Hindawi
Applied and Environmental Soil Science
Volume 2019, Article ID 1814937, 8 pages
https://doi.org/10.1155/2019/1814937

Research Article

Spatial Variability of the Physicochemical Properties of Soils from Seasonally Flooded Forest Fragments on a Tropical Plain

Marcus Vinicius Moreira Barbosa,[1] **Taynara Augusta Fernandes**,[1] **Guilherme Benko Siqueira**,[2] **Flávia Lucila Tonani de Siqueira**,[2] **and Paula Benevides de Morais**[1]

[1]*Postgraduate Program in Biodiversity and Biotechnology, BIONORTE Network, Federal University of Tocantins, Palmas, TO, Brazil*
[2]*Soil and Utilization of Agroindustrial Waste Laboratory, Federal University of Tocantins, Palmas, TO, Brazil*

Correspondence should be addressed to Marcus Vinicius Moreira Barbosa; marcus0588@hotmail.com

Received 14 May 2019; Accepted 17 August 2019; Published 7 October 2019

Academic Editor: Claudio Cocozza

Flooded ecosystems are conditioned to seasonal floods that promote specific soil conditions, such as low oxygen, hydromorphism, and peculiar chemical reactions. These environments are dependent on flood pulses that determine specific ecological conditions. *Ipucas* are seasonally flooded discontinuous forest patches that occur exclusively in the Araguaia Plain in Central Brazil. They are located 0.40 to 1.20 m lower than the surrounding plain, which promotes an accumulation of rainwater for five to six months of the year, being entirely or partially dry during the dry season. The aim of this study was to evaluate the horizontal (centre and edge) and vertical (depths: 0–0.20 m and 0.20–0.40 m) variability of physicochemical parameters in *Ipucas* soils, attempting to establish the importance of flood pulses and the leaching of surrounding areas in soil formation and composition. Samples were collected during the dry season in three *Ipucas* of similar size and circularity using a Dutch auger. The results reveal that flood pulses promote the deposition of sediments eroded from the surrounding plain, homogenizing the characteristics of the surface soil, from the edge to the centre of the *Ipucas*. However, biogeochemical processes, also linked to temporary flooding, account for the differences between the surface and deeper soil horizons because anoxic conditions during flooding promote chemical reactions characteristic of anaerobic environments, modifying the pH and organic matter content, in addition to the gleying of soils subjected to flooding, which are then covered by sediments after the dry season. Finally, *Ipucas* soils are susceptible to anthropic changes and are dependent on seasonal flood pulses.

1. Introduction

Flooded ecosystems are formed by seasonal or permanent floods and are often characterized by soils exposed to anaerobic processes and conditions [1] as well as reactions such as ferrolysis and redox cycles [2]. In general, these soils are hydromorphic soils with peculiar physicochemical characteristics, and they are adapted morphologically and physiologically to the hydroperiod of the system and dependent on water balance, topography, and subsurface [3]. It is estimated that approximately 20% of the Brazilian territory is covered by flooded areas, most of them subject to different seasonal flood pulses, with unstable water levels [4]. Flood pulses are important events that determine the ecological conditions in these ecosystems [5]. According to Faulkner and Richardson [6], there is a predominance of anaerobic conditions induced by flood pulses and soil saturation in the soils of flooded ecosystems. Flooding promotes the isolation between soil and atmospheric oxygen, activating biological and chemical processes that modify the aerobic system from aerobic oxidation to anaerobic reduction. That is, after flooding, oxygen is rapidly consumed by microbial respiration and chemical oxidation. After the consumption of oxygen, nitrate, manganese, and nitrite are used as electrodes, ferric iron is reduced to a ferrous state, sulphate transforms to hydrogen sulphite, and CO_2 converts to methane; thus, these soils have a high potential for nutrient cycling.

In Brazil, most of the flooded ecosystems dry seasonally, unlike temperate environments, where the areas are permanently flooded, such as marshes and swamps [7]. The soils under seasonal flood conditions exhibit discontinuous changes in their properties with increasing depth [8]. In addition, relief conditions also influence soil formation and are responsible for altering soil moisture content, the intensity of erosion processes, leaching, the microclimate, and groundwater level [9]. Thus, the position occupied by the soil in a plain also influences the variability of its physicochemical attributes [10].

Ipucas (or *Impucas*) are seasonally flooded forest patches located in depressions approximately 0.40 to 1.20 m lower than the surrounding plain. The intense rainy season and topography of the plains favour the development of flood pulses and the accumulation of water within these forest fragments, promoting a seasonal alternation between aquatic (December to May) and terrestrial (June to November) phases. Particular geomorphological features promote the natural emergence of these forest islands, occurring exclusively in the middle Araguaia Plain, in the states of Tocantins and Mato Grosso [11]. Eiten [12] and Marimon et al. [13] describe the *Ipucas* as temporally flooded forests that are heterogeneously distributed as forest patches in the middle of a nonflooded Cerrado (Brazilian savannah) vegetation matrix. The vegetation physiognomy is characterized by a dense structure, typically with two vegetation strata and a predominance of the following tree species: *Calophyllum brasiliense* Cambess, *Vochysia divergens* Pohl, *Licania parvifolia* Huber, and *Sclerolobium paniculatum* Vogel [14–17]. In this regard, *Ipucas* differ from the Amazonian *campinaranas* (dryland forests on white sandy soil) that form mosaics of savannah and forest grassland formations, especially in the Negro River Basin [18].

From an ecological perspective, *Ipucas* are important elements in the regional drainage system of the plain because they retain water from the surrounding areas during the rainy season and thereby establish a connection between the various rivers, streams, and lakes [14]. As wetlands, they provide high-value ecosystem services such as maintaining high diversity and productivity [19–21] and contribute significantly to global greenhouse gas transfer processes [22, 23]. Furthermore, they may be important conservation corridors, offering shelter and food for native fauna, because they are forest formations with structural floristics and physiognomics that differ from the adjacent area [24, 25]. According to Brito et al. [15] and Marimon et al. [13], *Ipucas* occur in tension zones in the transition between the Cerrado and the Amazon forest, which makes them regions of extreme biological importance. Scientists have stated that flooded ecosystems are economically more valuable in their natural state than if drained or modified for other uses, over time [26, 27]. However, the advancement of the agricultural frontier in this region has incorporated areas adjacent to *Ipucas* into agricultural or pastoral systems, often exceeding the protection limits established by law, the goal of which is to aid in the conservation of soil and water resources [28].

Martins et al. [14] performed a characterization of the pedoenvironments in the Araguaia Plain, discovering great diversity of soil types, with a predominance of gley, nutrient-poor soils, and subsurface plinthite and varying levels of organic carbon. Eutrophic Haplic Cambisols with marked chemical richness predominate in the highest area of the plain, whereas Plinthosols and Gleysols predominate in the lower areas, which are markedly poor in nutrients and acids, even under the forest formations of *Ipucas*. In addition, Martins et al. [14] reported a recent accumulation of organic matter in *Ipucas* due to the reducing acid hydromorphic environment, unlike the surrounding soil. This makes the study of these soils of great interest for identifying the factors impacting land use changes on the plain, especially agriculture, which can affect these regionally important flooded ecosystems.

In general, soils supporting natural vegetation have some variability in their physicochemical attributes, in both horizontal and vertical gradients [29]. In the case of the *Ipucas*, which belong to a spatially heterogeneous landscape, such gradients can define natural ecological boundaries that will create diverse structures, functions, and temporal dynamics [30]. The horizontal gradient may be associated with an edge effect, which corresponds to interactions in the contact zone between forest fragments or patches and neighbouring areas [31, 32]. Edges, unlike the interior, are subject to three effects: (i) abiotic, resulting from changes in microclimatic conditions (temperature, light); (ii) direct biotic, which correspond to changes in abundance and the distribution of plant species and microorganisms due to abiotic changes; and (iii) indirect biotic, resulting from changes in the interactions among species [31, 33]. Thus, soils along edges may have different physicochemical compositions due to the factors to which they are exposed.

This study addresses the horizontal and vertical variability of soils in seasonally flooded forest patches in the middle Araguaia Plain, the *Ipucas*, evaluating important aspects regarding their formation. To accomplish this, the physicochemical parameters of soils were analysed in the interior, at the edge (horizontal variation) and at different depths (vertical variation), attempting to identify the importance of local biogeochemical processes and sediment deposition promoted by flood pulses that leach soil particles from the surrounding areas to the interior of the *Ipucas*.

2. Methodology

The studied *Ipucas* are located at the Lago Verde farm, delimited by the Urubu River, Ribeirão Lago Verde, in the municipality of Lagoa da Confusão, state of Tocantins, Brazil. The region's climate is tropical, with two well-defined seasons: rainy, from October to April, and dry, from May to September [34]. For this study, three *Ipucas* were selected, in an area of 11.06 km^2, given their proximity, similar size, and circularity index [24]. In addition, these *Ipucas* are located in a region where the adjacent areas are not yet used for agriculture or pasture and are therefore characterized as a native environment (Table 1 and Figure 1).

Table 1: Geographic location and characteristics of the *Ipucas* studied.

Identification of *Ipucas*	Geographical coordinates in UTM	Area (HA)	Distance between the edge and center (m)	Index circularity
Ip_001	22L 0641172–8797554	1.44	69.40	0.78
Ip_002	22L 0641407–8797346	1.62	64.08	0.75
Ip_003	22L 0641195–8797110	1.26	88.15	0.66

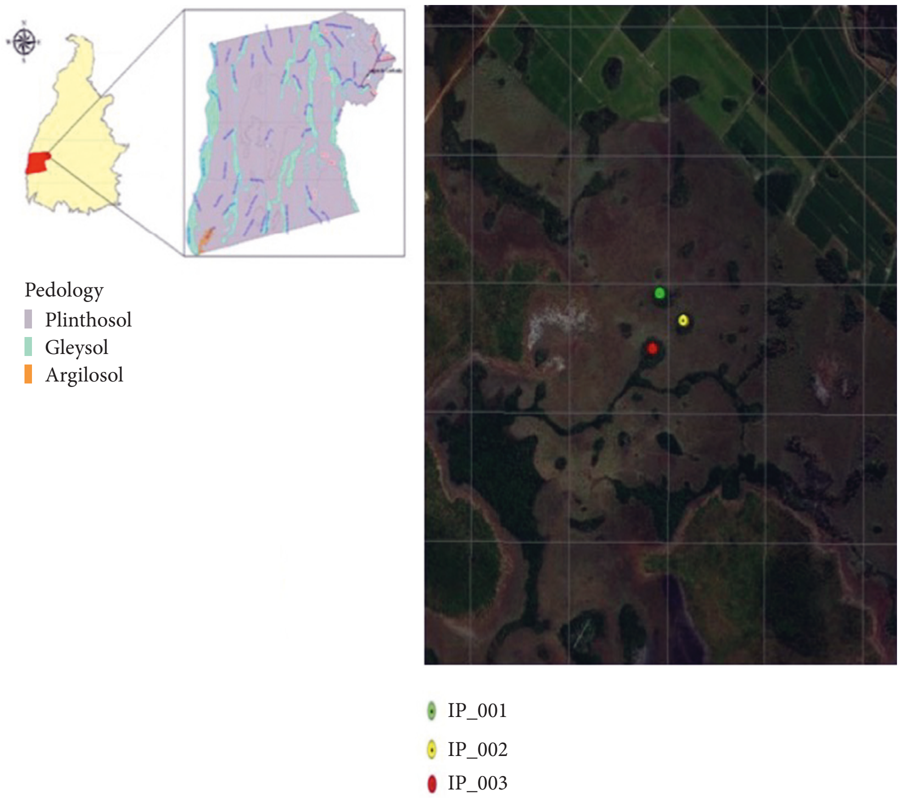

Figure 1: Map of the location of *Ipucas* studied in the municipality of Lagoa da Confusão, Tocantins, Brazil.

Soil samples were collected from these fragments in August 2015, when the *Ipucas* were not yet flooded, obtained from the centre and at the edges of the *Ipucas* and at two soil depths or layers: 0–0.20 m and 0.20–0.40 m. The sampling was performed using a Dutch auger and was composed of five subsamples obtained within a 5 m radius in each *Ipuca*. After collection, the samples were stored in plastic bags and sent to the Arasolos Soil Analysis Laboratory, which performed the physicochemical analyses. For the physical attributes, the particle size distribution was evaluated, namely, the amount of clay (g/kg), silt (g/kg), and total sand (g/kg). The following chemical parameters were analysed: organic matter (OM-g/dm^3), organic carbon ($C_{organic}$-g/dm^3), active acidity (pH-$CaCl_2$), potassium (K-mmolc/dm^3), phosphorus (P-mg/dm^3), calcium (Ca-mmolc/dm^3), magnesium (Mg-mmolc/dm^3), zinc (Zn-mg/dm^3), iron (Fe-mg/dm^3), manganese (Mn-mg/dm^3), and aluminium (Al-mmolc/dm^3). Additionally, the sum of bases (SB-mmolc/dm^3), base saturation (V-%), aluminium saturation (m-%), and cation exchange capacity (CEC-mmolc/dm^3) were estimated. For all parameters analysed, the methodology used was the one proposed by Raij et al. [35].

First, the soils were classified according to texture based on the proportions of clay, silt, and total sand of the locations and depths analysed, following the methodology proposed by EMBRAPA [36]. Then, the results were tested for normality using the Shapiro–Wilk test ($p < 0.05$); due to the lack of a normal distribution, the data were square root transformed. Next, ANOVA (analysis of variance) was calculated to identify significant differences in the parameters analysed between the locations (centre and edge) and between the depths (0–0.20 m and 0.20–0.40 m). Differences in the ANOVA were evaluated by Tukey's test ($p < 0.05$). A completely randomized design (CRD) was applied with split plots, where the plots were the locations, and the subplots were the depths analysed. The statistical analyses were performed using SISVAR software [37].

3. Results

The soils at the centre and edge of the *Ipucas* at a depth of 0–0.20 m were classified as sandy loam (Plinthosol) and at depths of 0.20–0.40 m as sandy clay loam (Gleysol) (Figure 2). The soil texture differed in the depth gradient but

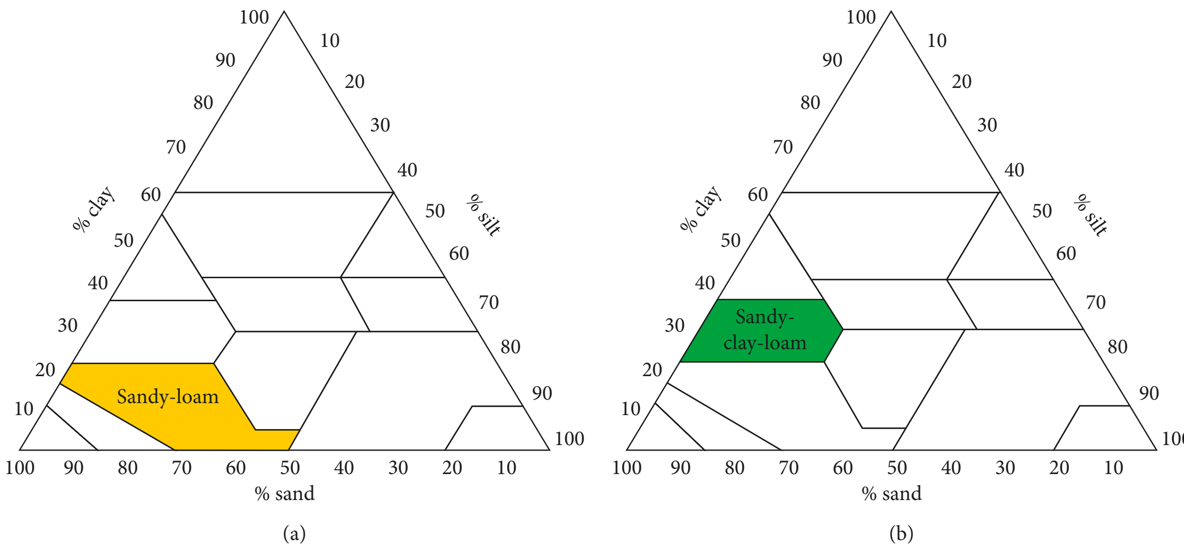

FIGURE 2: Soil textural classification. (a) Depth 0–0.20 m. (b) Depth 0.20–0.40 m.

not in the longitudinal gradient of the ecosystem (centre and edge).

The chemical attributes OM, $C_{organic}$, K, Ca, Mg, Zn, and SB did not differ statistically between the locations but were significantly different between the depths, with the more superficial layers exhibiting a higher concentration than the deeper layers. The attributes pH, P, and CEC exhibited significant differences both for depth and location. For the variable pH, the soil is more acidic in the surface layers compared with the deeper layers. Regarding the location, the soil is more acidic in the centre, compared with the edge only at a depth of 0–0.20 m, with no difference in the deeper layers. The P content was higher at the soil surface compared with the deeper layers and was higher in the centre than in the edges. The CEC value at the surface is greater than at a depth of 0.20–0.40 m and greater in the centre than in the edge only at a depth of 0–0.20 m, not differing at depths of 0.20–0.40 m.

The Fe concentration in the *Ipucas* soil was significantly different between the depths, with a higher value at 0–0.20 m compared with 0.20–0.40 m and exhibited significant differences between the centre and edge only at a depth of 0–0.20 m, with higher concentrations at the centre. For the Mn concentration, the difference between depths was observed only at the edge of the *Ipucas*, with higher values at depths of 0–0.20 m. Regarding the location, higher concentrations were found at the centre than at the edge only at a depth of 0.20–0.40 m. For Al, the values exhibited significant differences with depth only at the centre, where the surface layers had a higher concentration than the deeper layers. Regarding the location, significantly higher Al concentrations were observed at the centre than at the edge. Finally, the values of V% and m% did not differ statistically according to the depths and locations studied (Table 2).

4. Discussion

Ipucas soils exhibited no significant differences between the centre and edge locations for most chemical variables and the texture analysis. It is proposed here that this homogenization is due to the occurrence of a flood pulse, which leaches the fine sediments from the highest areas of the plain to the interior of the *Ipuca*, leaving it flooded with relatively stagnant water such that the transported sediments are distributed in a homogeneous manner throughout the surface soil of the entire fragment from the edge to the centre. According to Coringa et al. [2], hydromorphic soils are subject to natural alternation of flooding and dry periods, leading to a formation that is closely related to the nature of the source material and to the deposition and sedimentation processes. Martins et al. [14] stated that variations in the proportions of silt, clay, and sand in flooded areas of the Araguaia Plain reflect sedimentological variations, not pedogenetic variations, corroborating the findings of the sandy surface soils with low horizontal variability in *Ipucas*. This homogenizing effect was potentiated by the small size and circularity of the *Ipucas*, which decrease the edge effects on soil-forming biogeochemical processes and may indicate that a disturbance in the vicinity of *Ipucas* will affect the entire fragment and not only its boundaries with the adjacent disturbed ecosystem. This indicates the high fragility of the *Ipuca* ecosystem, which is subject to deleterious effects of any disturbance throughout its entire area, decreasing the likelihood of recovery or restoration.

Vertical variability (between depths) was observed for most chemical parameters and for the soil texture, which was characterized by more clay at a depth of 0.20–0.40 m. Ramos et al. [38] and Sousa et al. [39], studying the wetlands of *veredas* (palm swamps) in the Brazilian Cerrado, also identified the highest level of clay composition as being in the soil subsurface (0.40 m), compared with the surface layers, indicating that such variability may be common in flooded environments of the Cerrado.

Although poor in nutrients, *Ipucas* soils were characterized by higher organic matter content on the surface. The difference in OM and $C_{organic}$ content present between the

Table 2: Chemical attributes of the *Ipucas* soils, within the localities and depths evaluated.

Attributes	Depth (m)	Locality		CV 1 (%)	CV 2 (%)
		Center	Edge		
MO (g/dm^3)	0–0.20 0.20–0.40	92.06 Aa 22.00 Ba	92.13 Aa 18.33 Ba	32.45	17.55
C orgânico	0–0.20 0.20–0.40	53.39 Aa 12.75 Ba	53.45 Aa 10.4 Ba	33.59	18.77
pH ($CaCl_2$)	0–0.20 0.20–0.40	3.92 Bb 4.23 Aa	4.06 Ba 4.22 Aa	3.41	1.82
K (mmolc/dm^3)	0–0.20 0.20–0.40	1.32 Aa 0.41 Ba	1.45 Aa 0.49 Ba	28.54	18.74
P (mg/dm^3)	0–0.20 0.20–0.40	7.00 Aa 3.07 Ba	5.00 Ab 2.20 Bb	12.73	14.51
Ca (mmolc/dm^3)	0–0.20 0.20–0.40	2.73 Aa 1.53 Ba	2.80 Aa 1.67 Ba	22.40	19.23
SB (mmolc/dm^3)	0–0.20 0.20–0.40	5.78 Aa 3.01 Ba	6.05 Aa 3.28 Ba	12.04	15.91
CTC (mmolc/dm^3)	0–0.20 0.20–0.40	111.59 Aa 53.01 Ba	93.78 Ab 42.69 Ba	26.01	13.60
Mg (mmolc/dm^3)	0–0.20 0.20–0.40	1.73 Aa 1.07 Ba	1.80 Aa 1.13 Ba	14.85	18.22
Zn (mg/dm^3)	0–0.20 0.20–0.40	0.25 Aa 0.15 Ba	0.25 Aa 0.17 Ba	24.20	22.87
Fe (mg/dm^3)	0–0.20 0.20–0.40	24.8 Aa 5.8 Ba	12.2 Ab 5.4 Ba	32.22	32.29
Mn (mg/dm^3)	0–0.20 0.20–0.40	1.29 Aa 1.36 Aa	1.4 Aa 0.84 Bb	24.07	19.50
Al (mmolc/dm^3)	0–0.20 0.20–0.40	17.60 Aa 12.67 Ba	11.40 Ab 8.27 Ab	40.96	18.40
V%	0–0.20 0.20–0.40	5.33 Aa 9.07 Aa	6.80 Aa 11.00 Aa	39.55	30.70
m%	0–0.20 0.20–0.40	73.19 Aa 70.00 Aa	63.32 Aa 66.39 Aa	14.94	10.97

Uppercase letters represent the significant difference in depth (0–0.20 m and 0.20–0.40 m), whereas the lowercase letters represent the significant difference in location (center and border). Means followed by the same letter did not differ statistically by Tukey's test ($p < 0.05$). The coefficient of variation (CV) 1 corresponds to the variation within the localities, and the coefficient of variation (CV) 2 shows the variation within the depths.

studied depths is expected in flooded environments due to the sediment deposition process promoted by the flooding that enriches the surface layers with leachate from adjacent ecosystems [40] and that are added to the accumulation of senescent plant matter in the previous dry season. Organic matter directly and indirectly controls various soil attributes [41] because it improves the physical conditions of the substrate, increases the soil microbiota, retains moisture, and controls the thermal range, hydraulic conductivity and density, resulting in increased soil cation exchange capacity and nutrient retention [42–46]. In addition, *Ipucas* soil is saturated with water due to flood pulses; thus, much of the nutrients may be bound to the humic fraction, which also promotes a higher CEC value, according to Ribeiro et al. [47]. The greater CEC at the surface, compared with that at a depth of 0.20–0.40 m, reflects the active decomposition processes occurring therein of both the organic matter brought by the flood pulse and the input of senescent forest plant matter. According to Graf-Rosenfellner et al. [8], the progression of the development of temporally flooded soils causes a continuous decrease in $C_{organic}$ content with depth, especially of fractions with fast and intermediate turnover. The soils of forest ecosystems of the Cerrado and Amazon biomes in northern Brazil are largely poor in mineral nutrients, making their maintenance closely dependent on biogeochemical cycles [48], which leads to the rapid turnover of carbon and other nutrients as soon as available. Thus, OM accumulated in the surface soil of *Ipucas* is a result of insoluble by-products, such as humic and fulvic acids, from the decomposition process of deposited plant material ([14, 24], Barbosa et al., unpublished data), which explains the acidity in the surface layer.

Acidity may also be evidence of the oxidation and reduction of Fe under aerobic and anaerobic conditions, common in *Ipucas,* as described by Faulkner and Richardson [6] and Warmling et al. [49]. According to these authors, ferrolysis involves soil acidification and destruction of clays under the influence of exchange reactions involving Fe in alternating cycles of oxidation (dry period) and reduction (flooding period). In other words, in the absence of oxygen, due to the saturation of the soil with water and with the reduction in organic matter, Fe oxides and hydroxides are reduced to Fe^{2+}. However, as air comes into contact with the soil in the subsequent dry period, an oxidation phase is initiated, where exchangeable Fe^{2+} is oxidized to insoluble hydroxide Fe^{3+}. Part of this process occurs without the destruction of clay, which is then preserved in the deepest soil horizons, as observed in the *Ipucas*, which exhibited a higher percentage of clay in the deepest layers. Soil pH values that are considered acidic, approximately 3.92 to 4.23 ($CaCl_2$), seem to represent the typical conditions of soils of the Araguaia Plain, which is probably due to the hydromorphism of soils in the region [14, 50, 51]. The pH exerts a strong influence on the dynamics of various metal ions, which are more mobile under conditions of low pH, especially in soils with a high degree of weathering [52]. These acidic conditions may also be related to the insoluble byproducts generated from the OM decomposition and high concentrations of Al [53], which may have promoted a decrease in the availability of other minerals such as P, Ca, Mg, and K [54, 55]. Fe and Mg are important elements in the formation of hydromorphic soils by ferrolysis [6, 49]. The higher Fe concentrations in the surface layers and in the centre may be related to leaching by rainwater [56], which brings plinthite-rich materials from the uplifted edges of the plain, composed primarily of Petric Plinthosol on a lateritic iron crust (*cangas*), as discussed by Martins et al. [14].

In addition, the studies by Martins et al. [14] and Barbosa et al. [57] demonstrated the hydromorphism of *Ipucas* Gleysols, influenced by the groundwater level near the surface and surface layers characterized by acidic OM and higher surface carbon contents. Some of the nutrients, especially P, are concentrated or bound to the humic fraction at the surface. Martins et al. [14] showed that compared with the surrounding soils of the varjão (periodically flooded land with its hummocks), *Ipucas* soils are chemically richer, with higher Ca, Mg, and P contents, although they are acidic and have low CEC levels. The levels of exchangeable Al are very high in *Ipucas* soils and are associated with organic matter at the surface.

5. Conclusion

The spatial variability of soil physical and chemical properties in natural environments is essential for understanding soil formation and evolution processes [58–60]. Thus, it is demonstrated here that the formation of *Ipucas* soils is dependent on the sediment deposition process during a flood pulse, which results in a horizontal homogenization (centre and edge) promoting a nonsignificant edge effect (i.e., horizontal leaching homogenizes the soil characteristics within the *Ipucas* forest patches). The vertical variation (between depths) identified in the chemical and structural composition of the soils is likely the result of the deposition of fine sediments due to the low velocity of the flooding water and high persistence of this water depth leading to ferrolysis reduction processes, which are responsible for the characteristic hydromorphism and discontinuity of physical and chemical properties with increasing depth. On average, during the rainy season, *Ipucas* are submerged with water depths of 1.5 m [61], which can promote a mechanical force capable of producing vertical variability in the soil. Thus, the characteristic relief forms the depressions where the hydromorphism processes derived from the seasonal flood pulses form peculiar soils, which house unique forest patches, in the Araguaia Plains. The functional cycling processes of organic matter and nutrients of *Ipucas* strongly depend on flood pulses and the input of materials from neighbouring ecosystems, reinforcing the conclusions of Martins et al. [14]. *Ipucas* soils are susceptible to anthropogenic changes that may alter the hydrological cycle and soils of the Araguaia Plain as a whole.

Data Availability

Primary data for this study and the results contained therein are available and can be made available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Marcus V. M. Barbosa was involved in the conceptualization and development of the research, as well as in data collection and writing of the manuscript. Taynara A. Fernandes provided technical support in the development of the research, data collection, and writing of the manuscript. Guilherme B. Siqueira provided technical support in data analysis and in the development and quality of the manuscript. Flávia L. T. Siqueira provided technical support in the development and quality of the manuscript. Paula B. Morais guided the conceptualization of the study in which this manuscript is inserted, its organization and data analysis, interpretation of the results, and structuring of the manuscript.

Acknowledgments

The researcher Marcus V. M. Barbosa appreciates the financial support received through a scholarship funded by the Coordination of Improvement of Higher Education Personnel-CAPES.

References

[1] P. A. Keddy, *Wetland Ecology: Principles and Conservation*, Cambridge University Press, Cambridge, UK, 2000.

[2] E. d. A. O. Coringa, E. G. Couto, X. L. Otero Perez, and P. V. Torrado, "Atributos de solos hidromórficos no Pantanal Norte Matogrossense," *Acta Amazonica*, vol. 42, no. 1, pp. 19–28, 2012.

[3] A. B. P. Carvalho and C. P. Ozório, "Avaliação sobre os banhados do Rio Grande do Sul, Brasil," *Revista de Ciências Ambientais*, vol. 2, pp. 83–95, 2007.

[4] W. J. Junk, M. T. F. Piedade, R. Lourival et al., "Definição e classificação das Áreas Úmidas (AUs) Brasileiras: base científica para uma nova política de proteção e manejo sustentável," in *Classificação e Delineamento das Áreas Úmidas Brasileiras e de seus Macrohabitats*, C. N. Cunha, M. T. F. Piedade, and W. J. Junk, Eds., pp. 13–76, INCT-INAU—EdUFMT, Cuiabá, Brazil, 1st edition, 2014.

[5] W. J. Junk, P. B. Bayley, and R. E. Sparks, "The flood pulse concept in river- floodplain systems," *Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences*, vol. 106, pp. 110–127, 1989.

[6] S. P. Faulkner and C. J. Richardson, "Physical and chemical characteristics of freshwater wetlands soils," in *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricutural*, D. A. Harmer, Ed., pp. 41–72, Lewis Publishers, Boca Raton, FL, USA, 1st edition, 1989.

[7] W. J. Junk and M. T. F. Piedade, "Áreas Úmidas (AUs) Brasileiras: avanços e conquistas recentes," *Boletim da Associação Brasileira de Limnologia*, vol. 41, no. 2, pp. 20–24, 2015.

[8] M. Graf-Rosenfellner, A. Cierjacks, B. Kleinschmit, and F. Lang, "Soil formation and its implications for stabilization of soil organic matter in the riparian zone," *CATENA*, vol. 139, pp. 9–18, 2016.

[9] R. B. Daniels and R. D. Hammer, *Soil Geomorphology*, Jonh Willey, New York, NY, USA, 1992.

[10] D. W. Franzen, T. Nanna, and W. A. Norvell, "A survey of soil attributes in North Dakota by landscape position," *Agronomy Journal*, vol. 98, no. 4, pp. 1015–1022, 2006.

[11] G. Irion, G. M. Nunes, C. Nunes-da-Cunha et al., "Araguaia river floodplain: size, age, and mineral composition of a large tropical savanna wetland," *Wetlands*, vol. 36, no. 5, pp. 945–956, 2016.

[12] G. Eiten, "Vegetation near Santa Teresinha, NE Mato Grosso," *Acta Amazonica*, vol. 15, no. 3-4, pp. 275–302, 1985.

[13] B. S. Marimon, B. H. Marimon-Junior, H. S. Lima et al., "Pantanal do araguaia-ambiente e povo: guia de ecoturismo," *Unemat: Cáceres*, 2008.

[14] A. K. E. Martins, C. E. G. R. Schaefer, E. Silva, V. P. Soares, G. R. Corrêa, and B. A. F. D. Mendonça, "Relações solo-geoambiente em áreas de ocorrências de ipucas na planície do médio araguaia—estado de tocantins," *Revista Árvore*, vol. 30, no. 2, pp. 297–310, 2006.

[15] E. R. Brito, S. V. Martins, A. T. d. Oliveira-Filho, E. Silva, and A. F. d. Silva, "Estrutura fitossociológica de um fragmento natural de floresta inundável em área de campo sujo, lagoa da confusão, tocantins," *Acta Amazonica*, vol. 38, no. 3, pp. 379–386, 2008.

[16] R. F. Haidar, R. R. Dias, and J. R. R. Pinto, "Projeto de desenvolvimento regional sustentável," in *Secretaria de Planejamento do Estado do Tocantins (Org), Mapeamento das Regiões Fitoecológicas e Inventário Florestal do Estado do Tocantins: Regiões Fitoecológicas da Faixa Norte*, vol. I, pp. 84-85, Seplan/DZE, Palmas, TO, Brazil, 2013.

[17] B. M. Flores, M. Holmgren, C. Xu et al., "Floodplains as an Achilles' heel of Amazonian forest resilience," *Proceedings of the National Academy of Sciences*, vol. 114, no. 17, pp. 4442–4446, 2017.

[18] G. G. Vale, "O efeito do solo, inundação e topografia sobre as campinaranas inundáveis na Amazônia," in *Dissertação de Mestrado do Programa de Pós- Graduação em Cîencias de Florestas Tropicais*, p. 78, do Instituto de Pesquisas da Amazônia—INPA, Manaus, Brazil, 2012.

[19] C. A. Hickman, "Forested-wetland trends in the United States: an economic perspective," *Forest Ecology and Management*, vol. 33-34, pp. 227–238, 1990.

[20] J. H. Janse, A. A. van Dam, E. M. A. Hes et al., "Towards a global model for wetlands ecosystem services," *Current Opinion in Environmental Sustainability*, vol. 36, pp. 11–19, 2019.

[21] K. Rinke, P. S. Keller, X. Kong et al., "Ecosystem services from inland waters and their aquatic ecosystems," in *Atlas of Ecosystem Services*, M. Schröter, A. Bonn, S. Klotz, R. Seppelt, and C. Baessler, Eds., Springer, Cham, Switzerland, pp. 191–195, 2019.

[22] K. C. Ewel, "Ecoystem experiments in wetlands," in *Ecosystem Experiments*, H. A. Mooney, Ed., pp. 181–191, John Wiley & Sons, Chichester, UK, 1991.

[23] C. Craft, J. Vymazal, and L. Kröpfelová, "Carbon sequestration and nutrient accumulation in floodplain and depressional wetlands," *Ecological Engineering*, vol. 114, pp. 137–145, 2018.

[24] I. C. D. M. Martins, V. P. Soares, E. Silva, and R. S. Brites, "Diagnóstico ambiental no contexto da paisagem de fragmentos florestais naturais "ipucas" no município de lagoa da confusão, Tocantins," *Revista Árvore*, vol. 26, no. 3, pp. 299–309, 2002.

[25] S. V. Martins, E. R. Brito, A. T. D. Oliveira Filho, A. F. D. Silva, and E. Silva, "Floristic composition of two wetland forests in araguaian plain, state of Tocantins, Brazil, and comparison with other areas," *Revista Árvore*, vol. 32, no. 1, pp. 129–141, 2008.

[26] E. P. Odum and F. O. Sarmiento, *Ecologı́a: el Puente Entre Ciencia y Sociedade*, Mc Graw-Hill Interamericana, Mexico City, México, 1998.

[27] A. E. Sutton-Grier and P. A. Sandifer, "Conservation of wetlands and other coastal ecosystems: a commentary on their value to protect biodiversity, reduce disaster impacts, and promote human health and well-being," *Wetlands*, pp. 1–8, 2018.

[28] H. C. Delalibera, P. H. Weirich Neto, A. R. C. Lopes, and C. H. Rocha, "Alocação de reserva legal em propriedades rurais: do cartesiano ao holístico," *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 12, no. 3, pp. 286–292, 2008.

[29] Z. F. Montezano, E. J. Corazza, and T. Muraoka, "Variabilidade espacial da fertilidade do solo em área cultivada e manejada homogeneamente," *Revista Brasileira de Ciência do Solo*, vol. 30, no. 5, pp. 839–847, 2006.

[30] D. L. Strayer, R. E. Beighley, L. C. Thompson et al., "Effects of land cover on stream ecosystems: roles of empirical models and scaling issues," *Ecosystems*, vol. 6, no. 5, pp. 407–423, 2003.

[31] C. Murcia, "Edge effects in fragmented forests: implications for conservation," *Trends in Ecology & Evolution*, vol. 10, no. 2, pp. 58–62, 1995.

[32] K. A. Harper, S. E. Macdonald, P. J. Burton et al., "Edge influence on forest structure and composition in fragmented landscapes," *Conservation Biology*, vol. 19, no. 3, pp. 768–782, 2005.

[33] M. L. Moreno, M. L. Bernaschini, N. Pérez-Harguindeguy, and G. Valladares, "Area and edge effects on leaf-litter decomposition in a fragmented subtropical dry forest," *Acta Oecologica*, vol. 60, pp. 26–29, 2014.

[34] J. Ribeiro, G. R. Colli, R. Batista, and A. Soares, "Landscape and local correlates with anuran taxonomic, functional and phylogenetic diversity in rice crops," *Landscape Ecology*, vol. 32, no. 8, pp. 1599–1612, 2017.

[35] B. V. Raij, J. C. Andrade, H. Cantarella et al., *Análise Química Para Avaliação da Fertilidade de Solos Tropicais*, Instituto Agronômico, Campinas, Brazil, 2001.

[36] Empresa Brasileira de Pesquisa Agropecuária—EMBRAPA and Centro Nacional de Pesquisa de Solos, *Sistema Brasileiro de Classificação de Solos*, Embrapa Solos, Rio de Janeiro, Brazil, 2nd edition, 2006.

[37] D. F. Ferreira, "Sisvar: a guide for its bootstrap procedures in multiple comparisons," *Ciência e Agrotecnologia*, vol. 38, no. 2, pp. 109–112, 2014.

[38] M. V. V. Ramos, N. Curi, P. E. F. d. Motta, A. C. T. Vitorino, M. M. Ferreira, and M. L. N. Silva, "Veredas do triângulo mineiro: solos, água e uso," *Ciência e Agrotecnologia*, vol. 30, no. 2, pp. 283–293, 2006.

[39] R. F. d. Sousa, J. L. d. Nascimento, E. P. Fernandes, W. M. Leandro, and A. B. d. Campos, "Matéria orgânica e textura do solo em veredas conservadas e antropizadas no bioma Cerrado," *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 15, no. 8, pp. 861–866, 2011.

[40] J. M. Mello, E. G. Couto, R. S. S. Amorim, L. A. Chig, M. S. Johnson, and F. A. Lobo, "Dinâmica dos atributos físico-químicos e variação sazonal dos estoques de carbono no solo em diferentes fitofisionomias do pantanal Norte Mato-Grossense," *Revista Árvore*, vol. 39, no. 2, pp. 325–336, 2015.

[41] E. T. Viana, M. A. Batista, C. A. Tormena, A. C. S. d. Costa, and T. T. Inoue, "Atributos físicos e carbono orgânico em latossolo vermelho sob diferentes sistemas de uso e manejo," *Revista Brasileira de Ciência do Solo*, vol. 35, no. 6, pp. 2105–2114, 2011.

[42] M. N. Ciotta, C. Bayer, S. M. V. Fontoura et al., "Matéria orgânica e aumento da capacidade de troca de cátions em solo com argila de atividade baixa sob plantio direto," *Ciência Rural*, vol. 33, no. 6, pp. 1161–1164, 2002.

[43] B. L. M. Leroy, H. M. S. K. Herath, S. Sleutel et al., "The quality of exogenous organic matter: short-term effects on soil physical properties and soil organic matter fractions," *Soil Use and Management*, vol. 24, no. 2, pp. 139–147, 2008.

[44] J. P. S. Silva, C. W. A. Nascimento, D. J. Silva et al., "Alterações na fertilidade dos solos e teores foliares de nutrientes em cultivos de mangueira no Vale do São Francisco," *Brazilian Journal of Agricultural Sciences*, vol. 9, no. 1, pp. 42–48, 2014.

[45] S. S. Berilli, A. P. C. G. Berili, M. C. T. Leite et al., "Uso de resíduos na agricultura," in *Agronomia: Colhendo as safras do conhecimento*, C. F. Nicoli, C. Monhol, E. Marques-Junior et al., Eds., vol. 1pp. 10–38, CAUFES, Alegre, Brazil, 1st edition, 2017.

[46] R. A. Sales, R. A. Santos, W. Z. Quartezani et al., ""Influence of different sources of organic matter on physiological components of leaves of the species Schinus terebinthifolius Raddi. (Anacardiaceae)," *Revista Scientia Agraria*, vol. 19, no. 1, pp. 132–141, 2018.

[47] A. C. Ribeiro, P. T. G. Guimaraes, and V. H. Alvarez, *Recomendação para o uso de corretivos e fertilizantes em Minas Gerais: aAproximação*, Comissão de Fertilidade do Solo do Estado de Minas Gerais, Viçosa, MG, Brazil, 1999.

[48] G. L. Selle, "Ciclagem de nutrientes em ecossistemas florestais," *Bioscience Journal, Uberlândia*, vol. 23, no. 4, pp. 29–39, 2007.

[49] M. T. Warmling, J. A. Albuquerque, J. A. d. Almeida, and M. I. Warmling, "Characteristics of soils in highland wetlands as a subsidy to identifying and setting their limits," *Revista Brasileira de Ciência do Solo*, vol. 41, Article ID e0150407, 2017.

[50] Companhia de Desenvolvimento do Estado do Tocantins—CODETINS, *Estudo de Impacto Ambiental EIARIMA, "Projeto Javaés: sub-projeto Lagoa*, Companhia de Desenvolvimento do Estado do Tocantins—CODETINS, Palmas, TO, Brazil, 1996.

[51] S. A. ONA, "Engenharia, comércio e industria," *Projeto Rio Formoso: suplementação dos Recursos Hídricos*, vol. 1, p. 219, 2001.

[52] J. S. Rieuwerts, M. R. Ashnore, M. E. Farago, and I. Thornton, "The influence of soil characteristics on the extractability of Cd, Pb and Zn in upland and moorland soils," *Science of the Total Environment*, vol. 366, no. 2-3, pp. 864–875, 2006.

[53] N. M. G. Fernandes, Y. P. Ginoris, R. H. T. Rios, and C. C. S. Brandão, "Influência do pH de coagulação e da dose de sulfato de alumínio na remoção de oocistos de cryptosporidium por filtração direta descendente," *Engenharia Sanitaria e Ambiental*, vol. 15, no. 4, pp. 375–384, 2010.

[54] E. Malavolta, *Elementos de Nutrição Mineral de Plantas*, Editora Agronômica Ceres Ltda, São Paulo, Brazil, 1980.

[55] P. S. B. Miguel, F. T. Gomes, W. S. D. Rocha, C. E. Martins, C. A. de Carvalho, and A. V. de Oliveira, "Efeitos tóxicos do alumínio no crescimento das plantas: mecanismos de tolerância, sintomas, efeitos fisiológicos, bioquímicos e controles genéticos," *CES Revista*, vol. 24, pp. 13–30, 2010.

[56] M. C. C. Campos, "Atributos dos solos e riscos de lixiviação de metais pesados em solos tropicais," *Ambiência Guarapuava, Paraná*, vol. 6, no. 3, pp. 547–565, 2010.

[57] D. C. d. F. Barbosa, B. S. Marimon, E. Lenza, B. H. Marimon Junior, E. A. d. Oliveira, and L. Maracahipes, "Estrutura da vegetação lenhosa em dois fragmentos naturais de florestas inundáveis (impucas) no Parque Estadual do Araguaia, Mato Grosso," *Revista Árvore*, vol. 35, no. 3, pp. 457–471, 2011.

[58] I. A. D. Oliveira, M. C. C. Campos, M. D. R. Soares, R. E. D. Aquino, J. Marques Júnior, and E. P. D. Nascimento, "Variabilidade espacial de atributos físicos em um cambissolo háplico, sob diferentes usos na região sul do Amazonas," *Revista Brasileira de Ciência do Solo*, vol. 37, no. 4, pp. 1103–1112, 2013.

[59] I. A. d. Oliveira, J. Marques Junior, M. C. C. Campos et al., "Variabilidade espacial e densidade amostral da Suscetibilidade magnética e dos atributos de argissolos da região de Manicoré, AM," *Revista Brasileira de Ciência do Solo*, vol. 39, no. 3, pp. 668–681, 2015.

[60] R. E. d. Aquino, M. C. C. Campos, J. Marques Junior, I. A. d. Oliveira, D. D. B. Teixeira, and J. M. d. Cunha, "Use of scaled semivariograms in the planning sample of soil physical properties in southern Amazonas, Brazil," *Revista Brasileira de Ciência do Solo*, vol. 39, no. 1, pp. 21–30, 2015.

[61] H. d. J. Silva, Universidade Federal do Tocantins, M. V. M. Barbosa et al., "Estudos sazonais de aspectos limnólogicos de um fragmento florestal inundado na Planície do Araguaia, Tocantins, Brasil," *Journal of Bioenergy and Food Science*, vol. 2, no. 4, pp. 239–248, 2015.