about the several means of soil attributes to test the equality of the response variables, which are considered common predictors of the studied landscapes. To define whether the means are statistically significant, those attributes with the greatest contribution to PC1 and PC2 were selected for analysis: SB, t, T, Na, Mn, clay, P, OM, H+Al, pH KCl, pH H_2O, Zn, SSI.

Based on the Henze-Zirkler multivariate normality test (p-value <0.001), the data do not have a multivariate normality (a requirement for performing the MANOVA), which motivated the use of PERMANOVA.

In the PERMANOVA analysis, we observed a significant difference between environments, that is, the environment is influenced by the response variables. As PERMANOVA indicated a significant effect of environments, permutation groups were compared in a Euclidean distance matrix (Table 1).

Table 1 - Multiple comparison between permutation groups in a distance matrix

	baía	baía levee	salina levee
baía levee	0.0012**	-	-
salina levee	0.0012**	0.267ns	-
salina	0.0012**	0.0012**	0.0012**

Source: The authors (2022).

Based on the comparison test, the study found a significant difference (p<0.05) between the tested groups, except between the environments “baía levee” and “salina levee”, which have statistical equality of the simultaneously evaluated soil attributes.

Analytical Results and Descriptive Statistics

The results shown in Table 2 indicate the soil attributes of baías (B), levees (C), and salinas (S).

The fine sand fraction predominates in soils, especially in levees. Regarding baías, levees, and salinas, the average fine sand content in the soil granulometric composition is, respectively, 622, 696, and 557 g kg^{-1}. Higher clay contents and with high dispersion are observed in salinas (143±144 g kg^{-1}), followed by baías (92±28 g kg^{-1}). In levee environments, the clay content is, on average, 52 g kg^{-1}. Soil granulometry indicates the occurrence of different texture classes (Figure 7). Levee environments present a lower variability of texture classes.

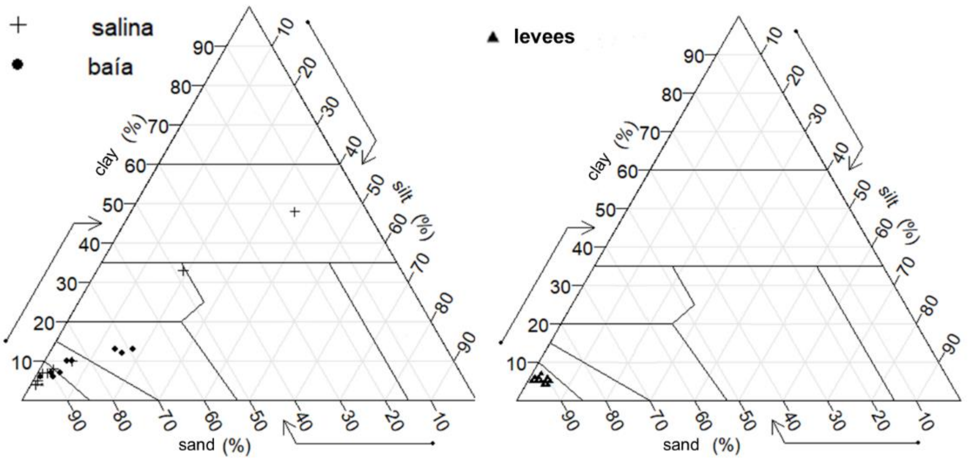
Table 2 - Results of physical, chemical, and soil organic matter analyses (arithmetic mean followed by standard deviation).

ID / Environment		Granulometry				P.d.	pH		P	Exchangeable cations				
		Coarse sand	Fine sand	Silt	Clay		H_2O	KCl	Mehlich	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}
		g kg^{-1}				kg dm^{-3}	-		mg kg^{-1}	mg kg^{-1}		cmolc kg^{-1}		
P1	S	166±11	767±11	10±1	57±16	2.61±0.04	10.2±0.0	9.2±0.2	5±0	130.13±45.44	351.77±63.46	0.4±0.1	0.0±0.0	0.0±0.0
P2	S	157±68	336±211	203±122	304±154	2.41±0.09	10.0±0.0	8.3±0.1	40±32	391.39±342.04	238.11±224.50	0.8±0.0	0.1±0.1	0.0±0.0
P3	S	346±49	569±41	19±9	66±9	2.61±0.03	8.8±1.9	7.5±2.3	18±6	410.47±146.53	832.37±106.43	0.7±0.3	0.1±0.1	0.0±.00
P5	B	175±12	703±22	46±2	76±15	2.57±0.04	5.5±0.1	4.0±0.0	1±0	32.80±3.46	6.23±1.47	0.8±0.1	0.1±0.0	0.2±0.1
P6	B	199±7	514±9	160±17	127±7	2.42±0.03	5.7±0.1	4.4±0.0	1±0	53.97±6.99	7.67±2.41	1.5±0.3	0.3±0.1	0.0±0.0
P8	B	241±13	651±25	34±22	74±17	2.54±0.04	5.1±0.5	3.9±0.2	1±0	10.87±10.01	1.10±1.56	0.4±0.2	0.0±0.0	0.3±0.1
P4	CB	192±13	712±8	52±1	44±5	2.63±0.03	5.8±0.2	4.9±0.3	5±1	38.50±9.61	0.00±0.00	1.1±0.3	0.2±0.1	0.0±0.0
P7	CB	189±20	740±23	12±8	59±2	2.61±0.03	5.6±0.2	4.0±0.1	2±0	20.77±5.05	0.00±0.00	0.1±0.0	0.1±0.0	0.3±0.1
P9	CB	244±13	661±25	41±22	54±17	2.62±0.04	5.5±0.2	4.5±0.2	7±3	26.97±7.43	0.00±0.00	0.9±0.1	0.3±0.1	0.1±0.1
P10	CS	203±34	726±35	24±13	47±4	2.61±0.01	5.2±0.3	4.4±0.5	4±1	23.27±10.20	0.00±0.00	0.7±0.5	0.2±0.1	0.2±0.1
P11	CS	195±14	726±12	23±6	56±8	2.61±0.03	5.2±0.1	4.3±0.2	9±2	23.10±3.43	0.00±0.00	0.5±0.3	0.1±0.0	0.1±0.1
P12	CS	301±84	612±94	39±9	48±2	2.64±0.03	5.7±0.1	4.7±0.1	8±2	33.93±4.13	0.00±0.00	1.0±0.2	0.3±0.0	0.0±0.0

ID / Environment		Acidity	Sortive complex				m	ISNa	microelements				P-rem	OM
		H+Al	SB	t	T	V			Cu	Mn	Fe	Zn		
		cmolc kg^{-1}	cmolc kg^{-1}			%	%		mg kg^{-1}				mg L^{-1}	g kg^{-1}
P1	S	0.0±0.0	2.3±0.2	23±0.2	2.3±0.2	100±0	0±0	67±5	0±0	13±3	7±1	0±0	40.7±3	0.3±0.1
P2	S	0.7±0.5	3.0±1.8	3.0±1.7	3.7±1.2	100±0	0±0	60±13	0±0	46±17	32±39	0±0	15.4±8	1.9±1.4
P3	S	0.5±0.8	4.4±1.8	4.4±1.8	4.9±1.3	86±19	0±0	68±4	0±0	77±26	197±148	0±0	26.4±5	0.2±0.2
P5	B	2.8±0.5	1.0±0.2	1.2±0.2	3.8±0.7	27±0	14±2	1±0	0±0	27±9	205±56	0±0	44.3±2	2.5±0.6
P6	B	2.9±0.4	1.9±0.4	1.9±0.4	4.8±0.8	40±1	0±0	1±0	0±0	39±5	248±51	1±0	43.4±3	2.4±0.4
P8	B	2.8±1.1	0.5±0.2	0.7±0.4	3.3±1.4	14±4	37±2	0±0	0±0	9±5	303±108	0±0	39.2±6	1.9±0.9
P4	CB	1.0±0.2	1.4±0.4	1.4±0.4	2.4±0.2	58±12	0±0	0±0	0±0	20±2	20±13	0±0	55.8±1	0.6±0.1
P7	CB	1.7±0.0	0.3±0.1	0.6±0.1	1.9±0.0	16±4	47±8	0±0	0±0	17±3	34±9	0±0	48.2±2	0.4±0.0
P9	CB	1.1±0.3	1.3±0.2	1.4±0.1	2.4±0.3	55±9	7±10	0±0	0±0	26±8	36±10	0±0	51.1±1	0.5±0.2
P10	CS	1.3±0.3	0.9±0.7	1.1±0.6	2.2±0.4	38±21	23±18	0±0	0±0	23±11	35±12	0±0	48.4±2	0.7±0.2
P11	CS	1.9±0.0	0.7±0.3	0.9±0.2	2.6±0.3	26±9	19±14	0±0	0±0	24±4	22±6	0±0	46.0±2	0.9±0.1
P12	CS	1.2±0.1	1.4±0.2	1.4±0.2	2.6±0.3	54±5	0±0	0±0	0±0	34±5	15±2	0±0	54.0±1	0.7±0.0

Source: The authors (2022). Legend: baía (B), baía levee (CB), salina levee (CS), and salinas (S).

Figure 7 - Texture triangles of baías, levees, and salinas

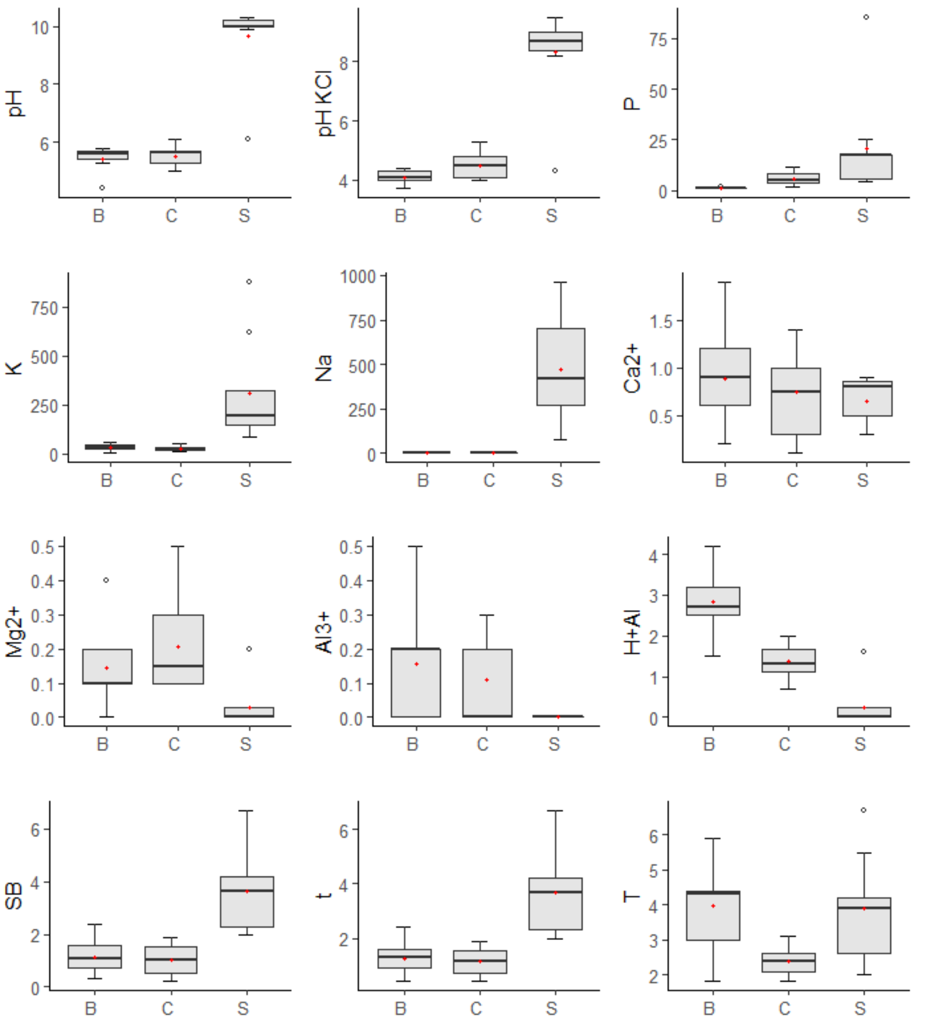


Source: Teixeira et al. (2017). Elaborated by the authors (2022).

The average PD in the levees is the highest (2.62 kg dm^{-3}) compared to that of baías and salinas (2.51 and 2.54 kg dm^{-3}, respectively).

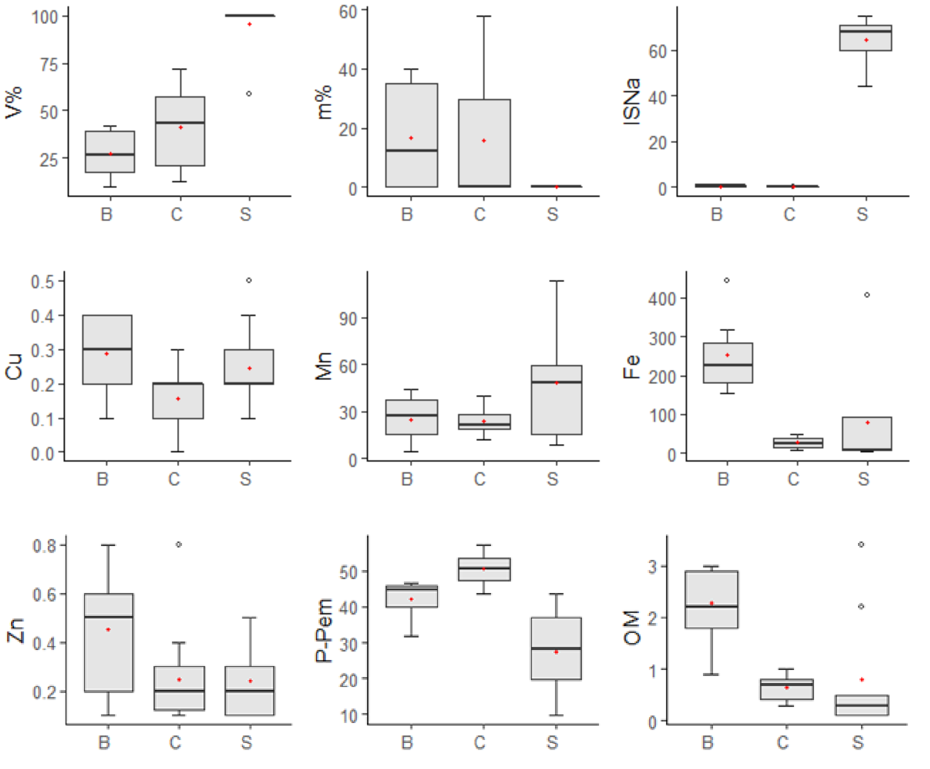
Boxplot graphs (Figures 8 and 9) compare the variability of chemical attributes and soil organic matter through measures of descriptive statistics (minimum, maximum, quartiles, IQR, median, mean, and database outliers).

Figure 8 - Boxplots of chemical soil attributes



Source: The authors (2022). Units: see table 2. Abbreviations: B = baía, C = levee, S = salinas.

Figure 9 - Boxplots of chemical attributes and organic matter of soils



Source: The authors (2022). Units: see table 2. Abbreviations: B = baía, C = levee, S = salinas.

Soil-Landscape Relationship

Baías are subject to the seasonal flood pulse of the Pantanal plains and are periodically connected to the river network through streams and ebbs. The most related soil attributes are H+Al, OM, and Fe.

Such attributes are traditionally related to the podzolization process (acid soils due to the accumulation of decomposing vegetation and consequent illuviation of OM and oxides in the spodic horizon). However, research studies (MENEZES et al., 2022; SCHIAVO et al., 2012) have been pointing out particularities (OM, pH, Al, Fe) of the Pantanal soils that diverge from the central literature on Podzols (Spodosols)—which is more related to cold bioclimatic regions with coniferous vegetation (RESENDE et al., 2014).

Comparing baías, levees, and salinas, we found that the highest OM contents were observed in baías, but at low levels (2.3±1.1 g kg^{-1}). In three profiles of a baía in Nhecolândia, Menezes et al. (2022) also determined, in surface horizons, low contents (< 10.7 g kg^{-1}) of OM, without observing the occurrence of iluvial accumulation in the typical subsurface of the podzolization process (MENEZES et al., 2022).

The condition of SOM (soil organic matter) input in the baías is attributed to anaerobiosis and deposition of organic remnants by the seasonal flood cycle, especially aquatic macrophytes (CARDOSO et al., 2016). In contrast, the low levels of OM verified are related to a higher rate of cycling of organic constituents in a dynamic tropical landscape.

SOM acts as a weak acid with a buffering action in a wide range of soil pH (SILVA; MENDONÇA, 2007). In our study, this process is related to the mean active acidity (pH H_2O 5.4±0,4) and, consequently, to the highest values observed (2.6±0.8 cmolc kg^{-1}) of potential acidity (H+Al) in the surface layer of baía soils. Also, under acidic pH, aluminum becomes more soluble, which contributes to a higher Aluminum Saturation Index (up to 40% m-value).

The H^+ activity is an indirect pH effect. It changes the solubility of the micronutrients in the soil, making them more available in a more acidic medium (SOUSA et al., 2007). This process is typical of the baía landscapes in our study, characterized by high levels of Fe (252±86 mg kg^{-1}) and, comparatively, Zn (0.5±0.2 mg kg^{-1}), even with incipient SOM.

Levee landscapes are located at slightly higher hypsometric levels than lake environments (up to ~5m). There, reduced pedogenesis predominates, as levees are not usually subject to flood cycles, and the climate has pronounced water deficits. Thus soils are poorly developed, with a sandy texture (sand fractions > 900 g kg^{-1}) and PD ranging from 2.59 to 2.66 kg dm^{-3} (Table 2), reflecting the dominant presence of quartz (specific weight of 2.65 kg dm^{-3}) in the mineralogical composition of the soil.

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The predominance of fine-grained sands, originating from source areas along the Taquari river megafan, is a suggestive process of paleoclimatic conditions in the Pleistocene due to wind deflation, with remobilization, transport, and sedimentation of fine sands (SOARES et al., 2003). With the a more humid period, new reworkings have been changing the landscape very quickly, accelerated by human action, with an increase in erosion and the input of sediments to the alluvial fan (ASSINE; SOARES, 2004).

Levee landscapes have low amounts of cations (Ca^{2+} + Mg^{2+} + K + H^{+} + Al^{3+}) in interchangeable condition (t); as well as low levels of CEC at pH 7 (T), indicating low capacity to retain cations in exchangeable form. Variations in soil attributes in these environments, such as aluminum saturation (m%), are not due to the influence of lake environments, a hypothesis verified by the PERMANOVA test (Table 1). The high P-rem averages in the levees are related to the soils' low adsorption in these landscapes, due to the low OM content and sandy texture (Table 2). Given the physical and chemical attributes of these landscapes, replacing levees with pastures favors soil erosion.

Saline-sodic soils resulting from water accumulating in canals abandoned in high topography during the Holocene are characteristic of salinas (FURQUIM et al., 2017). Salt-affected soils have characteristics that are poorly understood in many situations around the world (OLIVEIRA JUNIOR et al., 2019). The salinas were believed to have remained insulated from flooding at higher levels (GUERREIRO et al., 2018; RADAM-BRASIL, 1982). However, recent perspectives have been pointing to the salinas' degradation due to the atypical supply of fresh water. (FURQUIM et al., 2017)

Nhecolândia underwent general desalination as a result of fluvial dynamics established in humid climatic phases with the end of the Pleistocene. Thus, some salinas have been experiencing soil leaching by seasonal floods, which has modified the pedological attributes of these landscapes. They are under the influence of various pedogenetic processes: salinization, sodification, and solodization (FURQUIM et al., 2017). Our results point to the complexity of the pedogenesis of salinas' soils due to the great variability of the presented attributes, especially in relation to granulometry, pH, K, Na, H+Al, soil sorption capacity, Mn, and Fe.

In general, the studied salinas soils are alkaline (pH H_2O 9.8±0.6) and have a high base saturation (V%)—due to the high levels of (exchangeable) sodium available—and very low CEC. High levels of sodium saturation (SSI 64±9%) characterize them as sodic soils (SSI > 15%) (SANTOS et al., 2018).

Sodic soils' genesis are related to low precipitation combined with high evapotranspiration, which favors the dissolution of primary minerals with high levels of Na+. Under these conditions, there is greater dispersion of clays, which interferes with the soils' physical properties, such as filling the pore space and subsurface consolidation, disfavoring the soil base leaching, resulting in alkaline conditions (OLIVEIRA JÚNIOR et al., 2017).

Due to the high pH, Al precipitation is expected, and metallic ions such as Fe, Zn, Mn, and Cu become scarce in the exchange complex, leaving the basic cations in the soil solution in an exchangeable form (SOUSA et al., 2007). However, in the salinas in our study (P2 and P3), Fe and Mn are available despite the influence of alkaline pH, which is suggestive of an imbalance in nutrient cycling in these soils. With regard to total acidity, the P3 salina sample had a higher H+Al content, relating to the greater availability of Fe observed and lower SSI%, which indicates the occurrence of changes in the alkaline environmental patterns in these landscapes.

This study concludes that, in both areas, the fine sand fraction predominates, and the texture class of the soils varied from very sandy, medium sandy, and sandy loamy for the baías; very sandy for levees, with PD related to quartz mineralogy; and very sandy, medium sandy, clay loamy, and clayey for the salinas.

With regard to chemical attributes and organic matter, the baías stand out for their higher potential acidity (H+Al), slightly elevated OM contents, and availability of metallic ions, especially Fe. In levees, higher P-rem averages are more evident, whereas salinas' soils presented more alkaline pH values, high base saturation, and high levels of SSI. We can also infer that the soils of the Pantanal lake landscapes have specificities, probably due to the coexistence of lake systems with distinct geochemical characteristics. This is true, particularly in salinas' landscapes, which present great data variability and attributes that are not consistent with an alkaline environment.

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AUTHORS CONTRIBUTION

Diogo Costa Nascimento participated in fieldwork, carried out experiments in the laboratory, analyzed the data and contributed to the writing of the manuscript. Guilherme Resende Corrêa guided the study, participated in the fieldwork and contributed to the writing of the manuscript. Frederico dos Santos Gradella co-supervised the study, participated in fieldwork and contributed to the production of spatial information. Prímula Viana Campos co-supervised the study, participated in fieldwork, revised the main text and contributed to data analysis. Viviane Arantes Koch participated in fieldwork, performed laboratory experiments, and revised the manuscript. Bruno Nery Fernandes Vasconcelos participated in fieldwork, revised the main text and contributed to the discussion of results.