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Soil properties changing and carbon losses by anthropic drainage in savanna palm swamp (vereda), central Brazil

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ABSTRACT: In the Cerrado, the palm swamps (*veredas*) are characterized by being humid and stable environments that lead to the formation of Histosols (*Organossolos*). and soils with surface horizons of organic constitution, which are fragile and sensitive to anthropic action. This study aimed to evaluate the impact of anthropization (recurrent forest fires and livestock farming) on the chemical, physical and morphological properties of soils in two palm swamps in the Environmental Preservation Area (EPA) of Pandeiros River, Minas Gerais, namely: Água Doce, in preserved condition, and Taboa, in anthropized condition. Four soil profiles were morphologically described, two profiles in each palm swamp, with subsequent chemical and physical analyses, calculations of organic carbon stock and identification of the origin of organic matter. The results were analyzed using descriptive statistics and Pearson's correlation coefficient. Soil morphological properties were influenced by vegetation cover, drainage and anthropization conditions. As for the physical and chemical properties, adequate values were observed in the preserved palm swamp, including lower bulk density values and higher cation contents. Anthropic actions in the anthropized palm swamp caused degradation of soils, revealed by subsidence, reduction in organic carbon content, increase in bulk density and decrease in fertility. Changes promoted in the soils of the palm swamps compromise ecosystem services, indicating that actions at either local or governmental level should be stimulated for the preservation and conservation of these environments.

Keywords: organic matter, conservation unit, organic soils, Cerrado, Pandeiros River.

INTRODUCTION

Environmental Preservation Area (EPA) of the Pandeiros River has as main function to protect the Pandeiros River Basin, as the river has been subjected in recent decades to intense siltation, which is directly linked to anthropic actions: deforestation, forest fires, agriculture and livestock farming (Nunes et al., 2009).

Within the diversity of environments that compose the Pandeiros River EPA, the palm swamps are humid and stable environments that keep the water table high, ensuring water availability for vegetation and the main watercourses, even in dry seasons in the Cerrado (Antunes and Caminhas, 2020). Palm swamp makes up the phytophysiognomies of the Cerrado biome. Which, is identified by the presence of endemic plant species such as Mauritia flexuosa and Maurittiela armata (Augustin et al., 2009).

Carbon storage (carbon stock in the soil) and regulation and availability of water are environmental services provided by the palm swamps (Tonks et al., 2017). They also play an important social and economic role, depending on the supply of food resources. Other roles played by the palm swamps are climate regulation and biodiversity maintenance (Brasil et al., 2021), besides being important archives of paleoenvironmental and paleoclimatic changes (Horák-Terra et al., 2022a). Despite their multiple functions, the palm swamps have been affected by various activities related to the anthropization of vegetation cover and soil, as well as temperature increase in these environments (Brasil et al., 2021; Horák-Terra et al., 2022b).

Anthropic actions may favor fires in the palm swamp areas, which are less frequent compared to those in Cerrado areas, but with the same destructive potential (Maillard et al., 2009). These authors observed that unlike Cerrado vegetation, plant formations in the palm swamp do not have mechanisms of protection against fire, and this impact can permanently compromise the regeneration of vegetation.

For Veloso et al. (2018), factors such as the replacement of typical vegetation, anthropic drainage of the environment, and livestock farming on the edges and with access to the internal environment are some of the prerogatives contrary to the legislation in force (Law No. 12,651, of May 25, 2012) that should ensure the preservation of the palm swamp environments. It is possible to observe with some frequency changes in the soil caused by inadequate use of livestock farming, opening of roads and other anthropic actions, generating serious environmental problems in palm swamp areas located in the North (Antunes and Caminhas, 2020) and Northwest (Horák-Terra et al., 2022b) of Minas Gerais.

In the palm swamps, due to the specific conditions of relief, drainage and vegetation cover, the accumulation of organic matter in the areas of depression, within the drainage channels, is favored, leading to the formation of soils that have histic H horizon, sometimes with the occurrence of Histosols (*Organossolos Háplicos*) (Santos et al., 2018). On a global scale, the palm swamp can be considered a type of peatland (Maillard et al., 2009; Sales et al., 2020; Tonks et al., 2017) and, more specifically, treated as a swamp (National Wetlands Working Group, 1988).

Organic soils or soil with organic horizons are fragile when subjected to anthropic actions. Studies such as Horák-Terra et al. (2022b), in which the authors evaluated the effects of drainage in a palm swamp environment of an agricultural area of Central Brazil, demonstrate that the anthropization process contributed to the decline in carbon stock (~14 kg m^{-2}); in addition, impacts on other ecological functions were also observed, such as the soil's ability to retain water.

On the other hand, Sales et al. (2020) studied litterfall dynamics and carbon (C) and nitrogen (N) stocks in areas of palm swamps with different degrees of anthropization and concluded that their dynamics in the Cerrado around the palm swamps were affected by climatic conditions than by land-use and that litterfall decomposition was more accelerated in areas with a lower degree of anthropization than in degraded areas. The authors suggest that anthropic interventions in the areas where there was management with the addition of organic matter increased soil C and N stocks in the palm swamp.

The hypothesis of this study is that the anthropic action (forest fires and intense agricultural activities and/or the presence of domestic animals without stocking control) leads to the modification of soils in palm swamps and that this degradation occurs differently according to the drainage condition and the type of vegetation cover. This study aimed to evaluate the modification provided by anthropization (recurrent forest fires and livestock farming) on the chemical, physical and morphological properties of the soils of palm swamps in EPA of the Pandeiros River, MG, Brazil.

MATERIALS AND METHODS

Study area

The conservation unit Environmental Preservation Area (EPA) of the Pandeiros River, was created in 1995 by State Law No. 11.901 (IEF, 2022), with the objective of combining nature conservation with the use of water, and protecting biodiversity, palm swamps (veredas), marginal lagoons, swamps and tributary of the Pandeiros River, which integrates the São Francisco river basin. The area of the conservation unit is 396,060.407 hectares covering the entire Pandeiros River basin (IEF, 2022).

The study was conducted in two palm swamps within the Environmental Preservation Area (EPA) of the Pandeiros River, called Água Doce (508845.99 and 8316866.39 UTM coordinates, 648 m altitude) and Taboa (507087.22 and 8314503.10 UTM coordinates, 629 m altitude), both in the municipality of Bonito de Minas, northern region of the state of Minas Gerais, Brazil (Figure 1). The Água Doce palm swamp (Preserved) is in a preserved condition, while the Taboa palm swamp (Anthropized) is in an anthropized condition. In this study, anthropic environments are understood as areas of palm swamps that had their vegetation cover removed by recurrent anthropic forest fires and livestock farming.

Pandeiros River EPA is within a geological context of Proterozoic age that composes the São Francisco Craton, located in the sandy rocks of the Upper Cretaceous of the Urucuia Group (Oliveira, 2013). Soils of the Pandeiros River EPA are sandy, chemically poor and have high acidity (Bethonico, 2009; Nunes et al., 2009). As for the palm swamps present in the Pandeiros River EPA, these are classified according to Ferreira (2006) as Tabular Surface Palm Swamp - palm swamps that develop in plateau areas, originated from the extravasation of surface aquifers. These are usually the oldest palm swamps.

The climate of the region is savanna - Aw, according to Köppen's classification system, with dry winters between the months of April and September and rains concentrated in the months from October to March (rainy season of the region). The average annual rainfall is 1,057.4 mm and the average annual temperature is 25.5 °C (Alvares et al., 2013).

In the Pandeiros River EPA, the original and predominant vegetation is the Cerrado, with phytophysiognomies ranging from Thin Cerrado, Typical Cerrado, Dense Cerrado and Grassland (Bethonico, 2009; IEF, 2022). Also, deciduous and semideciduous forest (*Anadenanthera colubrina* (Vell.) Brenan, *Astronium fraxinifolium* Schott ex Spreng, *Dilodendron bipinnatum* Radlk, and *Myracrodruon urundeuva* Allemão) and palm trees (*Mauritia flexuosa* L. and *Mauritiella armata* (Mart.) Burret) are frequent in the area, which leads to the formation of riparian vegetation of mixed floristic constitution (Bethonico, 2009; Nunes et al., 2009).

Soil profiles and samples collection

After the recognition of the area by satellite images (Google Earth) and *in loco*, two soil pits were opened in September 2019 (dry season) in each palm swamp for analysis of soil profiles and collection of samples, P1 and P2 in the preserved palm swamp and P3 and P4 in the Anthropized palm swamp (Figure 2). We selected representative areas in each environment where trenches were open for soil description and collection. The profiles are under different conditions of relief, drainage and vegetation cover. Profiles P1 and P3 are located in an edge environment of the palm swamp with 3 % slope and in a poorly drained environment. Profiles P2 and P4 are located in an internal environment of the palm swamps with 1 % slope and in a very poorly drained environment.

In the Preserved palm swamp, the vegetation cover in the P1 profile area is composed of grasses of the families Poaceae and Cyperaceae, with the occurrence of shrubby thickets composed of the species *Macairea radula* (Bonpl.) DC., typical of formations adjacent to the palm swamps (Figure 2). In the area of P2, the soil cover is composed of gallery forest, with predominant presence of the species *Calophyllum brasiliense* Cambess, *Eugenia* sp., *Mauritia flexuosa* L.f. and *Xylopia emarginata* Mar. (Teixeira and Assis, 2011), and these species are endemic to the palm swamp environments.

In the anthropized palm swamp, the area of profile P3 is exposed due to the removal of the vegetation cover by anthropic actions (occurrence of recurrent forest fires and livestock farming). The P4 profile area is exposed, because all the vegetation was suppressed by

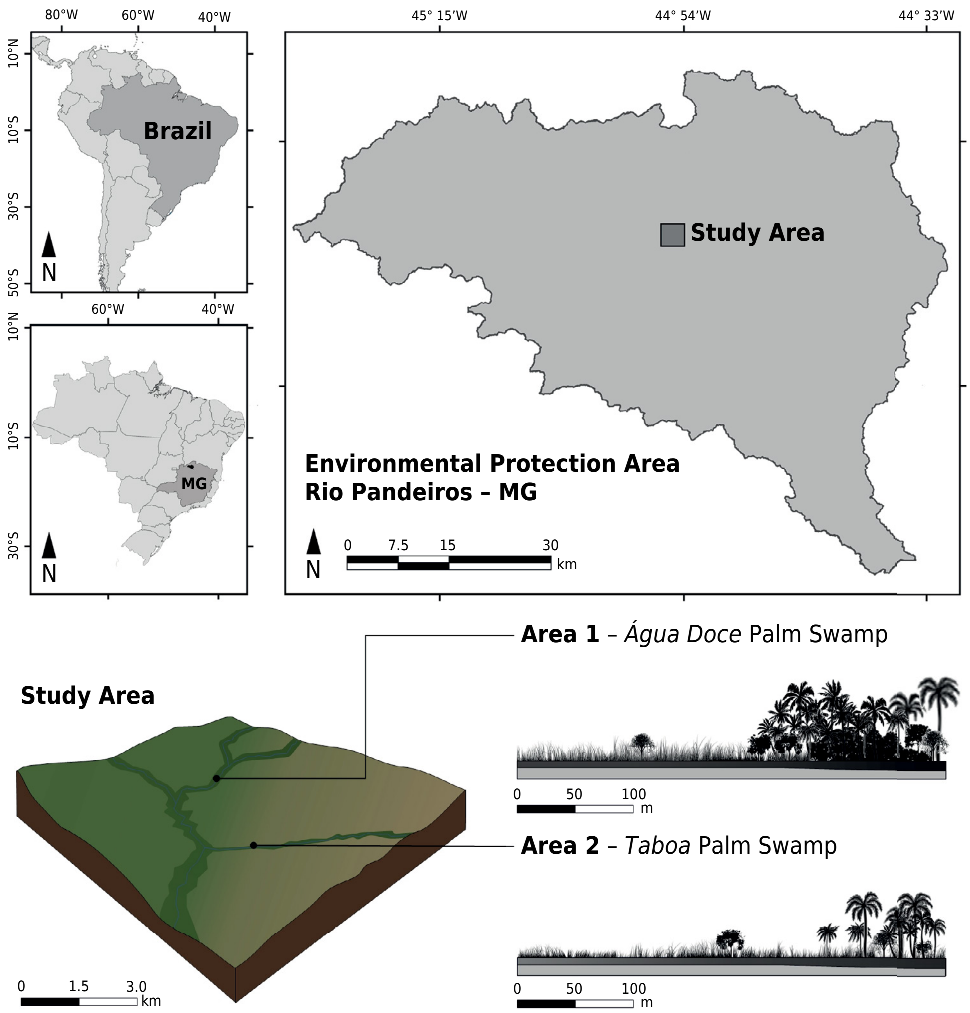

Figure 1. Location of the study areas in the Pandeiros River APA, North of Minas Gerais – Brazil.

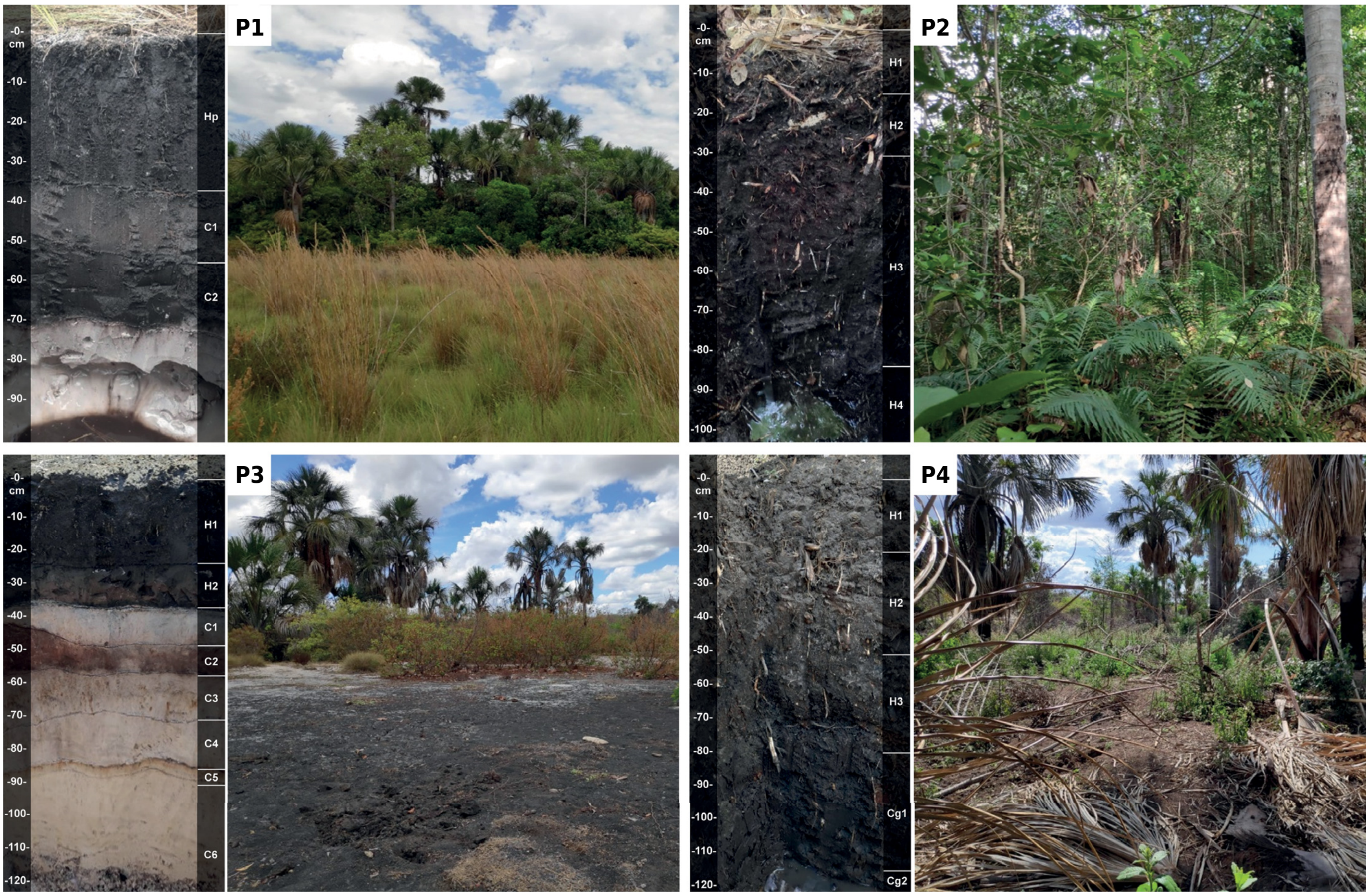

Figure 2. Studied soil profiles in the palm swamp environments. Profiles P1 and P2 collected respectively, on the edge and inside the preserved path (Água Doce Palm Swamp). Profiles P3 and P4 collected respectively on the edge and inside the anthropized path (Taboa Palm Swamp).

anthropic actions, with the presence of some individuals of the species *Mauritia flexuosa* L.f. which have resisted the anthropization processes.

The profiles were described and collected according to Santos et al. (2015) and classified according to the Brazilian Soil Classification System (Santos et al., 2018) and World Reference Base (WRB) (IUSS Working Group, 2015). Samples were collected by horizons and/or layers for chemical and physical analyses and in subsurface for isotopic analyses ($\delta^{13}C$). Disturbed samples were collected in each horizon, air dried, pounded to break up clods and passed through 2-mm-mesh sieve to obtain the Air-Dried Fine Earth (ADFE). As for the undrained samples (5 × 5 cm), one sample per horizon was collected for the determination of bulk density. The samples were dried in an oven at 105 °C for 24 h.

Edaphic properties

In each horizon or layer, soil fertility analyses were carried out to know the pH values and nutrient contents (Ca^{2+}, Mg^{2+}, Al^{3+}, P, K^+, Na^+, H+Al) (Teixeira et al., 2017). Physical analyses involved the evaluation of the particle size distribution and bulk density (Bd). In the horizons of organic constitution, the following analyses were also performed: % of plant fibers and von Post degree of decomposition (Santos et al., 2018).

Soil organic carbon stocks

Soil organic carbon (SOC) was determined by wet oxidation with potassium dichromate in acidic medium, subsequently titrated with ammoniacal ferrous sulfate solution (Yeomans and Bremner, 1988). Soil organic carbon stocks (SOCS) were calculated for each horizon, according to Wang and Dalal (2006) and Penman et al. (2003) (Equation 1):

$$\text{SOCS (Mg ha}^{-1}\text{)} = \text{SOC} \times \text{Bd} \times \text{d} \times 0.1 \qquad \text{Eq. 1}$$

in which: SOC is the organic carbon content in the soil horizon; d is the thickness of the soil horizon (cm); and Bd is the bulk density (Mg m^{-3}).

Total soil organic carbon stock (T-SOCS) was calculated for each soil profile, according to Penman et al. (2003), using the following mathematical expression (Equation 2):

$$\text{T-SOCS} = \sum_{\text{soil horizons...n}} \text{SOCS}_{\text{soil horizons}} \qquad \text{Eq. 2}$$

Isotopic analysis of $\delta^{13}C$

To understand the mechanisms of accumulation and stabilization of organic carbon in the area of each palm swamp, samples with no preserved structure were collected at the intervals of 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.40, 0.40–0.50, 0.50–0.60, 0.60–0.80 and 0.80–1.00 m. Samples were air-dried, pounded to break up clods and passed through a 2.0-mm-mesh sieve. Carbon contents of the soil samples and their isotopic compositions were determined using the Finnigan Mat Delta Plus mass spectrometer, located at the Technology and Science Support Foundation in Santa Maria, RS. Values of ^{13}C of the samples were estimated according to equation 3, having as standard the reference PDB (*Pee Dee Belemnite* – limestone from North Carolina, USA).

$$\Delta^{13}\text{C}(‰) = 10^{3} \times (R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}} \qquad \text{Eq. 3}$$

in which: R_{sample}: $^{13}C\backslash^{12}C$ is the isotopic ratio of the sample; $R_{standard}$: $^{13}C\backslash^{12}C$ is the isotopic ratio of the standard.

Statistical analysis

To evaluate the impact of anthropic changes on the soil profiles of the palm swamps, descriptive statistics were calculated for each evaluated property using SPSS 17.0 software (SPSS Inc., Chicago, IL, USA). Pearson's correlation coefficient (r) was also used to assess the correlations between soil properties using R software version 4.1.1 (2021-08-10) (R Core Team, 2021), and the corrplot library version 0.90 (Wei and Simko, 2021).

RESULTS

Soil morphology and classification

In the soil profiles collected in the edge areas of the palm swamps, histic horizons (H) (organic carbon content ≥80 g kg^{-1}, resulting from accumulations of plant residues, in varying degrees of decomposition, deposited on the surface) (Santos et al., 2018) were observed, with thicknesses ranging from 0.29 (P1) to 0.34 m (P3), with P3 (Anthropized palm swamp) formed by highly decomposed organic material (sapric) and P1 (Preserved palm swamp) formed by a material with higher content of plant fibers (hemic) (Santos et al., 2018) (Table 1). Below these horizons, layers (C) with texture ranging from sandy to sandy loam, with variations in color and structure, were observed. Groundwater table was observed only in profile P1, approximately 0.90 m from the surface, in the collection period of September 2019 (dry season). Both profiles were classified as *Neossolos Quartzarênicos Hidromórficos organossólicos* (Santos et al., 2018) (Histic Arenosol - WRB, IUSS Working Group, 2015).

Table 1. Main morphological soil properties in palm swamp of the Pandeiros River APA

Soil	Layer	Munsell	Soil	Consistence$^{(2)}$		Plasticity$^{(3)}$	Stickiness$^{(4)}$	RF$^{(5)}$	Gm$^{(6)}$	von Post		Texture Class $^{(7)}$
		Color (moist)	Structure$^{(1)}$	(dry)	(moist)					score	class	
	m	moist						%				
					Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P1)							
Hp1	0.00-0.29	N2.5/	m	sh	vfr	po	so	17	32.8	H5	Hemic	Organic
Cg1	0.29-0.44	10YR 3/1	m	sh	vfr	ps	ss	14	16.4	-	-	Sandy-loam
Cg2	0.44-0.67	N2/	m	vh	vfr	po	so	14	20.1	-	-	Sandy-loam
Cg3	0.67-1.00	10YR 6/1	sg			po	so	-	15.3	-	-	Sandy
					Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P3)							
Hp1	0.00-0.23	10YR 3/1	m	vh	fr	po	so	18	23.2	H8	Sapric	Organic
Hp2	0.23-0.34	10YR 2/1	m	eh	fr	ps	ss	9	18.2	H8	Sapric	Organic
Cg1	0.34-0.42	10YR 5/2	sg			po	so	7	7.5	-	-	Sandy-loam
Cg2	0.42-0.56	10YR 3/4	sg			po	so	0	3.4	-	-	Sandy-loam
Cg3	0.56-0.69	10YR 5/2	sg			po	so	0	3.8	-	-	Sandy
Cg4	0.69-0.85	10YR 7/3	sg			po	so	0	3.6	-	-	Sandy
Cg5	0.85-0.88	10YR 6/3	m			ps	ss	0	3.9	-	-	Sandy
Cg6	0.88-1.20	2.5YR 7/2	m			ps	ss	0	4.1	-	-	Sandy
					Organossolo Háplico Hêmico típico (Haplic Histosol) (P2)							
Hd1	0.00-0.15	N2/	m			po	so	17	47.3	H5	Hemic	Organic
Hd2	0.15-0.30	10YR 2/1	m	vh	fr	po	so	18	44.2	H4	Hemic	Organic
Hd3	0.30-0.85	10YR 3/1	m	sh	vfr	po	so	18	51.6	H4	Hemic	Organic
Hd4	0.85-1.15	10YR 3/1	m	so	vfr	po	so	17	47.2	H6	Hemic	Organic
					Organossolo Háplico Sáprico típico (*Haplic Histosol*) (P4)							
Hd1	0.00-0.20	10YR 3/1	m	sh	vfr	po	so	19	22.3	H7	Sapric	Organic
Hd2	0.20-0.52	10YR 3/1	m		fr	po	so	20	55.2	H7	Sapric	Organic
Hd3	0.52-0.82	10YR 3/1	m	vh	vfr	po	so	10	28.4	H8	Sapric	Organic
Cg1	0.82-1.15	10YR 3/1	m	vh	vfr	ps	ss	0	12.7	-	-	Loam
Cg2	1.15-1.20	10YR 3/1	m	vh		ps	ss	0	11.8	-	-	Sandy-loam

$^{(1)}$ Soil structure (m: massive; sg: single grain); $^{(2)}$ Consistence (so soft; sh: slightly hard; vh: hard/very hard; eh: extremely hard; fr: friable; vfr: very friable); $^{(3)}$ Plasticity (po: Nonplastic; ps: Slightly Plastic); $^{(4)}$ ss: slightly sticky; so: nonsticky; $^{(5)}$ Rubbed fiber; $^{(6)}$ Gravimetric moisture; $^{(7)}$ According to Santos et al. (2018).

Soil profiles collected inside the palm swamp also have horizons of organic constitution (H), having thicknesses greater than 1.15 m (P2 - Preserved palm swamp) and 0.82 m (P4 - Anthropized palm swamp). These horizons have dark colors and massive structure.

Both in the internal environment of the anthropized palm swamp (P4) and its edge area (P2), the histic horizons showed sapric organic material, while in the preserved palm swamp in any of the positions, the organic material was classified as hemic, due to the intermediate degree of decomposition, verified by the presence of plant fibers in the composition of the horizons. Profile P2 was classified as *Organossolo Háplico Hêmico típico* (Santos et al., 2018) and profile P4 as *Organossolo Háplico Sáprico típico* (Santos et al., 2018) (Haplic Histosol - WRB, IUSS Working Group, 2015).

Chemical and physical soil properties

The main physical and chemical properties of the profiles are presented in table 2. In the preserved palm swamp area, the profiles showed lower bulk density (Bd), with average values of 0.28 ± 0.12 Mg m^{-3} in the histic horizons and 1.30 ± 0.32 Mg m^{-3} in the mineral layers. In the anthropized palm swamp area, the average values of Bd were 0.43 ± 0.08 Mg m^{-3} in the histic horizons and 1.63 ± 0.22 Mg m^{-3} in the mineral layers

(Table 2). Active acidity [pH(H_2O)] also differed between the areas, with higher average values in the preserved palm swamp area (pH = 6.25 ± 0.13 in P1 and pH = 6.73 ± 0.21 in P2). In the anthropized palm swamp area, the values were lower and, unlike the preserved area, in the histic horizons, pH values were lower than those observed in the mineral layers (pH = 4.88 ± 0.45 in P3 and pH= 5.26 ± 0.39 in P4) (Table 2). Regarding the values of potential acidity (H+Al), a wide variation was observed between and within the profiles. In the preserved palm swamp, the average values were H+Al = 7.28 ± 2.98 $cmol_c\ kg^{-1}$ in the histic horizons and H+Al = 9.57 ± 5.58 $cmol_c\ kg^{-1}$ in the mineral horizons. In anthropized palm swamp, the average values were H+Al = 21.28 ± 12.22 $cmol_c\ kg^{-1}$ in the histic horizons and H+Al = 2.16 ± 1.64 $cmol_c\ kg^{-1}$ in the mineral horizons (Table 2).

Contents of basic cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and available P were higher in the profiles of *Organossolos* (P2 and P4), close to the drainage channels of the palm swamps (Table 2). The average values of the sum of bases (SB) were 0.58 ± 0.18 $cmol_c\ kg^{-1}$ (P1), 19.36 ± 6.11 $cmol_c\ kg^{-1}$ (P2), 0.71 ± 0.30 $cmol_c\ kg^{-1}$ (P3) and 8.17 ± 1.93 $cmol_c\ kg^{-1}$ (P4) (Table 2). The same pattern was observed in base saturation (V%), with average values of 8.6 ± 6.0 (P1), 75.5 ± 10.2 (P2), 29.2 ± 15.4 (P3) and 50.6 ± 7.9 (P4) (Table 2). For available P, the average values were 0.23 ± 0.04 mg kg^{-1} (P1), 1.33 ± 0.94 mg kg^{-1} (P2), 0.30 ± 0.23 mg kg^{-1} (P3) and 0.60 ± 0.16 mg kg^{-1} (P4) (Table 2). Contents of

Table 2. Physical and chemical properties of soils in palm swamp of the Pandeiros River APA

Horizon	Layer	Bd	pH	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	H+Al	T	V	m	P
	m	Mg m^{-3}	H_2O					$cmol_c\ kg^{-1}$				%		mg kg^{-1}
						Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P1)								
Hp	0.00-0.29	0.5	6.13	0	0.7	0	0	0.7	0.1	14.4	15.06	4.7	7	0.3
Cg1	0.29-0.44	1.19	6.38	0	0.5	0	0	0.5	0.1	9.8	10.32	4.8	17	0.2
Cg2	0.44-0.67	0.94	6.12	0	0.8	0	0	0.8	0.2	17.7	18.54	4.3	16	0.2
Cg3	0.67-1.00	1.78	6.37	0	1.3	0	0	0.3	0.1	1.2	1.46	20.6	25	0.2
						Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P3)								
Hp1	0.00-0.23	0.37	3.68	0	0.8	0.01	0	0.71	4	42.4	43.11	1.6	36	0
Hp2	0.23-0.34	0.63	4.35	0	0.7	0	0	0.8	0.5	30.7	31.49	2.5	38	0.7
Cg1	0.34-0.42	1.5	4.88	1	0.8	0	0	1.7	0.1	2.5	4.18	40.7	6	0.5
Cg2	0.42-0.56	1.74	5.07	0	0.8	0	0	0.8	0.5	2.8	3.61	22.1	38	0.2
Cg3	0.56-0.69	1.78	5.29	0	0.6	0	0	0.6	0.1	0.6	1.26	47.6	14	0.1
Cg4	0.69-0.85	1.76	5.98	0	0.2	0	0	0.2	0	0.3	0.53	37.7	0	0.6
Cg5	0.85-0.88	1.87	4.97	0	0.3	0	0	0.3	0.1	0.7	0.96	31.3	25	0.2
Cg6	0.88-1.20	1.87	4.82	0	0.5	0	0	0.5	0.2	0.5	1	50.3	29	0.1
						Organossolo Háplico Hêmico típico (Haplic Histosol) (P2)								
Hd1	0.00-0.15	0.13	7.1	26.4	5.1	0.06	0.01	31.57	0	1.3	32.89	95.9	0	3.2
Hd2	0.15-0.30	0.14	6.77	14.5	3.2	0.05	0.01	17.75	0	6.3	24.02	73.9	0	1.1
Hd3	0.30-0.85	0.27	6.53	14	1.5	0.01	0	15.51	0	7.6	23.1	67.1	0	0.5
Hd4	0.85-1.15	0.35	6.51	11.7	0.9	0	0	12.61	0	6.8	19.37	65.1	0	0.5
						Organossolo Háplico Sáprico típico (*Haplic Histosol*) (P4)								
Hd1	0.00-0.20	0.41	4.54	8.7	1.4	0	0.01	10.12	0.1	14.5	24.64	41.1	1	1
Hd2	0.20-0.52	0.34	5.93	9	0.8	0	0	9.81	0.1	13.5	23.34	42	1	0.6
Hd3	0.52-0.82	0.38	5.04	8	1.4	0	0	9.4	0.1	5.3	14.68	64	1	0.5
Cg1	0.82-1.15	0.96	5.22	4.5	2.9	0	0	7.4	0.2	5.6	13.01	56.9	3	0.4
Cg2	1.15-1.20	1.56	5.56	3.5	0.6	0	0	4.1	0	4.3	8.39	48.9	0	0.5

Al^{3+} were predominantly lower than 0.3 $cmol_c$ kg^{-1} (with the exception of horizons H1 = 4.0 $cmol_c$ kg^{-1}, H2 and C2 = 0.5 $cmol_c$ kg^{-1}, in P3) (Table 2).

Soil organic carbon - concentration and stocks

The average soil organic carbon (SOC) contents in the profiles of the preserved palm swamp (P1 and P2) were 251.44 ± 125.93 g kg^{-1} in the histic horizons and 29.13 ± 12.96 g kg^{-1} in the mineral layers. In the anthropized palm swamp, the average values were 156.86 ± 49.59 g kg^{-1} in the histic horizons and 9.81 ± 8.75 g kg^{-1} in the mineral layers. The average values per profile were 54.73 ± 38.39 g kg^{-1} (P1), 281.43 ± 127.43 g kg^{-1} (P2), 46.06 ± 16.99 g kg^{-1} (P3) and 97.16 ± 61.09 g kg^{-1} (P4).

The average values of soil organic carbon stocks (SOCS), in the histic horizons, were 153.37 ± 72.43 Mg ha^{-1} in the preserved palm swamp and 145.28 ± 51.53 Mg ha^{-1} in the anthropized palm swamp. Although P2 had the highest SOC values in the surface horizons, it also had the lowest SOCS values due to the lower bulk density (Bd) of these horizons. The total soil organic carbon stocks (T-SOCS) were around 305.9 ± 50.3 Mg ha^{-1} (P3), 404.6 ± 46.5 Mg ha^{-1} (P1), 522.8 ± 55.7 Mg ha^{-1} (P4), and 576.2 ± 67.6 Mg ha^{-1} (P2) (Table 3).

Table 3. Soil organic carbon (SOC), organic carbon stock (SOCS) and total organic carbon stock (T-SOCS) of soils in palm swamp of the Pandeiros River APA

Horizon	Layer	Thickness	SOC	SOCS	T-SOCS
	m		g kg^{-1}	Mg ha^{-1}	
Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P1)					
Hp	0.00-0.29	29	131.5	190.7	404.6±46.5
Cg1	0.29-0.44	15	29.3	52.3	
Cg2	0.44-0.67	23	48.4	104.6	
Cg3	0.67-1.00	33	9.7	57	
Neossolo Quartzarênico Hidromórfico organossólico (Histic Arenosol) (P3)					
Hp1	0.00-0.23	23	239.8	204.1	305.9±50.3
Hp2	0.23-0.34	11	100.3	69.5	
Cg1	0.34-0.42	8	23.9	28.7	
Cg2	0.42-0.56	14	0	0	
Cg3	0.56-0.69	13	0	0	
Cg4	0.69-0.85	16	0.6	1.7	
Cg5	0.85-0.88	3	3.4	1.9	
Cg6	0.88-1.20	32	0.5	3	
Organossolo Háplico Hêmico típico (Haplic Histosol) (P2)					
Hd1	0.00-0.15	15	399.6	77.9	576.2±67.6
Hd2	0.15-0.30	15	418.1	87.8	
Hd3	0.30-0.85	55	200.1	297.1	
Hd4	0.85-1.15	30	107.9	113.3	
Organossolo Háplico Sáprico típico (Haplic Histosol) (P4)					
Hd1	0.00-0.20	20	135.2	110.9	522.8±55.7
Hd2	0.20-0.52	32	197.9	215.3	
Hd3	0.52-0.82	30	111.1	126.7	
Cg1	0.82-1.15	33	15.7	49.7	
Cg2	1.15-1.20	5	25.9	20.2	

Carbon stocks were more related to horizon thickness than to organic carbon contents, probably due to the lower bulk density (Bd) in horizons with high organic matter content. In Pearson's correlation analysis (point biserial model), carbon concentrations were positively correlated with the contents of basic cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and available P, indicating the close relationship between the fertility of the palm swamp soils and the organic matter contents (Figure 3).

Isotopic composition ($\delta^{13}C$)

Greater amplitude of variation of the isotopic composition ($\delta^{13}C$) was observed in the profiles of *Neossolos* collected in the edge areas of the palm swamps (Figure 4). In profile P1, the values of $\delta^{13}C$ ranged from -23.49‰ at the base of the profile (0.80-1-00 m) to -15.78 ‰ (0.60-0.80 m). From 0.60 m, a trend of impoverishment of the $\delta^{13}C$ signal was observed, reaching -18.51 ‰ (0.20-0.30 m) and -17.58 ‰ in the surface layer (0.00-0.05 m). In P3, at the base of the profile the values were -18.29 ‰ (0.80-1.00 m) and -17.39 ‰ (0.60-0.80 m). The most impoverished value was observed in 0.50–0.60 m (-22.56 ‰). From this depth, there is a trend of enrichment in the $\delta^{13}C$ values toward the top, reaching the most enriched value in 0.05–0.10 m (-16.29 ‰). It is assumed that the composition of stable carbon isotopes ($\delta^{13}C$) of plant species with the photosynthetic cycle C_3 ranges from -22.0 ‰ to -32.0 ‰, with an average of -27.0 ‰, while the $\delta^{13}C$ values of plant species with the photosynthetic cycle C_4 range from -9.0 to -17.0 ‰, with an average of – 13 ‰ (Figure 4) (Boutton, 1996; Boutton et al., 1998). Values between -17.0 and -22 ‰ indicate a mixture of C_3 and C_4 plants.

In the profiles of *Organossolos* (P2 and P4) (Figure 4), the variations of $\delta^{13}C$ were lower, with values between -24.93 and -29.47 ‰. In P2, at the base of the profile, the values ranged from -26.87 (0.80-1.00 m) to -27.51 ‰ (0.30-0.40 m). In the 0.20-0.30 m layer, there was an enrichment of the $\delta^{13}C$ values (24.93 ‰) and, from this depth, they become more impoverished in $\delta^{13}C$, reaching -29.47 ‰ in the surface layer (0.00-0.05 m). In profile P4, less variation was observed, with values between -26.10 (0.00-0.05 m) and -27.39 ‰ (0.50-0.60 m), but with a general, though subtle, trend of enrichment in $\delta^{13}C$ values.

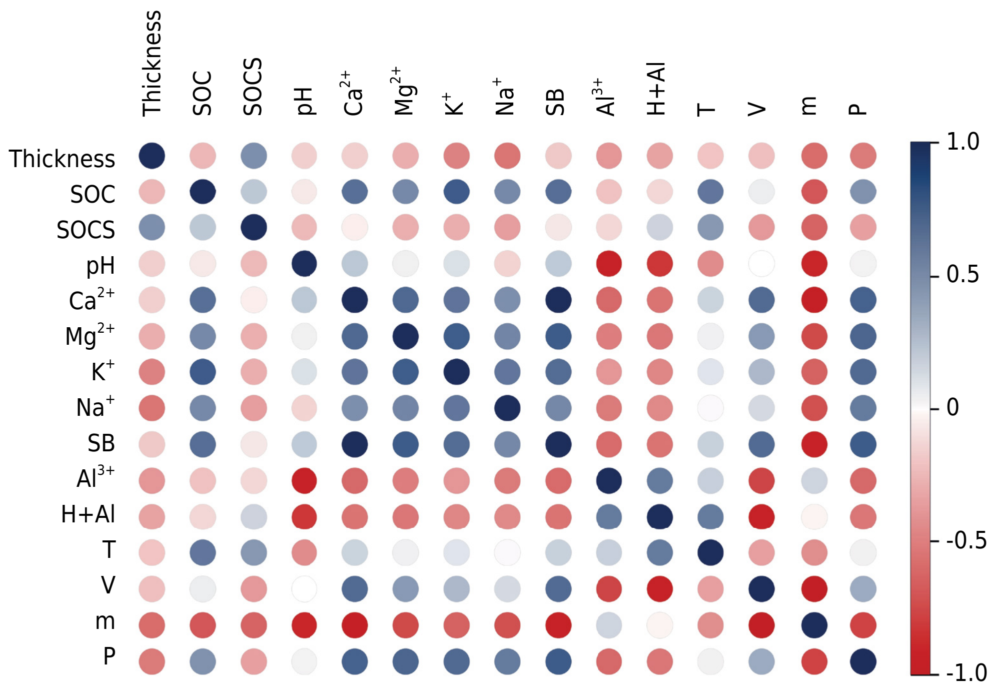

Figure 3. Correlation between the properties of the studied soils, collected in the Água Doce and Taboa palm swamp.

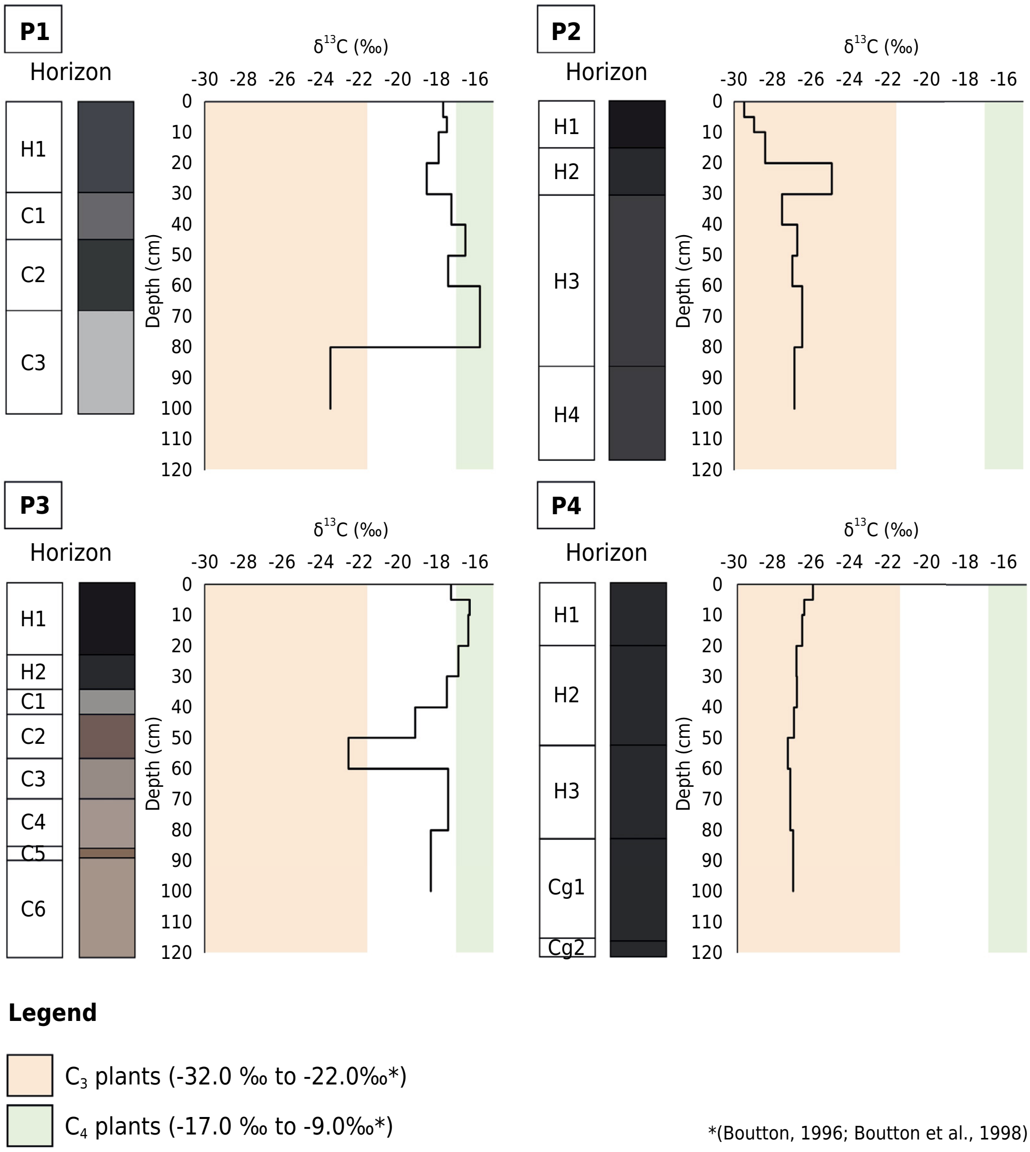

Figure 4. Natural abundance of ^{13}C in soils in a palm swamp environment in the Pandeiros River APA.

DISCUSSION

Soil properties

In the Pandeiros River EPA, most of the relief is composed of flattened surfaces of the peripheral depression of the San Francisco, whose evolution is related to the denudation processes carried out by the drainage of the São Francisco River (Augustin et al., 2009; Almeida, 2021). The properties of the studied soils are closely linked to the total or partial saturation by water conditioned by the flattened surfaces that characterize the relief of the region. Groundwater fluctuation is governed by river flow and precipitation periods. Palm swamp environments, in general, are characterized by the occurrence of hydromorphic soils such as *Gleissolos* and *Organossolos* associated with relatively shallow groundwater, due to variations in topography (these usually occur in valley bottoms) and alternation of soil layers with different levels of permeability (Ramos et al., 2006; Oliveira et al., 2009; Bijos et al., 2017; Horák-Terra et al., 2022a,b).

The formation of histic horizons (H) in the studied soils is related to the conditions of excess water, where the low availability of oxygen reduces the decomposition of organic matter (Pereira et al., 2005). The properties of the *Organossolos* observed in this study are similar to those described in the literature in the study of Histosols in Brazil (e.g., Ebeling et al., 2013; Horák-Terra et al., 2014, 2020). Several authors report the occurrence of soils with organic horizons in palm swamps in the region of central Brazil (e.g., Barberi et al., 2000; Guimarães et al., 2002; Ramos et al., 2006, 2014; Resende et al., 2013; Soares et al., 2021; Horák-Terra et al., 2022a,b).

Variations in groundwater level, and consequently in the conditions of anoxia in the soil, can lead to the decomposition of organic matter and degradation of these horizons through the subsidence process (Horák-Terra et al., 2022b). This may explain the morphological differences observed between the histic horizons of the preserved palm swamp area (P1 and P2) compared to anthropized palm swamp (P3 and P4). In the preserved palm swamp, the groundwater was observed at a depth of approximately 0.90 m in the collection period of September 2019 (dry season), which was not observed in the anthropized palm swamp (except in P4). In the profiles of the preserved palm swamp, a higher fiber content was also observed, even in the subsurface horizons, indicating greater preservation of the plant material deposited in the soil. Another difference is the thickness of the histic horizons, which was lower in the anthropized palm swamp, probably due to the subsidence process and/or soil erosion. Palm swamps are extremely sensitive to erosion and, with the removal of vegetation, the occurrence of grooves and gullies is common (Wantzen et al., 2006).

The layers of mineral constitution observed at the base of the profiles are formed by sandy sediments deposited in a fluvial environment, with quartz as the most abundant mineral. In the northern part of the Minas Gerais State, most soils have sandy texture, resulting from geological formations of metasedimentary origin of the north of Minas Gerais, especially the formations of the Bambuí Group (Nunes et al., 2009; Horák-Terra et al., 2022a,b). The sandy texture of the material reduces the water holding capacity, which may have contributed to the gleization process (reduction and solubilization of iron, expressing neutral colors resulting from clay minerals or even precipitation of iron, leading to the formation of mottles) to have been observed with low significance, even under water accumulation conditions.

Regarding the physical and chemical properties, the results show the effect of deforestation, fire and the action of animals on the soils of the palm swamps. However, the high values observed for the chemical properties (pH, Ca^{2+}, Mg^{2+} and SB) of the *Organossolos* (Table 3) differ from the values commonly observed for most Brazilian *Organossolos*, which are dystrophic or alic (Valladares, 2003). This fact is attributed to the presence of limestone rocks upstream of the Pandeiros River EPA, which contribute to the increased availability of basic cations and neutralization of acidity (Veloso et al., 2018).

The higher Bd values observed in the anthropized area reflect soil compaction caused by vegetation removal and inadequate use of the areas with pasture with a high number of animals. Soils from savannah palm swamp are very fragile due to weak grade of development of soil structure, especially in this case with animal trampling. This practice results in soil compaction caused by cattle trampling and contributes to the degradation of soil and natural vegetation (Guimarães et al., 2002; Rezende et al., 2016). Both soil classes observed in the palm swamps (*Neossolos* and *Organossolos*) can be considered high structural fragility and susceptibility to compaction, erosion and/or reduction of soil carbon content (Lal, 1997; Castro and Hernani, 2015). Although the soils do not have a structure with aggregation, the maintenance of structural quality depends on the permanence of the vegetation of the palm swamps.

Chemical properties evaluated also reflect the impact of anthropic changes on the soils of the palm swamps. Comparatively, in the anthropized palm swamp, the soils became more acidic (lower pH values and higher potential acidity) and with lower concentrations of basic cations (lower SB and V%). These changes indicate losses of nutrients (Ca^{2+}, Mg^{2+}, K^+, Na^+) by leaching, associated to the soil characteristics (sandy), and also caused by the removal of vegetation and absence of soil cover, in addition to the reduction in the cation exchange capacity (CEC) of the soil due to the decrease in SOC contents. Especially in sandy soils, most of the CEC is associated with the quantity and quality of the organic matter present. Additionally, there may be losses of nutrients due to volatilization caused by fires, which mainly affect the surface peat horizons. The concentration and type of organic matter cause a faster spread of fire, leading to the destruction of flora and fauna of these environments (Nunes et al., 2009). Fires and the removal of native vegetation to use the areas for pasture, construction of dams, and the opening of roads are the main factors responsible for disfiguring the palm swamp in the Pandeiros River EPA (Nunes et al., 2009; Bethonico, 2010; Fagundes and Ferreira, 2016).

Soil organic carbon stocks

The analysis of the results showed that anthropization processes are reducing organic carbon in soils of the palm swamps, corroborating results found in previous studies, indicating reductions in carbon content in soils of the palm swamps in the Cerrado when subjected to anthropic action (e.g., Wantzen et al., 2012; Sousa et al., 2015; Soares et al., 2021; Horák-Terra et al., 2022b). Commonly, the literature reports the effects of changes in land-use in tropical ecosystems caused by deforestation, as well as cattle grazing and trampling, leading to drastic reductions in carbon stocks in vegetation and soils (Sy et al., 2015, 2019; Neill et al., 2018; Cerri et al., 2018; Veldkamp et al., 2020).

Considering the SOCS, the highest reductions were observed in the soils collected at the edge of the palm swamps (*Neossolos*), under grass vegetation, with SOCS losses of ~25 % (98.7 Mg ha^{-1}). In *Organossolos*, SOCS losses were ~10 % (53.4 Mg ha^{-1}). Reductions in carbon concentrations can be attributed to both soil losses due to erosion and decomposition of organic matter due to the subsidence process. Vegetation removal and soil surface exposure increase water losses by evaporation, contributing to the lowering of the groundwater. With the reduction in groundwater depth and increase in soil aeration, the decomposition of organic matter occurs, especially in the surface histic horizons, favoring the subsidence process (Figure 5). The presence of the groundwater, observed in the profiles of the preserved area, and the higher values of soil moisture (Gm) in the preserved palm swamp (Table 1) support this interpretation.

In the palm swamp areas, SOC accumulates in wetlands due to reduced oxygen availability. Disturbances caused by the removal of native vegetation, soil drainage, fires, construction of roads and conversion to agricultural use change the soil conditions of paths from anoxic to aerobic (Xu et al., 2018; Moreira et al., 2021; Horák-Terra et al., 2022b). Hydrological conditions of the palm swamp soils increase carbon cycling (Moreira et al., 2021), which results in the loss of organic carbon, the emission of gases and the reduction of available water (Wantzen et al., 2006, 2012; Sousa et al., 2015; Horák-Terra et al., 2022b). Thus, palm swamps should be considered carbon reservoirs very sensitive to environmental changes and, therefore, prioritized in environmental conservation projects.

C stable isotopes ($\delta^{13}C$) and sources of organic matter

The composition of stable carbon isotopes ($\delta^{13}C$) indicates different sources of organic matter in the soils of the palm swamps, which is determined by floristic diversity, litter characteristics and occurrence of forest fires (Araújo et al., 2002; Rezende et al., 2017). Palm swamp vegetation is adapted to soils with seasonal or permanent flooding. Variation in relief conditions and soil water availability create different environmental conditions directly associated with floristic composition, depending on the species'

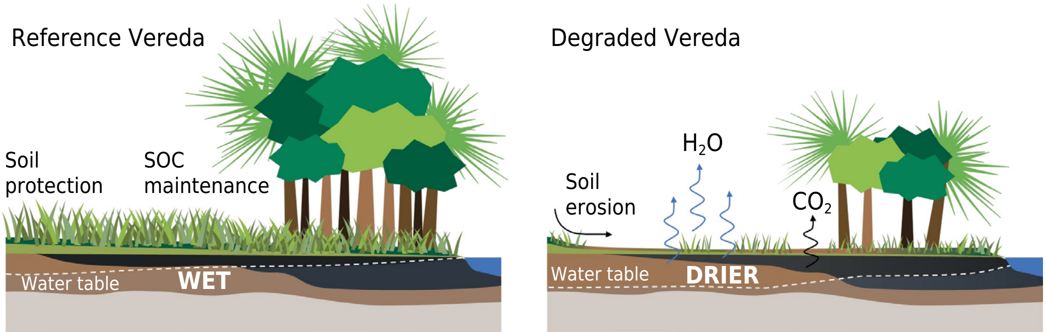

Figure 5. Schematic representation of the effects of deforestation on the soils in a palm swamp Água Doce (reference) and Taboa (degraded).

tolerance to flooding (Santos and Munhoz, 2012). Specifically, the profiles located in the edge areas of the palm swamps (P1 and P3) are formed by alluvial deposits accumulated in the drainage channels of the Pandeiros River Basin. This explains the largest variations in the $\delta^{13}C$ values of these profiles. The differences in morphological, physical and chemical properties also indicate different sedimentation phases in the formation of these soils.

A recent study in the Grande Sertão Veredas National Park, in the northern Minas Gerais state - Brazil (Horák-Terra et al., 2022a), indicated different phases of paleoenvironmental changes recorded in the witness area of the Pau Grande palm swamp. Through a multiproxy study (stratigraphy and morphological, chemical, physical and isotopic properties) with a multivariate approach, the authors identified four main genesis processes/drivers in the Histosol in the palm swamp area: (1) the relative accumulation of organic matter × mineral matter; (2) hydromorphism conditions; (3) the incorporation of inorganic material through the deposition of dust from regional sources; and (4) sources of organic matter. As reported in other studies, Horák-Terra et al. (2022a) observed that the palm swamp began its formation during the end of the Pleistocene. Thus, palm swamps should be valued as stable carbon reservoirs, accumulated about 30,000 years ago (Barberi et al., 2000; Pires et al., 2016; Horák-Terra et al., 2022a).

When evaluating the late Holocene in central Brazil, considering vegetation changes and humidity variability in a tropical wetland, Sabino et al. (2021) observed that changes in the swampy environment of the Pandeiros river ecosystem occurred during the Late Holocene. Regarding the Pandeiros River Basin vegetation, Sabino et al. (2021) observed that since the beginning of the Late Holocene, there has been a reduction in the floristic cover. According to the authors, this pattern agrees with pollen records carried out in the north region of Minas Gerais in transition environments between the Cerrado and the Caatinga.

CONCLUSIONS

Anthropic actions in the palm swamps cause soil degradation due to subsidence, contributing to reduction in organic carbon content, increase in bulk density and reduction in fertility. Degradation of the palm swamps considerably reduces soil carbon storage, with a greater decrease in the areas of *Neossolos Quartzarênicos Hidromórficos organossólicos*, which are located at the edge of the palm swamps. Changes caused in this environment compromise the ecosystem services performed by these soils, especially organic carbon stock and water storage, indicating that actions at either local or governmental level should be stimulated for the preservation and conservation of these environments.

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