Division – Soil in Space and Time | Commission – Soil Genesis and Morphology

Soil characterization and drainage effects in a savanna palm swamp (*vereda*) of an agricultural area from Central Brazil

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ABSTRACT: Brazilian palm swamps (*veredas*) are fundamentals in the hydrological balance of watercourses in the Brazilian savanna (Cerrado). The "sponge effect" of their soils is the main factor controlling local hydrology, storing rainwater, and functioning as headwaters. The restricted knowledge of these tropical ecosystems has led to increased losses, poor preservation, and reduction in their ecosystem services. *Veredas* have become refuges surrounded by croplands, often drained and inappropriately managed. This study shows the impacts of anthropization on soil processes and properties of a *vereda* in an agricultural area. Two soil profiles were selected and characterized as preserved and anthropized, respectively upstream and downstream of the studied *vereda*. Morphological, physical, chemical and microbiological properties were analyzed. Principal Components Analysis (PCA) was applied to synthesize the data and provide evidence of the main properties and underlying processes that most responded to the degradation action. The arrangement of this analysis shows three main distinguish drivers: one joining the properties related to the humification of organic matter and relative accumulation of mineral matter versus accumulation of organic matter; the second with properties related to soil chemical reactivity; and the third reflecting the mineralization of organic matter. Our results suggest that the anthropic action has strongly caused the organic carbon reduction (~22 %). After 20 years, the anthropized soil presents not only a great decline in carbon stock (~14 kg m^{-2}), but also strong impacts on several other ecologic functions, such as water holding capacity. *Veredas* are complex and fragile environments, and they should be fully protected to maintain their ecosystem services.

Keywords: tropical wetlands, Cerrado biome, Histosols, water drainage, ecosystem services.

INTRODUCTION

Veredas (Brazilian palm swamp) are tropical wetlands exclusive to the Cerrado Biome (Brazilian savanna) and are easily recognized by the dominance of the Buriti palms (*Mauritia flexuosa* L.f.; Arecaceae) (Ribeiro and Walter, 1998; Resende et al., 2013; Padovesi-Fonseca et al., 2015). Defined as geo-ecosystems by Augustin et al. (2009), *veredas* often occur along shallow kilometer-long valleys on extensive flat plateaus, known as *chapadas* and *chapadões,* which constitute wide and old planation surfaces of the Brazilian Central Plateau (mean elevation of 1,000 m a.s.l.) (King, 1956; Braun, 1971).

In general, a layer with high organic matter content occurs in the valley bottom (thalweg) of this ecosystem, classified as a histic horizon (IUSS Working Group WRB, 2015). This type of horizon according to its position in the soil profile can defines classes of *Organossolos* [Histosols in the IUSS Working Group WRB (2015)], similar to the tropical peatlands (mires) of the Serra do Espinhaço Meridional (Minas Gerais, Brazil) (Silva et al., 2009a,b; Horák et al., 2011; Horák-Terra et al., 2014). In the ecosystem of *veredas*, the formation of these soils is associated with prolonged, or almost permanent, water saturation from groundwater and rainfall, enabling the imbalance between accumulation/decomposition–mineralization of organic matter (Ramos et al., 2006).

Since *vereda* vegetation is dominated by the Buriti palm, its remains (leaves, fruits, stems and roots) are important sources of organic matter for *Organossolo* formation. Individuals of palms at different stages of development can reach heights between 15 and 30 m and diameters between 0.30 and 0.50 m (Gregson, 1995), with a density of up to 300 individuals per hectare (Sampaio et al., 2012). In addition, large leaves fall on the soil surface, with each plant producing 5 to 12 leaves per year (Gregson, 1995).

The "sponge effect" is a characteristic of these soils, storing rainwater and making it available to main watercourses through slow discharge, even in the driest periods of the year. Therefore, *veredas* play a fundamental role in the hydrological balance of watercourses in the Cerrado environment (Ramos et al., 2006). Many tributaries of the São Francisco river, which is one of the most important rivers in Brazil and South America, located in northwestern Minas Gerais (region of the present study), have *veredas* as headwaters, except in karst areas (Boaventura, 1978).

Furthermore, the presence of organic soil in these environments maintains carbon stored as a sink, avoiding its release as greenhouse gases (Kasimir-Klemedtsson et al., 1997; Wantzen et al., 2012; Sousa et al., 2015). Also, due to its ability to accumulate and preserve sequences of autochthonous organic material for thousands of years (reducing environment), it contains detailed records of the history of the local and regional vegetation and heavy metal depositions, making it an ideal place to study environmental and climate change (Salgado-Labouriau et al., 1997; Horák-Terra et al., 2015, 2020, 2022; Cassino et al., 2018).

Despite their environmental and scientific importance, *veredas* remain largely neglected (Rosolen et al., 2014). Since 1934, the Brazilian Forest Code, and its subsequent versions of 1965, 1989, and the last two of 2012, have been unclear about the preservation of these environments. Currently, the Law Project 10982/18 has reinforced *veredas* as permanent preservation areas (PPAs) in the Forest Code (Law 12.651/12) for rural and urban areas. Thus, these must be fully protected, and minimum borders of 50 meters from their permanently wet areas should be included. Since 1988, the state of Minas Gerais has had its own legislation for the conservation of *veredas* (State Law 9682/88), whereby these should be protected and considered as PPA. However, Brazilian states and municipality laws tend to be more permissive than federal laws (Rosolen et al., 2014). In addition, a former Brazilian government program was created during the 1980s, called *Pró-Várzeas Nacional*, encouraging the drainage of wetlands in general for irrigated land use, which, associated with the Cerrado use intensification to support

agricultural activities, has been collaborating in the degradation of these environments, making them highly vulnerable and susceptible to degradation.

The restricted knowledge regarding important aspects of these tropical ecosystems has led to increased losses, poor preservation, and reduction in their ecosystem service provision. Inadequate soil management practices or even direct use of their waters for irrigation are current practices in northwestern of Minas Gerais. In Brazil, the highest concentration of center pivot irrigation is in this region located on the flat plateau (Ferreira et al., 2011; Freitas and Andrade, 2017), with higher productivity of different annual crops (beans, soybeans, corn and sorghum). Therefore, the real scenario shows *veredas* as refuges surrounded by croplands. In situations of drainage and/or improper management of these environments, subsidence is the operating and dominant process, reducing soil volume, in addition to oxidation (degradation) of its organic matter. Normally, when organic soils are drained, their pores are reduced, and their solid materials become hardened (like rock) (Alaoui et al., 2011; Grzywna, 2017). In such cases, these soils become unusable for agricultural use, since roots are unable to penetrate and develop. They also become much more susceptible to fires, since dry organic matter is a potent fuel.

Few studies have described some soils from *veredas*, and most of them have been conducted in the Triângulo Mineiro region, covering the municipalities of Uberlândia and Uberaba in Minas Gerais State, Brazil (Embrapa, 1976, 1978, 1986; Epamig, 1978; Couto et al., 1985; Côrrea, 1989; Amaral, 2002; Ramos et al., 2006, 2014; Wantzen et al., 2012; Sousa et al., 2015; Ribeiro et al., 2019). However, a lack of knowledge remains regarding the general characterization of these ecosystems' organic soils (Ramos et al., 2014). This is because *veredas* are quite different, even within a given region, since they are located in different conditions on the landscape, with different geomorphological surfaces and over different parent material, resulting in distinct characteristics (Ramos et al., 2014). Therefore, more detailed investigations of *vereda* soils should be carried out to contribute to the knowledge on these environments.

In *veredas*, artificial drainage changes the water dynamics of these environments, which triggers organic matter degradation processes due to oxidation. This study presents two soil profiles in different conditions, preserved (PP) and anthropized (AP), selected at different and representative landscape positions, respectively upstream and downstream within the same *vereda* (called Primavera), to: (i) characterize these soils based on morphological, physical, chemical and microbiological properties; (ii) characterize the organic fractions of their organic matter; (iii) identify the processes/drivers which may be controlling the nature and changes of these soils in the studied *vereda*; and (iv) support discussions on the use of these environments.

MATERIALS AND METHODS

Study area

The Primavera *vereda* is inserted on the Chapada de Bonfinópolis, a flat plateau in the Bonfinópolis de Minas municipality, in the northwestern region of the state of Minas Gerais, Brazil (Figure 1a), and located within a private property that produces seeds for pasture. According to information from the farm manager (not identified here) and to time series of Google Earth images (from 1985), an artificial drainage channel was opened, and its original vegetation was removed about 20 years ago to use the *vereda*'s water for irrigation of the surrounding annual crops. These croplands are about 300 m from the *vereda*'s central longitudinal axis (Figure 1b).

The local geology and basal lithology comprise the Três Marias Formation, corresponding to the Bambuí Group and São Francisco Supergroup, composed mostly of arkoses and pelites. Clayey and loamy clay Oxisols are the main soils around the *vereda*, probably

formed from tertiary-quaternary sediments, mainly detritic-lateritic, detrital and eluvial coverings, which are generally found on other planation surfaces in the Brazilian Central Plateau (Branco and Costa, 1961).

The Primavera *vereda* has an important role as an open and permanent water source embedded in the dissected surfaces and inserted in a sub-watershed, which stores rainwater, especially in its organic soils. It is a headwater of the Almas stream (natural drainage channel), since its waters flow into this watercourse, which is used to supply the urban population of the Bonfinópolis de Minas municipality. Almas stream is one of the main tributaries of the Urucuia river, which, in turn, is a tributary of the São Francisco river.

Resembling peatlands, the Primavera *vereda* can also follow the classification system proposed by Lindsay (1995), considered as minerogenic, valley swamps, and presenting the following main characteristics: standing water or water gently flowing through pools and channels; waters originating from mineral soils (minerotrophic); and dominant peat material is strongly to slightly acidic, well-decomposed woody peat (National Wetlands Working Group, 1988).

Climate of the study area is classified as tropical savanna with dry-winter characteristics, according to Köppen classification system (Alvares et al., 2013). The mean annual temperature is 23 °C, varying between 17 and 32 °C. The months from May to August are considered the coldest, and from September to April the warmest. Mean annual
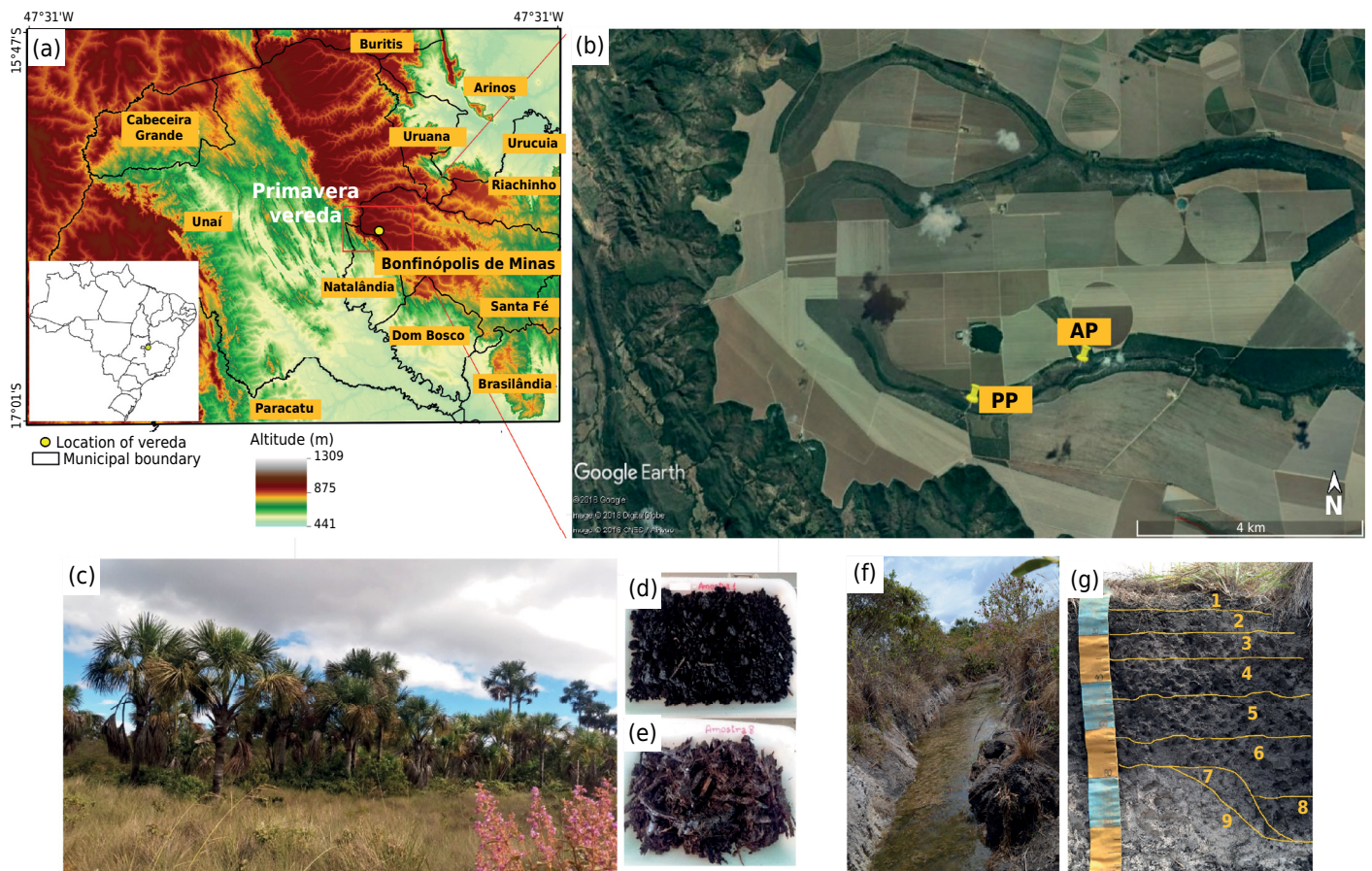

Figure 1. Location of the Primavera *vereda*. Hypsometric map of the northwestern region of the state of Minas Gerais (Brazil), where *veredas* are positioned on flat plateau depressions (a). Primavera *vereda* placed in a subwatershed, whose waters flow into the Almas stream (northwest-southeast direction) (b). Primavera *vereda* upstream in preserved condition where PP is installed (c). Hd1 horizon (0.00-0.20 m) (d) of PP. Ho2 horizon (1.40-1.60 m) (e) of PP. Primavera vereda downstream in anthropization/degradation condition through original vegetation removal and opening of a drainage channel (f). AP soil with all horizons exposed (g). PP: preserved soil profile. AP: anthropized soil profile.

precipitation is between 1,000 and 1,400 mm, with the greatest rainfall frequency occurring from November to March, and the driest period corresponding to the months from April to October. The mean annual potential evapotranspiration is 1,104 mm and its values are higher than the precipitation in the driest period, where there is a precipitation deficit. The period from 1950 to 1990 was used to compute this information.

Regional vegetation is typical of the Cerrado biome (savanna), with representative phytophysiognomy of *veredas* only found in central Brazil (Ribeiro and Walter, 1998). The Buriti palm (*Mauritia flexuosa* L.f.; Arecaceae) stands out in the arboreal stratum of a gallery forest occupying the hydromorphic environment. In the herbaceous stratum, Poaceae, Cyperaceae and Xyridaceae families are the main occurrences, which is typical of wet grassland (*Campo Limpo Úmido*) and dry grassland (*Campo Limpo Seco*). However, extensive forage (pasture) cultivated fields are also associated with the natural vegetation, and many center pivot irrigation areas occur.

Sampling and soil classification

Two profiles, PP and AP, were collected from the Primavera *vereda.* They are positioned on the same central longitudinal axis of a natural drainage channel (~2.5 km apart from each other) in the same basin, exactly on the flat bottom of the valley (thalweg line) (Figure 1b). The first profile (PP) has a thickness of 1.60 m and is in a preserved condition. It is located at 16° 24′ 18.37″ S and 46° 28′ 43.34″ W, at 933 m a.s.l. upstream of the sub-watershed where the *vereda* is inserted (Figure 1c). The second profile (AP) has a thickness of 1.20 m and is in an anthropized/degraded condition, characterized by removal of the original vegetation and the opening of an artificial drainage channel (~100 m in length) transverse to the stream channel (Figure 1d). It is located at 16° 23′ 56.45″ S and 46° 27′ 32.10″ W, at 920 m a.s.l. downstream of the sub-watershed. It is possible to observe on the satellite image (Google, 2018) how the *vereda*'s vegetation extends downstream and upstream from the position of AP, providing continuity to the impacted ecosystem (Figure 1b).

Soil sampling was carried out in 2017, whereby the PP was sampled using a plastic tube with 3″ in diameter and 1/8″ of thickness, which was manually pushed into the soil using a mallet and jaws, while the AP samples were taken directly from the wall within the artificial drainage channel (perpendicular to the stream channel) after a careful cleaning operation. After PP sampling, the tube was opened lengthwise with a circular saw, and samples were immediately collected every 0.20 m. In both situations, around 500 g of soil were sampled for each horizon and depth. Soil samples from both profiles were stored in zip lock plastic bags and immediately refrigerated upon arrival at the laboratory later the same day.

The Brazilian Soil Classification System - SiBCS (Santos et al., 2018) and the World Reference Base - WRB (IUSS Working Group, 2015) were used for soil classification. The soil horizons of each profile were described according to Field Description and Soil Collection Manual (Santos et al., 2015). Morphological attributes such as matrix color, structure, plasticity, stickiness and boundaries between soil horizons were determined in the field using the above-mentioned references. The von Post scale (VP) was used to assess the degree of organic matter decomposition (Stanek and Silc, 1977), which was also determined in the field.

Analytical determinations

According to the characterization tests for *Organossolos* (Lynn et al., 1974), described in Santos et al. (2018), the following properties were determined: unrubbed (URF) and rubbed fibers (RF), pH($CaCl_2$), bulk density (BD), bulk density of organic matter (BDO), gravimetric moisture (GM), minimum residue (MR) and mineral material content (MM). The volumetric moisture (VM) was calculated according to Teixeira et al. (2017).

For the quantification of organic carbon (C_{org}) contents, two methods were used based on wet oxidation of organic matter (Walkley-Black, 1934; Teixeira et al., 2017) and determination of organic matter (OM) by ignition in a muffle oven (Lynn et al., 1974; Goldin, 1987; Santos et al., 2018). For the carbon Walkley-Black (C_WB), potassium dichromate was used in a sulfuric medium for oxidation, followed by titration with ammonium ferrous sulfate with diphenylamine as indicator. For the organic carbon muffle oven (C_M), the OM content was determined through the loss of mass of the incinerated soil, considering incineration ranging from 105 °C/24 h to 600 °C/6 h {MO = [(105 °C dry weight − 600 °C dry weight)/(105 °C dry weight) × 100]}. The C_{org} contents were calculated by dividing the OM values by the "van Bemmelen" factor (1.724). For each profile, the C_{org} stock (kg m^{-2}) was calculated by adding the multiplication among C_WB (dimensionless), thickness (m), and BD (kg m^{-3}) of each horizon (Batjes, 1996). Nitrogen (N) quantification was carried out through digestion and distillation (Kjeldahl method) as described in Teixeira et al. (2017).

The chemical analyses [Mehlich-1 extracted phosphorus and elements of the assorted complex (Ca^{2+}; Mg^{2+}; K^+)] were carried out on dry, macerated, and sieved samples according to Teixeira et al. (2017). The H+Al extraction was performed with calcium acetate 0.5 mol L^{-1} (Teixeira et al., 2017). From these results, the sum of bases (SB = Ca^{2+} + Mg^{2+} + K^+ + Na^+), cation exchange capacity (CEC = SB + H+Al), and base saturation [BS = (SB × 100)/CEC] were calculated, according to Santos et al. (2018).

The mineral soil particle size distribution (sand, silt and clay contents) was determined using the pipette method (Teixeira et al., 2017), after total oxidation of the samples' organic matter with hydrogen peroxide to obtain the mineral fraction. The fractionation of organic matter was carried out using the method recommended by the International Humic Substances Society (IHSS) (Swift, 1996), with pre-treatment of samples by HCl 0.1 mol L^{-1} and using NaOH 0.1 mol L^{-1} as a solvent. Determinations of carbon in the humic fractions were performed on three laboratory replicates per sample, using potassium dichromate as an oxidizer and ferrous ammonium sulfate to determine the carbon equivalent in each fraction (Yeomans and Bremner, 1988). After determining the organic carbon values, the following quality indices were calculated according to Labrador Moreno (1996): CHA/CFA; CH/(CHA+CFA); and (ΣC_HF/C_WB) × 100, in which ΣC_HF is the sum of carbon from humic fractions (CHA + CFA + CH), and C_WB is the organic carbon determined through dichromatometry (Yeomans and Bremner, 1988).

Microbial biomass was determined using the method proposed by Anderson and Domsch (1978), based on the increase in the rate of microbial respiration, up to the maximum, when an excess of a readily decomposable carbon source is added to the soil (Dionísio et al., 2006). Samples of 20 g (in triplicate) of dry soil were transferred to flasks with an airtight lid, and 60 mg of anhydrous glucose, diluted in distilled water, was added over the soil. After homogenizing the soil and glucose, these were sealed and pre-incubated in an oven at 22 °C for 2 h. After pre-incubation, test tubes containing 10 mL of NaOH 0.1 mol L^{-1} were added to the flasks, then incubated for a further 4 h at 22 °C. The NaOH was then transferred from the test tubes to Erlenmeyer flasks for the titration procedure with HCl 0.025 mol L^{-1}.

Basal soil respiration in a static system was determined according to the method of Alef (1995). Samples of 100 g of soil (in triplicate), with humidity of 60 % of water holding capacity, were placed in flasks with airtight lids. Test tubes containing 15 mL of standardized NaOH 0.5 mol L^{-1} were placed inside the flasks to capture the CO_2 produced and another tube containing 10 mL of distilled water to maintain the humidity of the environment. The flasks were hermetically sealed and on the third day after incubation, the test tubes were removed to titrate with HCl 0.5 mol L^{-1}.

Statistical analysis

Mean comparison using the Student's t-test was performed between profiles to identify which analytical properties showed significant differences. For each profile, the mean values of these properties were calculated to be compared at a significance level of 5 % (α = 0.05) in the R program (version 3.6.2). Von Post scale data (VP), matrix color, structure, plasticity, stickiness, and the boundary between horizons were not included in the mean test, because these are field tests and have qualitative significance.

Principal Components Analysis (PCA) was carried out on the data matrix of the properties that showed significant differences regarding their mean comparisons (p-value≤α). The PCA enables an intuitive interpretation from a pedological point of view, whereby each component brings a meaning in terms of the main factors and processes characterizing these profiles. The input data were log-transformed (except pH, C/N, MM, MR, URF, RF, BD, BDO, sand, silt, and clay) and standardized prior to analysis (Reimann et al., 2008). The IBM SPSS Statistics for Windows, version 20.0 (IBM Corp., Armonk, N.Y., USA) was used to perform the PCA in the correlation mode, and a varimax rotation was applied to maximize the variables' loadings in the components (Eriksson et al., 1999).

RESULTS

Profile description and soil classification

The PP and AP profiles have differences between horizons based on the main morphological features, taking into account organic material decomposition stages and consistency, mineral material texture and consistency, matrix color in wet samples, soil structure, and preserved features (thick and thin plant roots, and partially decomposed wood fragments) (Table 1 and Figures 1c and 1f). In general, a predominance of histic horizons (H) is seen in PP (Table 1), while umbric horizons (A), and some with aquic conditions (Cg), predominate in AP. The PP is 1.60 m thick and consists of 8 horizons (Hd1, Hd2, Hd3, Hdo1, Hdo2, Hdo3, Ho1 and Ho2), while AP is >1.20 m and has 9 horizons (Hodp, A1, A2, A3, A4, Cg1, Cg2, Cg3 and Cg4). In PP, the top-to-base sequence of horizons is sapric (0.00-0.60 m; Figure 1d), hemic (0.60-1.20 m; Figure 1e), and fibric (1.20-1.60 m). For AP, although it is a high organic content mineral soil nowadays, the sequence is hemic (0.00-0.48 m) and sapric (0.48- > 1.20 m) (Figure 1g).

Very dark colors tending to black (Figures 1c and 1f) are due to the very low values and chromas, which vary between 2 and 2.5, and 1 and 2, respectively (Table 1). The hues showed greater variation, with colors ranging between 2.5YR and 10YR, with greater presence of yellow pigments at the top and bottom, and red pigments in the middle of the profiles.

Massive structures predominate in PP (0.40-1.60 m), but also medium subangular blocks and small lumpy granular are seen in the most superficial horizons (0.00-0.40 m). In turn, AP shows the predominance of small, medium and large subangular blocks that come undone in granular and lumpy granular (0.00-0.88 m). Massive structures also occur in AP, but in the bottom three horizons of the profile.

In the sapric horizons of PP, the material tends to be slightly plastic and slightly sticky, with silty clay loam texture, while the sapric horizons of AP are plastic and sticky with sandy clay loam texture. The hemic and fibric horizons of PP are non-plastic and non-sticky with loamy textures reaching organic nature textures, and the hemic horizons of AP are slightly plastic and slightly sticky to non-sticky with clay loam to loam textures. The PP soil was classified as *Organossolo Háplico Sáprico típico* [Hyperdystric Sapric Histosol] and the AP soil as *Gleissolo Melânico Tb distrófico* [Hyperdystric Oxygleyic Umbric Gleysol (Loamic, Drainic, Profundihumic)].

Table 1. Morphological properties of the studied profiles

Hor.	Layer	Color	Struc	Pl	Stick	Bound	VP	URF	RF
	m							——— % ———	
				PP					
Hd1	0.00-0.20	10YR 2/1	Mo, S, LGR	SPL	SST	–	9	52	36
Hd2	0.20-0.40	10YR 2/1	St, M, SB	SPL	SST	–	9	64	44
Hd3	0.40-0.60	5YR 2.5/1	MA	SPL	SST	–	7	64	56
Hdo1	0.60-0.80	2.5YR 2.5/1	MA	NPL	SST	–	5	64	52
Hdo2	0.80-1.00	2.5YR 2.5/1	MA	NPL	SST	–	5	64	52
Hdo3	1.00-1.20	5YR 2.5/1	MA	NPL	NST	–	5	72	56
Ho1	1.20-1.40	10YR 2/1	MA	NPL	NST	–	4	68	56
Ho2	1.40-1.60	10YR 2/2	MA	NPL	NST	–	3	76	68
Mean±SD								66±7	53±9
				AP					
Hodp	0.00-0.14	7.5YR 2.5/1	W, S/M, SB; Mo, S/M, LGR	SPL	NST	CS	5	...	...
A1	0.14-0.20	5YR 2.5/1	W, S/M SB; Mo, S/M, LGR	SPL	SST	CS	5	...	...
A2	0.20-0.31	5YR 2.5/1	Mo, S/M, SB; W, S/M, GR	PL	SST	CS	5	...	...
A3	0.31-0.48	2.5YR 2.5/1	Mo, L/VL, SB; Mo, M, GR	PL	ST	CS	6	...	...
A4	0.48-0.64	2.5YR 2.5/1	St, L/VL, SB; St, L, GR	PL	ST	CS	7	...	...
Cg1	0.64-0.88	2.5YR 2.5/1	W, M/L, SB; St, L, GR	VPL	VST	CB	9	...	...
Cg2	0.75-1.06	2.5YR 2.5/1	MA	PL	ST	AW	10	...	...
Cg3	0.88-1.06	5YR 2.5/1	MA	PL	ST	AW	10	...	...
Cg4	0.75-1.20[+]	10YR 7/1	MA	PL	ST	–	10	...	...
Mean±SD								...	...

Hor: Horizon. Color: matrix color (wet sample). Struc: structure [W: weak; Mo: moderate; St: strong; S: small; M: medium; L: large; VL: very large; GR: granular; LGR: lumpy granular; B: blocks; SB: subangular blocks; MA: massive]. Pl: plasticity [NPL: non-plastic; SPL: slightly plastic; PL: plastic; and VPL: very plastic]. Stick: stickness [NST: non-sticky; SST: slightly sticky; ST: sticky; and VST: very sticky]. Bound: boundary [CS: clear smooth; CB: clear broken (discontinuous); and AW: abrupt wave]. VP: von Post degree of peat decomposition. URF: unrubbed fibers. RF: rubbed fibers. "–" not applicable numerical data. "..." not available numerical data.

Morphological, physical, chemical and microbiological properties

Degree of evolution of organic soil material

In PP, unrubbed fibers (URF) are between 52 and 76 %, with a mean of 66 ± 7 %, and rubbed fibers (RF) between 36 and 68 %, with a mean of 53 ± 9 % (Table 1). In general, both fiber contents increased with depth for this profile. The von Post degree of peat decomposition varies between classes 3 and 9, thus covering the three stages of decomposition, fibric (3 and 4), hemic (5), and sapric (7 and 9). Classes 7 and 9 are seen at the top (0.00-0.60 m), class 5 in the middle (0.60-1.20 m), and classes 4 and 3 at the bottom (1.20-1.60 m).

Fibers are also observed in AP with many fine roots in the first two horizons (0.00-0.20 m), common very thin roots in the two subsequent horizons (0.20-0.48 m), and few very thin roots in the other horizons. In general, the organic material changes from hemic in the first four horizons (classes 5 and 6), indicating moderately decomposed organic

matter, to sapric (classes 7, 9 and 10), indicating a predominance of advanced stage decomposition across horizons at greater depths. The contents of these constituents could not be determined through the URF and RF test, or rather, it was decided not to determine them (Table 1). Using the fiber determination method, there was an overestimation of the results when considering part of the mineral fraction (higher contents in AP than in PP) retained in the sieve (it then counts as fiber, but this is not true).

Soil water content, soil bulk density and bulk density of organic matter

The gravimetric (GM) and volumetric (VM) moistures, soil bulk density (BD) and bulk density of organic matter (BDO) are very different between profiles (Table 2). In PP, values vary between 2.04 and 8.77 g g^{-1}, with a mean of 6.42 ± 2.33 g g^{-1} for GM; between 0.64 and 0.81 cm^3 cm^{-3}, with a mean of 0.74 ± 0.06 cm^3 cm^{-3}, for VM; between 0.09 and 0.31 mg m^{-3}, with a mean of 0.14 ± 0.08 Mg m^{-3}, for BD; and between 0.08 and 0.18 Mg m^{-3}, with a mean of 0.11 ± 0.03 Mg m^{-3}, for BDO. Meanwhile, in AP, values range between 0.26 and 0.55 g g^{-1}, with a mean of 0.38 ± 0.10 g g^{-1}, for GM; between 0.25 and 0.53 cm^3 cm^{-3}, with a mean of 0.35 ± 0.09 cm^3 cm^{-3}, for VM; between 0.48 and 1.36 Mg m^{-3}, with a mean of 0.96 ± 0.29 Mg m^{-3}, for BD; and between 0.14 and 0.20 Mg m^{-3}, with a mean of 0.16 ± 0.02 Mg m^{-3}, for BDO.

For PP, the values of GM and VM tend to increase in depth, while BD has an opposite behavior. On the other hand, the general trends are reversed in AP, with GM and VM values decreasing and BD increasing in depth. The BDO values show the same trend in both profiles, with decreasing values, although higher values are seen in AP (Table 2).

Mineral material and minimum residue

In PP, the mineral material (MM) contents are between 4 and 42 %, with a mean of 18 ± 13 %, and minimum residue (MR) is between 0.01 and 0.09 m m^{-1}, with a mean of 0.02 ± 0.03 m m^{-1} (Table 2). For AP, MM contents are between 57 and 89 %, with a mean of 81 ± 10 %, and MR is between 0.18 and 0.77 m m^{-1}, with a mean of 0.53 ± 0.21 m m^{-1}. As BD and BDO, the values of MM and MR are also much higher in AP than in PP. In addition, they also follow the same trends in both profiles, whereby the values are also decreasing in PP and increasing in AP.

Soil reaction

The pH range is between 3.75 and 4.16 with a mean of 3.90 ± 0.14 for PP and between 3.88 and 4.17 with a mean of 4.06 ± 0.10 for AP (Table 3). These values indicate strongly acidic to acidic conditions. The behavior is similar in both profiles, with values increasing until a certain depth (up to 0.80-1.00 m in PP and up to 0.64-0.88 m in AP) and a slight decrease thereafter.

Organic composition

Besides the carbon contents varying between soil horizons in both profiles, they also vary between analysis methods. The organic carbon values determined by ignition in a muffle oven (C_M) are much higher than those values obtained by wet combustion - Walkley-Black method (C_WB) (Table 3). According to Walkley-Black (1934), the determination of organic carbon by wet oxidation quantifies only those easily oxidizable or decomposable organic materials. Therefore, other carbon sources, such as carbonates or recalcitrant compounds (charcoal), or fibers containing vegetation remains and fragments not yet decomposed (mainly in PP, with the highest values of URF and RF; Table 1), possibly were discriminated in the determination by the Walkley-Black and counted by the muffle.

In general, PP shows much higher values than those determined in AP, with C_M values between 33.8 and 58.5 %, a mean of 49.1 ± 8.0 %, and C_WB values between 20.0 and

33.0 %, with a mean of 25.9 ± 5.2 %. However, for AP, the C_M values are between 6.5 and 24.7 %, with a mean of 11.1 ± 6.0 %, and C_WB values are between 0.3 and 11.9 %, with a mean of 3.7 ± 3.5 %. From top to base, carbon contents show a general increase in PP and a decrease in AP, although significant variations are found at different soil horizons in the latter profile.

Regarding C_{org} stocks, PP presents a value of 53.25 kg m^{-2}, while AP has a stock of 39.11 kg m^{-2}. Taking PP as reference, it is believed that the anthropization effect, caused mainly by the artificial drainage in AP, favored a significant reduction in carbon stock. If the mean values of C_WB are taken into account, this degradation has produced an organic carbon loss of around 22 %.

Nitrogen contents are also much higher in PP (Table 3). In this case, the values are between 1.28 and 1.72 %, with a mean of 1.5 ± 0.1 %, while the N values are between 0.02 and 1.13 g kg^{-1}, with a mean of 0.3 ± 0.3 %, in AP. In PP, the N contents remain more or less constant throughout the profile, while in AP these values decrease with depth.

For C/N ratios, the values are also much higher for AP than PP (Table 2). For PP, the C/N ratios vary between 20.5 and 45.7, with a mean of 33 ± 7.9, and these ratios vary between 21.9 and 92.9, with a mean of 52 ± 21.7, for AP. In general, the values increase with depth in both profiles, but with some fluctuations.

Table 2. Values of physical properties of the studied profiles and their mean comparison results

Hor.	Layer	Sand	Silt	Clay	GM	VM	BD	BDO	MM	MR
	m		%		g g^{-1}	cm^3 cm^{-3}		Mg m^{-3}		%	m m^{-1}
					PP					
Hd1	0.00-0.20	45	34	21	2.04	0.64	0.31	0.18	42	0.09
Hd2	0.20-0.40	50	29	21	4.48	0.71	0.16	0.12	24	0.03
Hd3	0.40-0.60	34	45	21	4.51	0.68	0.15	0.11	24	0.02
Hdo1	0.60-0.80	54	25	21	6.48	0.80	0.12	0.10	15	0.01
Hdo2	0.80-1.00	53	26	21	8.68	0.80	0.09	0.09	8	0.02
Hdo3	1.00-1.20	58	26	16	8.10	0.74	0.09	0.08	7	0.02
Ho1	1.20-1.40	58	31	11	8.29	0.76	0.09	0.09	4	0.01
Ho2	1.40-1.60	54	35	11	8.77	0.81	0.09	0.09	nd	nd
Mean±SD		51^A±7	32^A±6	18^A±4	6.42^A±2.33	0.74^A±0.06	0.14^A±0.08	0.11^A±0.03	18^A±13	0.02^A±0.03
					AP					
Hodp	0.00-0.14	42	27	31	0.52	0.25	0.48	0.20	57	0.18
A1	0.14-0.20	43	21	36	0.41	0.30	0.73	0.18	76	0.37
A2	0.20-0.31	50	14	36	0.28	0.25	0.88	0.14	85	0.50
A3	0.31-0.48	49	20	31	0.39	0.33	0.83	0.14	83	0.46
A4	0.48-0.64	50	19	31	0.32	0.36	1.10	0.14	87	0.64
Cg1	0.64-0.88	37	23	41	0.55	0.53	0.97	0.17	82	0.53
Cg2	0.75-1.06	58	6	36	0.26	0.36	1.36	0.15	89	0.80
Cg3	0.88-1.06	64	0	36	0.31	0.40	1.30	0.15	88	0.77
Cg4	0.75-1.20$^+$	59	0	41	...		...	...	...	...
Mean±SD		50^A±8	14^B±9	35^B±4	0.38^B±0.10	0.35^B±0.09	0.96^B±0.29	0.16^B±0.02	81^B±10	0.53^B±0.21
p-value		92 10^{-2}	86 10^{-5}	76 10^{-8}	24 10^{-5}	2.39 10^{-7}	6.35 10^{-5}	0.01	5 10^{-7}	0.02 10^{-3}

Hor: horizon. GM: gravimetric moisture. VM: volumetric moisture. BD: bulk density. BDO: bulk density of organic matter. MM: mineral material content. MR: minimum residue. "–" not applicable numerical data. "..." not available numerical data. Superscript capital letters (A and B) indicate a statistically significant difference between means when comparing the properties of different soil profiles.

Table 3. Values of chemical properties of the studied profiles and their mean comparison results

Hor.	Layer	pH(CaCl$_2$)	C_M	C_WB	ΔC	N	C/N	Ca^{2+}	Mg^{2+}	K$^+$	P	H+Al	SB	CEC	BS
	m				%			cmol$_c$ dm^{-3}			mg dm^{-3}	cmol$_c$ dm^{-3}			%
							PP								
Hd1	0.00-0.20	3.75	33.8	20.0	13.8	1.65	20.5	0.29	0.04	0.11	5.24	5.68	0.45	6.13	7.28
Hd2	0.20-0.40	3.76	44.4	20.6	23.8	1.46	30.4	0.29	0.04	0.07	4.44	5.62	0.39	6.01	6.49
Hd3	0.40-0.60	3.93	44.0	21.6	22.4	1.56	28.2	0.29	0.03	0.02	2.71	4.65	0.34	4.99	6.74
Hdo1	0.60-0.80	3.83	49.2	29.2	20.0	1.72	28.6	0.31	0.03	0.03	2.94	5.23	0.37	5.60	6.61
Hdo2	0.80-1.00	4.16	53.5	22.7	30.8	1.60	33.4	0.33	0.03	0.01	2.62	3.62	0.36	3.98	9.07
Hdo3	1.00-1.20	4.01	53.7	28.7	25.0	1.49	36.0	0.32	0.02	0.01	1.44	4.25	0.35	4.60	7.59
Ho1	1.20-1.40	3.86	55.5	33.0	22.5	1.36	40.8	0.36	0.02	0.01	1.44	5.05	0.40	5.45	7.24
Ho2	1.40-1.60	3.88	58.5	31.0	27.5	1.28	45.7	0.31	0.02	0.01	0.70	4.92	0.34	5.26	6.46
Mean±SD		3.90^A ±0.14	49.1^A ±8.0	25.9^A ±5.2	23.2^A ±4.7	1.52^A ±0.1	33.0^A ±7.9	0.31^A ±0.02	0.03^A ±0.01	0.04^A ±0.03	2.69^A ±1.45	4.88^A ±0.65	0.37^A ±0.03	5.25^A ±0.67	7.18^A ±0.81
							AP								
Hodp	0.00-0.14	3.88	24.7	11.9	12.8	1.13	21.9	0.32	0.04	0.25	5.62	4.92	0.60	5.52	10.94
A1	0.14-0.20	3.93	14.2	5.9	8.3	0.46	30.9	0.33	0.03	0.10	1.37	4.65	0.46	5.11	8.96
A2	0.20-0.31	4.07	9.0	3.0	6.0	0.20	45.0	0.28	0.02	0.08	0.73	3.98	0.39	4.36	8.76
A3	0.31-0.48	4.07	9.6	3.1	6.5	0.18	53.3	0.32	0.03	0.06	0.51	3.98	0.41	4.38	9.24
A4	0.48-0.64	4.12	7.6	2.1	5.5	0.12	63.3	0.33	0.02	0.03	0.32	3.79	0.39	4.17	9.27
Cg1	0.64-0.88	4.17	10.3	3.7	6.6	0.21	49.0	0.30	0.02	0.03	0.35	3.58	0.35	3.93	9.01
Cg2	0.75-1.06	4.14	6.5	1.3	5.2	0.07	92.9	0.35	0.03	0.02	0.26	3.70	0.40	4.10	9.73
Cg3	0.88-1.06	4.1	6.8	2.1	4.7	0.11	61.8	0.39	0.03	0.02	0.10	3.85	0.44	4.29	10.18
Cg4	0.75-1.20$^+$	4.1	...	3.0	...	0.02	...	0.34	0.03	0.02	0.22	3.85	0.38	4.23	9.03
Mean±SD		4.06^B ±0.10	11.1^B ±6.0	3.7^B ±3.5	7.0^B ±2.4	0.28^B ±0.3	52.3^B ±20.3	0.33^A ±0.03	0.03^A ±0.01	0.07^A ±0.07	1.05^B ±1.65	4.03^B ±0.42	0.42^A ±0.07	4.46^B ±0.49	9.46^B ±0.67
p-value		0.01	8 10^{-8}	3 10^{-7}	8 10^{-6}	7.9 10^{-7}	0.04	0.22	0.82	0.24	0.06	0.01	0.10	0.02	4.75 10^{-5}

Hor.: horizon. C_M: carbon by muffle oven ignition (600 °C/6h). C_WB: Carbon by Walkley-Black method. ΔC: difference between carbons estimated by muffle oven ignition and Walkley-Black method. C/N: C/N ratio (here, the carbon is determined in muffle oven). H+Al: potential acidity. SB: sum of bases. CEC: cation exchange capacity. BS: base saturation. "..." not available numerical data. Superscript capital letters (A and B) indicate a statistically significant difference between means when comparing the properties of different soil profiles.

Chemical behavior

In general, Ca^{2+}, Mg^{2+}, and K$^+$ have the same behavior in the studied profiles (Table 3). For PP, the Ca^{2+} concentration varies between 0.29 and 0.36 cmol$_c$ dm^{-3}, with a mean of 0.31 ± 0.02 cmol$_c$ dm^{-3}, and in AP it ranges between 0.28 and 0.39 cmol$_c$ dm^{-3}, with a mean of 0.33 ± 0.03 cmol$_c$ dm^{-3}. In PP, Mg^{2+} varies between 0.02 and 0.04 cmol$_c$ dm^{-3}, with a mean of 0.03 ± 0.01 cmol$_c$ dm^{-3}, while in AP, this variation is between 0.02 and 0.04 cmol$_c$ dm^{-3}, with a mean of 0.03 ± 0.01 cmol$_c$ dm^{-3}. For K$^+$, however, the concentrations are between 0.01 and 0.11 cmol$_c$ dm^{-3}, with a mean of 0.04 ± 0.03 cmol$_c$ dm^{-3}, in PP; and between 0.02 and 0.25 cmol$_c$ dm^{-3}, with a mean of 0.07±0.07 cmol$_c$ dm^{-3}, for AP. The concentrations for Mg^{2+} and K$^+$ are higher in the topsoil horizons, while higher Ca^{2+} concentrations are found at the bottom.

Sum of bases (SB) shows values between 0.34 and 0.45 cmol$_c$ dm^{-3}, with a mean of 0.37 ± 0.03 cmol$_c$ dm^{-3}, for PP, and the sum of these exchangeable basic cations ranges between 0.35 and 0.60 cmol$_c$ dm^{-3}, with a mean of 0.42 ± 0.07 cmol$_c$ dm^{-3}, for AP (Table 3). Higher values are also found at the top of the profiles in both situations. Phosphorus contents vary between 0.70 and 5.24 mg dm^{-3}, with a mean

of 2.69 ± 1.45 mg dm^{-3}, in PP, and between 0.10 and 5.62 mg dm^{-3}, with a mean of 1.05 ± 1.55 mg dm^{-3}, in AP (Table 3). The highest P concentrations are also more evident in the topsoil horizons.

Potential acidity (H+Al) varies between 36.2 and 56.8 cmol$_c$ dm^{-3}, with a mean of 48.8 ± 6.5 cmol$_c$ dm^{-3}, in PP, and between 35.8 and 49.2 cmol$_c$ dm^{-3}, with a mean of 40.3 ± 4.2 cmol$_c$ dm^{-3}, in AP (Table 3). In PP, cation exchange capacity (CEC) ranges between 37 and 57 cmol$_c$ dm^{-3}, with a mean of 49 ± 7 cmol$_c$ dm^{-3}, and in AP it is between 36 and 50 cmol$_c$ dm^{-3}, with a mean of 41 ± 4 cmol$_c$ dm^{-3}. Higher values are also seen at the top of both profiles for these two attributes. Base saturation (BS) varies from 0.69 to 0.99 %, with a mean of 0.77 ± 0.09 %, in PP, and between 0.98 and 1.21 %, with a mean of 1.03 ± 0.08 %, in AP (Table 3). However, these values are very low, and do not show a clear trend with depth.

Organic matter fraction

In PP, humic acid (HA) ranges between 0.10 and 0.26 %, with a mean of 0.15 ± 0.05 %, fulvic acid (FA) between 0.06 and 0.18 %, with a mean of 0.11 ± 0.03 %, and humin (H) between 5.18 and 16.00 %, with a mean of 10.20 ± 3.61 % (Table 4). In AP, percentages of HA vary between 0.40 and 1.90 %, with a mean of 1.08 ± 0.50 %, FA varies between 0.29 and 1.39 %, with a mean of 0.73 ± 0.31 %, and H between 24.85 and 114.73 %, with a mean of 67.43 ± 30.68 %. The percentages are much higher for AP.

In PP, the humic acid carbon content (C_{HA}) is between 0.028 and 0.054 g kg^{-1}, with a mean of 0.039 ± 0.010 g kg^{-1}, fulvic acid carbon content (C_{FA}) is between 0.016 and 0.038 g kg^{-1}, with a mean of 0.027 ± 0.008 g kg^{-1}, and the carbon content of humin (C_H) is between 1.49 and 3.37 g kg^{-1}, with a mean of 2.54 ± 0.69 g kg^{-1} (Table 4). In AP, the C_{HA} values vary between 0.015 and 0.061 g kg^{-1}, with a mean of 0.034 ± 0.014 g kg^{-1}, C_{FA} varies between 0.016 and 0.035 g kg^{-1}, with a mean of 0.023 ± 0.007 g kg^{-1}, and C_H is between 0.88 and 3.10 g kg^{-1}, with a mean of 2.09 ± 0.70 g kg^{-1}. In general, carbon content of all fractions in PP appears to show a downward trend to a certain intermediate position (~0.80-1.00 m), after which content increases to the bottom, reaching values close to those seen in the first two horizons. In AP, however, the trend is for the contents of all fractions to decrease with depth. Both the humic fraction percentage and carbon concentration follow the same decreasing sequence: H>HA>FA.

Soil organic matter quality indices

The C_{HA}/C_{FA} is an index of organic matter condensation, while $C_H/(C_{HA}+C_{FA})$ represents the structural stability of organic matter, and $(\Sigma C\_HF/C\_WB) \times 100$ measures the degree of humification of organic matter (Labrador Moreno, 1996). In general, the means of C_{HA}/C_{FA} between the profiles are very close, with 1.48 ± 0.16 for PP (varying between 1.15 and 1.75) and 1.47 ± 0.31 for AP (varying between 0.93 and 1.76) (Table 4). Similarly for $C_H/(C_{HA}+C_{FA})$, the mean values are also very close, with 40.21 ± 11.42 for PP (varying between 25.06 and 57.14) and 36.84 ± 3.99 for AP (varying between 28.92 and 42.13). However, the means of $(\Sigma C\_HF/C\_WB) \times 100$ are quite different for both profiles, with 10.46 ± 3.66 % for PP (varying between 5.39 and 16.28 %) and 69.24 ± 31.45 % for AP (varying between 25.54 and 118.12 %).

In PP, there is a general trend for the three indices, with a decrease from the top up to ~0.50 m, a slight increase between 0.70 and 0.90 m and, after that, a return to the previous decrease to the base. However, the highest values of C_{HA}/C_{FA} occur between 0.70 and 1.10 m, with the highest values of $C_H/(C_{HA}+C_{FA})$ also between 0.70 and 1.10 m and in the superficial horizon. The highest values of $[(\Sigma C\_HF/C\_WB) \times 100]$ are in the uppermost horizons from the top up to 0.50 m and in lower horizons after 1.10 m to the base. In general, the trends are different for the indices in AP, with increasing

Table 4. Humic soil fractions (percentage and carbon content of the respective fractions), microbiological properties, soil quality indices based on carbon contents of the humic soil fractions of the studied profiles, and their mean comparison results

Hor.	Layer	HA	FA	H	C_{HA}	C_{FA}	C_H	MBC	BR	C_{HA}/C_{FA}	$C_H/(C_{HA}+C_{FA})$	$(\Sigma C\_HF/C\_WB) \times 100^{(1)}$
	m				%			— µg g^{-1} day^{-1} —				%
							PP					
Hd1	0.00-0.20	0.17	0.11	16.00	0.034	0.022	3.20	228	1.20	1.55	57.14	16.28
Hd2	0.20-0.40	0.26	0.18	15.53	0.054	0.037	3.20	234	1.53	1.47	35.29	15.97
Hd3	0.40-0.60	0.16	0.11	6.88	0.035	0.024	1.49	333	1.26	1.44	25.06	7.16
Hdo1	0.60-0.80	0.10	0.06	8.38	0.028	0.018	2.45	305	1.41	1.56	53.19	8.54
Hdo2	0.80-1.00	0.12	0.07	10.78	0.028	0.016	2.45	305	2.47	1.75	55.61	10.97
Hdo3	1.00-1.20	0.12	0.08	5.18	0.035	0.024	1.49	273	1.48	1.44	25.06	5.39
Ho1	1.20-1.40	0.16	0.11	10.20	0.054	0.037	3.37	262	1.41	1.47	37.13	10.48
Ho2	1.40-1.60	0.14	0.12	8.67	0.043	0.038	2.69	245	0.01	1.15	33.17	8.93
Mean±SD		0.15^A ±0.05	0.11^A ±0.03	10.20^A ±3.61	0.039^A ±0.010	0.027^A ±0.008	2.54^A ±0.69	273^A ±36	1.35^A ±0.63	1.48^A ±0.16	40.21^A ±12.42	10.46^A ±3.66
							AP					
Hodp	0.00-0.14	0.40	0.29	24.85	0.048	0.034	2.96	119	0.97	1.41	36.22	25.54
A1	0.14-0.20	1.03	0.59	52.52	0.061	0.035	3.10	130	1.24	1.76	32.51	54.14
A2	0.20-0.31	1.26	0.72	79.06	0.038	0.022	2.37	115	1.32	1.75	39.87	81.04
A3	0.31-0.48	1.17	0.68	75.07	0.036	0.021	2.33	111	1.30	1.71	40.69	76.91
A4	0.48-0.64	1.85	1.08	114.73	0.039	0.023	2.41	115	1.34	1.72	39.26	117.75
Cg1	0.64-0.88	0.83	0.52	50.07	0.031	0.019	1.85	130	0.71	1.60	36.99	51.42
Cg2	0.75-1.06	1.90	1.39	114.84	0.025	0.018	1.49	152	1.18	1.37	34.95	118.12
Cg3	0.88-1.06	0.77	0.81	66.44	0.016	0.017	1.40	146	1.53	0.95	42.13	68.02
Cg4	0.75-1.20$^+$	0.49	0.53	29.29	0.015	0.016	0.88	...	...	0.93	28.92	30.30
Mean±SD		1.08^B ±0.50	0.73^B ±0.31	67.43^B ±30.68	0.034^A ±0.014	0.023^A ±0.007	2.09^A ±0.70	127^B ±14	1.20^A ±0.24	1.47^A ±0.31	36.84^A ±3.99	69.24^B ±31.45
p-value		8.03 10^{-4}	4.07 10^{-4}	7.13 10^{-4}	4.73 10^{-1}	3.04 10^{-1}	2.25 10^{-1}	0.29 10^{-7}	0.57	9.25 10^{-1}	5.11 10^{-1}	7.08 10^{-4}

Hor: horizon. HA: humic acid. FA: Fulvic acid. H: Humin. CHA: carbon of humic acid. CFA: carbon of fulvic acid. CH: carbon of humin. MBC: microbial biomass carbon. BR: basal respiration. CHA/CFA: condensation index of organic matter. CH/(CHA+CFA): structural stability index of organic matter. "..." not available numerical data. [1] (ΣC_HF/C_WB) × 100: humification degree of organic matter; ΣC_HF: sum of the humic fractions'carbon content (fulvic acid+humic acid+humin). Superscript capital letters (A and B) indicate a statistically significant difference between means when comparing the properties of different soil profiles.

values up to 0.88 m for C_{HA}/C_{FA} and $C_H/(C_{HA}+C_{FA})$, and up to 0.64 m for [(ΣC_HF/C_WB) × 100]. Subsequently, their trend is one of general decrease.

Microbial biomass carbon and basal respiration

In PP, the microbial biomass carbon (MBC) varies between 228 and 333 µg g^{-1} day^{-1}, with a mean of 273 ± 36 µg g^{-1} day^{-1}, and basal respiration (BR) is between 0.01 and 2.47 µg g^{-1} day^{-1}, with a mean of 1.35 ± 0.63 µg g^{-1} day^{-1}. For AP, MBC values are between 111 and 152 µg g^{-1} day^{-1}, with a mean of 127 ± 14 µg g^{-1} day^{-1}, and BR values between 0.71 and 1.53 µg g^{-1} day^{-1}, with a mean of 1.20 ± 0.24 µg g^{-1} day^{-1} (Table 4). The PP presents greater data variation for both MBC and BR. Up to 0.60 cm, MBC values increase, reaching their maximum value, after which there is a sharp decrease. For BR, however, values increase up to 1.00 m, also reaching their maximum value, after which the values decrease sharply. The AP shows little variation in MBC and BR, whereby decreasing trends of MBC are seen between 0.14 and 0.81 m, and of BR between 0.48 and 0.81 m.

Principal components analysis (PCA)

Three principal components were extracted, accounting for ~95 % of the dataset's total variance (Table 5). Soil morphological properties, such as color, structure, plasticity, the

boundary between horizons, and the von Post organic matter decomposition degree were not included in the PCA due to their qualitative and non-continuous nature. After the mean comparison test, only 21 properties with significant differences between profiles were chosen from all quantitative properties (37 properties) (Tables 1, 2, 3 and 4) for the PCA. Silt and VM were not used in the PCA, because the first one was not analytically obtained, while the second one, related to water content as well as GM, is not the physical property mentioned in characterization tests for *Organossolos* (Santos et al., 2018)*.

The first principal component (PC1) explains ~52 % of the data variance and shows high positive loadings (0.70-0.92) for BDO, MM, H, HA, FA, clay, (ΣC_HF/C_WB) × 100, BD, BS and MR; and high negative loadings (-0.74 to -0.90) for MBC, GM, ΔC, C_M, and C_WB (Table 5). It reflects the opposition between mineral matter content and humification of organic matter versus relative accumulation of organic matter content. The second component (PC2) explains ~22 % of the variance, showing high positive loadings (0.92) for H+Al and CEC, and high negative loading (-0.92) for pH, which indicates the chemical

Table 5. Factor loadings for the three principal components extracted by PCA using morphological, physical, chemical and microbiological properties of the studied profiles

Property	PC1	PC2	PC3
BDO	**0.92**	0.08	0.20
MBC	**-0.90**	0.20	0.22
MM	**0.89**	-0.27	-0.34
H	**0.88**	-0.16	-0.33
HA	**0.88**	-0.15	-0.37
GM	**-0.87**	0.30	0.37
FA	**0.86**	-0.14	-0.45
Clay	**0.85**	-0.40	-0.14
ΔC	**-0.83**	0.26	0.47
(ΣC_HF/C_WB) × 100	**0.80**	-0.25	-0.46
C_M	**-0.79**	0.35	0.49
BD	**0.74**	-0.37	-0.54
C_WB	**-0.74**	0.41	0.52
BS	**0.70**	-0.60	0.03
MR	**0.70**	-0.39	-0.58
H+Al	-0.21	**0.92**	0.32
CEC	-0.15	**0.92**	0.35
pH	0.21	**-0.92**	-0.32
C/N	0.19	-0.41	**-0.83**
P	-0.27	0.46	**0.79**
N	-0.63	0.42	**0.65**
Eigv	16.15	2.72	1.02
Var (%)	51.66	21.85	21.22
Var_ac	51.66	73.52	94.73

BDO: bulk density of organic matter; MBC: microbial biomass carbon; MM: mineral material content; H: humin; HA: Humic acid; GM: gravimetric moisture; FA: fulvic acid; ΔC: difference between carbons estimated by muffle oven ignition and Walkley-Black method. (ΣC_HF/C_WB) × 100: humification degree of organic matter; ΣC_HF: sum of the humic fractions'carbon content (fulvic acid+humic acid+humin). C_M: carbon estimated by muffle oven ignition; BD: bulk density; C_WB: carbon estimated by wet combustion – Walkley-Black method; BS: base saturation; MR: minimum residue; CEC: cation exchange capacity; C/N: C/N ratio. Eigv: autovalores; Var (%): variance percentage; Var_ac: accumulated variance.

reactivity of the studied soils. Finally, the third component (PC3) explains ~21 % of the variance and shows high positive loading for P (0.79), moderate positive loading for N (0.65), and high negative loading for the C/N ratio (-0.83), specifically reflecting the mineralization process of organic matter.

The variance proportion of each property explained by each principal component is represented by the length of the bar segment in figure 2, where much of the variance of a property is correctly explained by one of the three principal components. Each principal component can be considered a good proxy for the underlying processes/drivers, since the maximum contribution of each property is linked with each of these. However, due to autogenic processes in these environments, most properties may also have a small fraction of their variances associated with more than one component.

DISCUSSION

The analyzed properties have to be interpreted as proxies of the processes/drivers that control the nature of the studied profiles. Thus, each principal component represents a combination of morphological, physical, chemical and microbiological proxies related to an underlying factor.

Humification versus preservation of organic matter

The properties with positive loadings of PC1 (Table 5) are related to the increment in mineral matter content (MM, MR, BD and clay), increased degree of organic matter humification [FA, HA, and H fractions, (ΣC_HF/C_WB) × 100, and BDO], and release of exchangeable bases (BS). The humic substances are the main component of organic matter derived from the decomposition of plant and animal wastes on the surface of soils, waters and sediments (Canellas and Santos, 2005), representing the most stable part of the organic matter. The (ΣC_HF/C_WB) × 100 is an index that measures the degree of organic matter humification (Labrador Moreno, 1996), like BDO, which indicates more humified organic matter (Andriesse, 1988). Therefore, properties with positive loadings of PC1 can be considered proxies of soils with more humified organic matter, followed by an increase in mineral material.

The properties with negative loadings of PC1 are related to the increment in organic carbon (ΔC, C_M, and C_WB), high water content (GM), and greater microbiota activity linked to a high proportion of living organic matter more sensitive to initial changes in decomposition (MBC) (Jenkinson and Rayner, 1977; Jenkinson and Ladd, 1981; Powlson et al., 1987; Wardle, l992). Thus, these properties are associated and suggest environments with highly preserved and poorly humified organic matter. The high water content is probably associated with greater porosity due to more preserved organic matter with many fibers (sponge effect). This is corroborated by the abundance of plant macro-remains measured by URF and RF in PP (Table 1). Although the correlation analysis has not been shown here, these properties have a high correlation (r = 0.89 between GM and URF; and r = 0.86 between GM and RF).

The opposite loadings indicate that as the organic matter humification processes and mineral matter contents increase in the studied soils, their contents of organic matter decrease. Therefore, PC1 reflects the signal of organic matter humification in association with the increment of mineral material, versus preservation of organic matter. Under more unstable conditions with major disturbances (in our study a drainage channel was opened), the organic matter goes into a process of subsidence, due to its exposure to more oxic conditions, either through heterotrophic oxidation (Ambak and Melling, 2000; Dradjad et al., 2003) by aerobic microorganisms (Tate, 1980) and/or by burning the plant material (Ebeling et al., 2013).

The PP shows an unexpected sequence of sapric, hemic, fibric organic horizons from top to bottom, respectively, for a natural condition without any disturbance. Thus, the upper part of the profile is more decomposed than the lower part. Most of the organic matter accumulated in this *vereda* originates from the decay of Buriti palm roots with a partial contribution from degradation of their leaves, fruits, and stems, as well as roots and aerial parts of hygrophilous plants of the herbaceous strata (Poaceae, Cyperaceae, and Xyridaceae) (this information was observed in loco). Certainly, the reduction conditions should vary with depth, following the changing hydrological conditions over time, which would explain a higher degree of decomposition in the upper part (0.00-0.60 m). Due to the oscillation of the water table, especially in the Cerrado's well-defined dry season, there could be a greater microbial activity, as previously discussed, despite the fact that the age of the organic material at depth must be hundreds or thousands of years older. Another possibility takes into account that the palms have launched more recent roots to greater depths as horizontal, dense, finely rooted, centrimetrical layers (Van Donselaar-Ten Bokkel Huinink, 1966), considering that there may have been progressive lowering of the water table level in the last decades due to artifical drainage in AP. Thus, the last hypothesis considers a renewal of organic matter at depth.

The highest clay content occurs in a more degraded environment and is mainly due to the decomposition process of organic matter and the effective nutrient cycling processes (including desorption of elements and mineralization). In addition, the input of the surrounding alluvial/colluvial materials of Oxisols positioned on the slopes may also contribute to increased clay content. This input is higher in AP, mainly due to greater vegetation suppression (gallery forest) in this profile, besides its lower position. In PP,
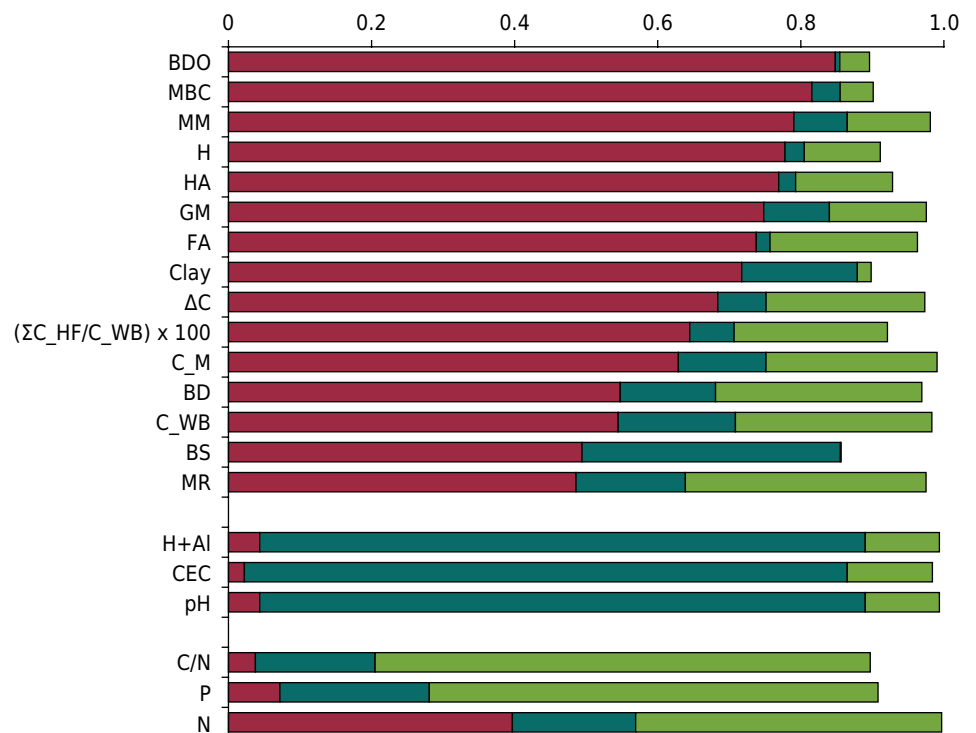
Figure 2. Fractionation of the variables' communalities used in the PCA. The communality of each variable (i.e., the proportion of its variance explained by each component) corresponds to the total length of the bar, and the segments of the bars represent the proportion of variance in each principal component. The variables are ordered by the component with the largest share of variance. Black: PC1; Grey: PC2; and White: PC3. BDO: bulk density of organic matter; MBC: basal respiration; MM: mineral material content; H: humin; HA: humic acid; GM: gravimetric moisture; FA: fulvic acid; ΔC: difference between carbons estimated by muffle oven ignition and Walkley-Black method; (ΣC_HF/C_WB) × 100: humification degree of organic matter. C_M: carbon by muffle oven ignition (600 °C/6h); BD: bulk density; C_WB: carbon by Walkley-Black method; BS: base saturation; MR: minimum residue; H+Al: potential acidity; CEC: cation exchange capacity; C/N: C/N ratio (here, the carbon is determined in muffle oven).

the more preserved vegetation has been working as a filter that retains the input of this sediment. All these situations related to the clay content increase, incrementing MM and MR, can produce a relative dilution of the organic matter content in these soils (Horák-Terra et al., 2014). The release of exchangeable bases, which causes an increase in base saturation values, is in fact associated with greater degradation in these soils ($r = 0.66$ between Mg^{2+} and clay; and $r = 0.45$ between K^+ and clay).

For N, a significant proportion (40 %) of its variance (Figure 2) is associated with the negative loading of PC1, although this component is not the main controlling factor of its behavior. There are chemical structure models described in the literature that propose that nitrogen (biophyllic element) is one of the main constituents of organic matter and its main component (humic substances) being, for example, present in the elementary composition presented by the proposal of Schulten and Schnitzer (1993). This is in agreement with and related to more preserved organic matter in a less disturbed environment.

In figure 3a, the changes in PC1 scores with depth can be seen in both PP and AP. The highest scores are observed in AP with all positive values. Meanwhile, most values are negative in PP, except in the superficial horizon. Therefore, the data show much more humified organic matter with a greater increase in inorganic materials in AP, indicating a disturbance at different depths related to more oxidized environments. On the other hand, the organic matter is much more preserved in PP, especially below 0.30 m. More preserved organic matter, in addition to its higher concentrations, is related to environments with greater preservation of plant remains in a more anoxic and alive environment (Bispo et al., 2016).

Horák-Terra et al. (2014) also found associated behavior among C, N and GM properties (means of 21 ± 14 %, 0.6 ± 0.6 %, and 59 ± 26 %, respectively), related to more preserved environments in Pleistocene and Holocenic age peatlands of the Serra do Espinhaço Meridional (Minas Gerais State, Brazil). The oldest age recorded for the peat is 43,254 ± 784 cal BP for the São João da Chapada mire and for the mineral sediment is 210,000 ± 47,000 cal BP for the Pinheiro mire. The same authors also verified that MM, MR, BD and Si (means of 58 ± 29 %, 0.27 ± 0.29 mm^{-1}, 0.5 ± 0.4 mg m^{-3}, and 13 ± 14 %, respectively) were correlated and indicated moments of greater instability in these peatlands, with the input of quartz transported from the catchment soils to the mires, since the main geological material in that region is quartzite. The BDO values found by Horák-Terra et al. (2014) ranged between 0.02 and 0.3 mg m^{-3}, with a mean of 0.14 ± 0.06 mg m^{-3}. For other peatlands in the Serra do Espinhaço Meridional, Silva et al. (2009a) found clay values between 0 and 55 %, BS values between 1 and 11 %, and MBC values between 10.3 and 716.6 µg g^{-1} day^{-1}. For the same mires, the carbon contents of the humic fractions found by Silva et al. (2009b) were as follows: between 2.35 and 31.26 % for HA, between 0.59 and 74.46 % for FA, and between 4.27 and 96.26 % for H, although the authors did not show the humic fraction contents.

It seems that there is no research in the literature showing this data analysis approach for *vereda* soils, and there are only a few studies focusing on their properties. To mention a few, Ramos et al. (2006) studied *vereda* soils from the Triângulo Mineiro region (Minas Gerais, Brazil), and found ~50 % and ~15 % organic matter for two distinct geomorphic surfaces called Chapada and Bauru, respectively. These authors found maximum clay contents of ~60 %, this value being observed on both surfaces. Ribeiro et al. (2019) also studied *vereda* soils in the same Triângulo Mineiro region, near the municipality of Uberlândia, where total carbon contents ranging from 0.41 to 13.75 % were found. In this same study, clay contents varied between 13.8 and 86.3 %, since the geology of the area is characterized by sedimentary deposits, including clay sediments and sandstones of the Bauru Group. In addition to the previous authors, Rosolen et al. (2015) also found organic carbon values ranging from 0.5 to 11.6 % for a *vereda* soil in the same region,
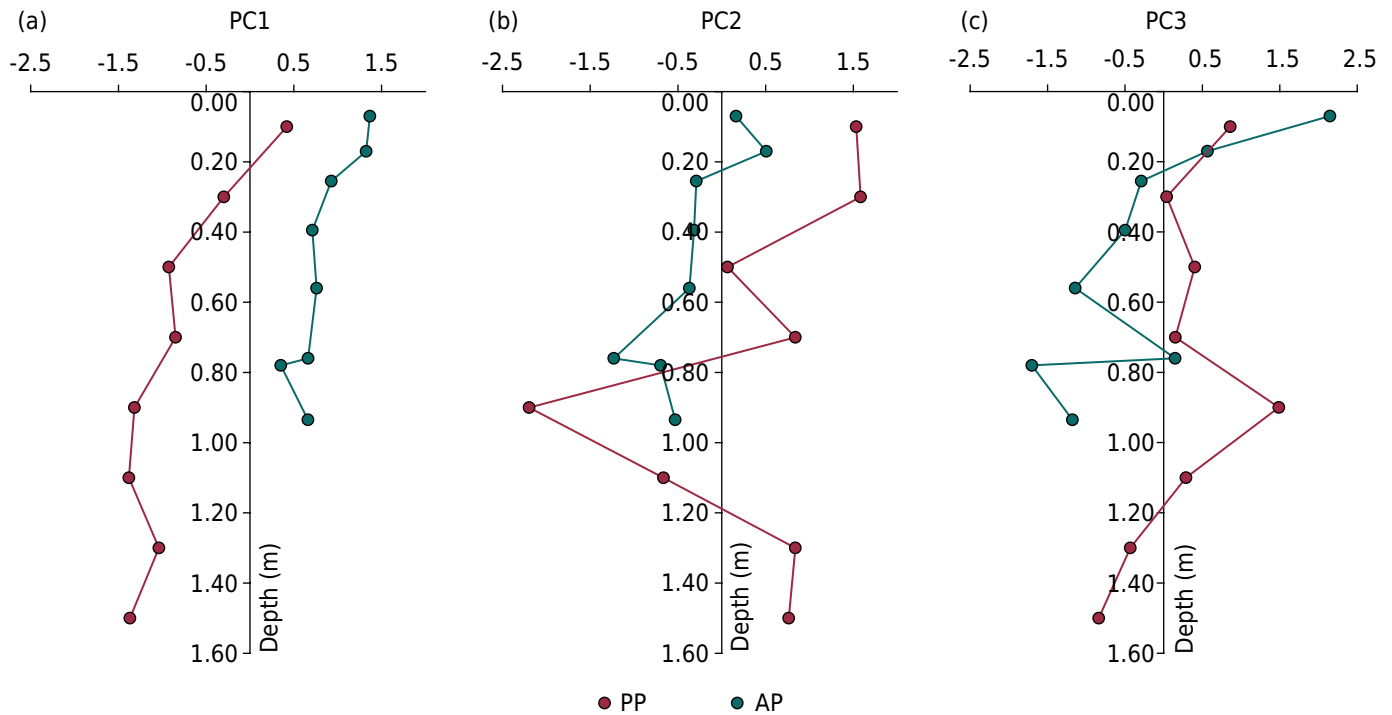
Figure 3. Profile of the PCA factor scores of the three components using morphological, physical, chemical and microbiological properties of the studied profiles.

around Uberlândia. Sousa et al. (2015) studied *vereda* soils located in the municipality of Bela Vista de Goiás (Goiás state, Brazil), and obtained the following values for organic matter and clay, respectively, for the different land uses: 1.6-7.3 % and 38.3-39.3 % in a preserved area, 1.6-7.7 % and 33.3-41.3 % in pasture, and 1.6-3.5 % and 35.0-39.0 % in an agricultural area.

Soil chemical reactivity

The second principal component (PC2) mainly represents the chemical reactivity of the studied soils. The properties with positive loadings of PC2 (H+Al and CEC) (Table 5) increase when soils tend to be more acidic, that is, with lower pH values, the latter presenting negative loading. As all these attributes include manifested properties, that is, those which are not part of its essence or inherent characteristics of an object, but instead related to the responses and/or stimulus exerted (behavior or evidenced reaction), there has to be one or more attributes involved as a controller (driver) for others to express themselves. However, with the dataset used here for PCA, this supposed controller is probably hidden, and a more exploratory analysis should be used.

For the studied soil profiles, PP with the highest organic matter contents tends to have the highest values of potential acidity, whereby a higher concentration of H+ ions to the detriment of low pH values is their main reason. Silva et al. (2008) found higher organic carbon values associated with higher H+Al values by comparing methods for estimating potential acidity in peatlands' organic soils from the Serra do Espinhaço Meridional (Minas Gerais, Brazil). Therefore, high values of organic matter are associated with more acidic environments and consequently more preserved *veredas*.

Although the organic matter fractions (humic acid, fulvic acid and humin) did not properly contribute to PC2 (Figure 2), they show high values of negative correlations with pH (HA: -0.76; HF: -0.76; and H: -0.64) and positive correlations with H+Al and CEC (HA: 0.77; HF: 0.76; and H: 0.68). Such correlations suggest that the more stable compartment of this organic matter is one of the main agents controlling the acidity and reactivity of these environments. It is worth noting that CEC values are high mainly due

to the greater contribution of H+Al in their calculations, which is associated with low concentrations of exchangeable basic cations. With the beginning of the degradation processes, the reduction of less decomposition resistant fractions (fulvic and humic acids), to the detriment of humin, produces a reduction in acidity and reactivity of the environment, corroborated by the lower correlations of these attributes (pH, H+Al and CEC) with the most resistant fraction (humin).

In figure 3b, changes in the PC2 scores with depth can be seen for both profiles. In general, the highest scores are observed in PP, most with positive values at the top and bottom. The trend of these scores is to decrease from the top to ~0.90 m, and then increase in the last 0.60 m. For AP, most scores are negative, especially below ~0.20 m, and its general trend is almost always decreasing. Thus, PP shows a more reactive soil, which is probably due to the larger organic matter content with a greater proportion of less labile fractions to decomposition, which is linked to more preserved soils. On the other hand, AP presents less reactive soil with a lower organic matter content of more labile fractions (easier decomposition), characterizing organic soils with a degradation factor.

Silva et al. (2008) and Silva et al. (2009a) found pH values in CaCl$_2$ between 2.8 and 4.1 cmol$_c$ dm^{-3}, and H+Al values between 5.0 and 146.4 cmol$_c$ dm^{-3} in peatlands' organic soils from the Serra do Espinhaço Meridional. In these same peatlands, Silva et al. (2009a) found CEC values from 4.7 to 150 cmol$_c$ dm^{-3}. For Rosolen et al. (2015), pH values were between 4.5 and 5.8 in the *vereda* soil close to Uberlândia. In the *vereda* of Bela Vista de Goiás, Sousa et al. (2015) found H+Al and CEC values between 5.1 and 6.8 cmol$_c$ dm^{-3} and 5.5 and 7.3 cmol$_c$ dm^{-3}, respectively, for a preserved area; between 3.5 and 5.1 cmol$_c$ dm^{-3} and 3.9 and 5.5 cmol$_c$ dm^{-3}, respectively, for pasture; and between 3.1 and 5.5 cmol$_c$ dm^{-3} and 3.1 and 5.5 cmol$_c$ dm^{-3}, respectively, for an agricultural area.

Mineralization of organic matter

The third principal component (PC3) shows positive loadings for P and N, and negative loading for C/N ratio (Table 5). Phosphorus and N are part of the structure of organic compounds that are mainly plant residues, in addition to microbial tissues, which contribute to the formation of organic soils (Schulten and Schnitzer, 1993). Their positive loadings indicate higher concentrations associated with less mineralized organic matter, which can be fresher (recent deposition) or of difficult decomposition, with higher levels of lignin and polyphenols. They may also be associated with the state of preservation (more preserved), enabling these elements to remain in the system. Negative loading represents the increase in the C/N ratio, which, besides indicating the type of organic matter (C/N ≥20 suggests higher terrestrial plants, and 4≤ C/N ≤10 suggests the presence of phytoplankton and bacteria) (Talbot and Johannessen, 1992), is also an excellent proxy of intense mineralization processes (Swift, 1996; Horák-Terra et al., 2014). The mineralization of organic matter is mainly related to environments with more oxygenated organic soils.

In figure 3c, changes in PC3 scores with depth can be seen in both profiles. In general, the highest scores are observed in PP with positive values along almost its entire extension, except at the bottom (in the last two horizons). The trend of scores for this profile increases from the top to ~0.90 m, and then decreases in the last 0.60 m. For AP, most scores are negative, except for from 0 to ~0.20 m. The general trend for this profile is decreasing, with an increase at around 0.76 m, after which it decreases again. Thus, PP has higher content of less mineralized organic matter, mainly due to its current state of preservation. It should be noted that the positive peak score at 0.90 m may have resulted from a greater contribution of vegetation with more recalcitrant organic matter and/or from the condition of a more humid climate at the time of formation of these strata, in relation to current conditions (drier conditions trigger higher rates of organic matter mineralization). Moreover, the lowest scores in the last two horizons of PP are probably due to older organic matter, following the classic deposicional sequence

proposed by Steno in 1669. In AP, mineralization is much higher than PP, mainly due to the effect of degradation (anthropization). In its first two horizons, the freshest organic matter is less mineralized because there was not enough time for the intensification of mineralization to occur. A peak is also observed at ~0.80 m, similarly to that verified in PP, probably due to the same constitution in terms of vegetation (a more recalcitrant organic matter) contributing to the formation of these strata.

In peatlands of the Serra do Espinhaço Meridional, P and N contents varied from 1.5 to 77.2 mg kg^{-1} and from 0.2 to 2.0 %, respectively (Silva et al., 2009b). According to Horák-Terra et al. (2014), the C/N ratio of these peatlands ranged between 12 and 92 with a mean of 44 ± 18, while these values ranged from 14 to 40 in Silva et al. (2009b).

In *vereda* soils from the Triângulo Mineiro, Ramos et al. (2006) found P-Mehlich values ranging between ~2 and 5 mg dm^{-3} for surface horizons and between ~1 and 3.5 mg dm^{-3} for subsurface horizons in both the Chapada and Bauru geomorphic regions. For total N in the *veredas* of Bela Vista de Goiás, Sousa et al. (2015) found contents between 0.26 and 0.52 % in a preserved area, 0.19 and 0.82 % in pasture, and 0.20 and 0.31 % in an agricultural area.

Effects of degradation: vereda behavior in phase space

The behavior of the studied soil profiles can be examined using a phase space diagram, as proposed by Dearing (2008). This is a bivariate plot showing the signal combinations based on the studied morphological, physical, chemical and microbiological properties through the projections of PCA scores (PC1, PC2 and PC3) for both profiles. In figure 4a, the PC1 vs. PC2 projection represents the combination of organic matter humification (PC1) and chemical reactivity (PC2) signals. The PC1 vs. PC3 projection shows the combination of organic matter humification (PC1) and mineralization (PC3) signals (Figure 4b). The PC2 vs. PC3 projection represents the combination of chemical reactivity (PC2) and organic matter mineralization (PC3) signals (Figure 4c).

The different preservation states of the profiles are clearly shown in the different scatter plots, where a clear distinction can be observed between scores corresponding to PP and those belonging to AP. According to the PC1 vs. PC2 projection (Figure 4a), the greater effect of organic matter humification in AP decreases the reactivity in this profile. The opposite is found in PP with more preserved organic matter and, thus, more reactive soil. In the PC1 vs. PC3 projection (Figure 4b), it can be observed that the effect of anthopization by opening the artificial drainage channel intensifies the associated processes of mineralization and humification of organic matter in AP. In PP, the most active degradation process is due to mineralization. When the PC2 vs. PC3 projection is observed (Figure 4c), the least reactive soil corresponds to the most mineralized soil for AP. The opposite behavior is observed in PP, however, its soil sample distribution is a little more spread. The role of organic matter degradation as the main underlying process (driver) is evident, whereby its influence clearly separates the scores of each profile on the first two scatter plots.

Vereda degradation sequence after artificial drainage

Figure 5 represents a likely sequence of stages related to the effects of removing the original vegetation and water over the 20 years elapsed since the anthropic action by opening the drainage channel. The stage 0 (Figure 5a) refers to the previous period before opening the drainage channel in AP. The pedogenesis and maintenance of these soils are basically the result of water table stability combined with rainwater recharge during periods of greater precipitation. However, rainwater is retained and stored in the soil profiles even in drier periods, which is probably due to their more preserved fibrous organic matter and higher porosity.

In stage 1 (Figure 5b), a break in water control occurs immediately after opening the artificial drainage channel, followed by the beginning of vegetation suppression. The water table level is lowered, mainly through subsurface lateral flow, which drags the surface recharged-water, due to a hydraulic gradient between the channel and surrounding soil, draining them as a single water body. At this time, the surface horizons of both PP and AP are exposed and become unsaturated, which triggers the acceleration and intensification of organic matter degradation/humification processes in these portions (Saidy et al., 2018).

In stage 2 (Figure 5c), the water can not be retained for long periods in surface, even with subsequent recharges by precipitation, since the organic matter becomes increasingly degraded, less fibrous, and probably less hygroscopic, resulting from higher oxygenation (higher O_2 input). After infiltrating the profile, the recharge water tends to move at depth and laterally, rarely remaining stagnant for long periods in association with the upper limit of the water table (as it was before opening the channel). A constant oscillation of recharge water infiltration, approaching the upper limit of the water table, and associated with its fluctuation, probably occurs in this stage.

Alternating wetting and drying cycles and strong carbon content decay lead to the formation of mineral soil material from the former organic material, whereby polyhedral and/or granular aggregates develop through swelling and shrinkage, strongly changing the soil consistency. In fact, this situation could be classified as evidence of the strong disturbance of artificial drainage, according to the German Manual of Soil Mapping (Säurich et al., 2019). However, since the distance between recharge-water oscillation
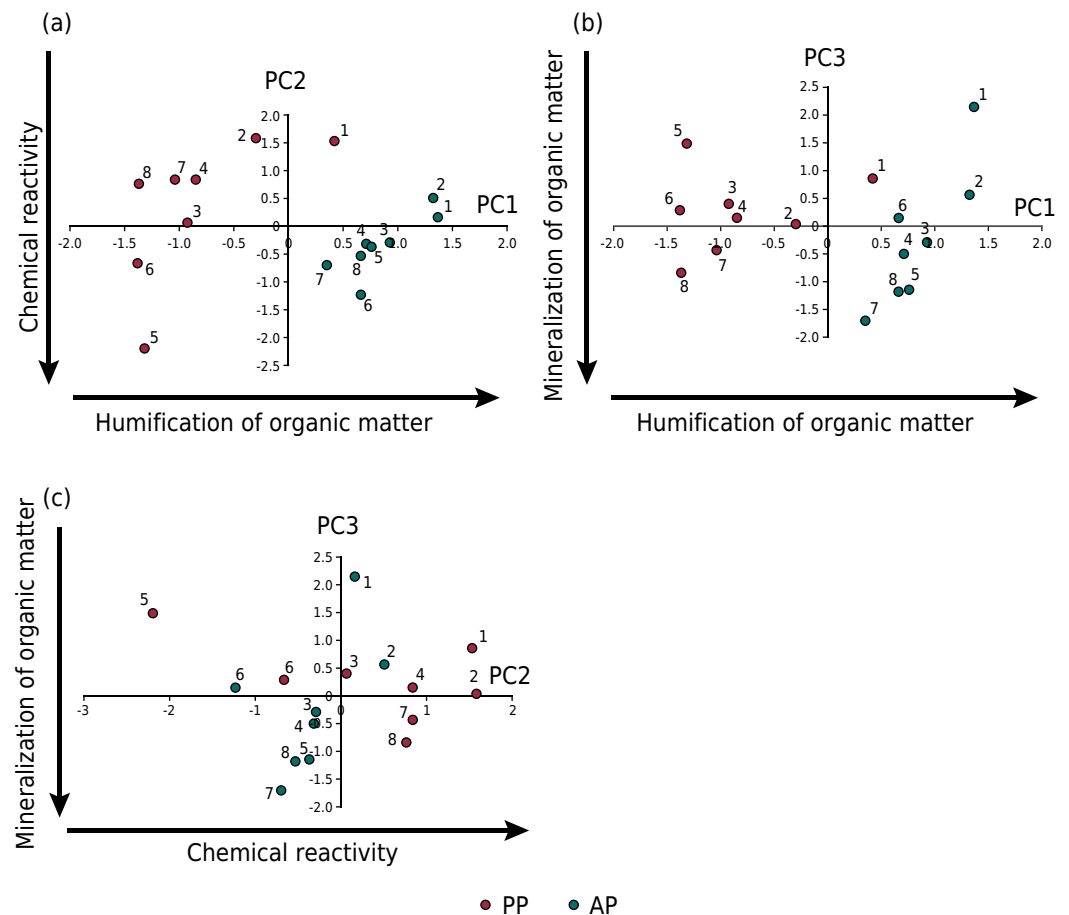
Figure 4. Phase space diagram of the three principal components. (a) PC1-PC2. (b) PC1-PC3. (c) PC2-PC3. The numbers represent samples of each profile's horizons. For PP = 1: Hd1. 2: Hd2. 3: Hd3. 4: Hdo1. 5: Hdo2. 6: Hdo3. 7: Ho1. 8: Ho2. For AP = 1: Hodp. 2: A1. 3: A2. 4: A3. 5: A4. 6: Cg1. 7: Cg2. 8: Cg3.
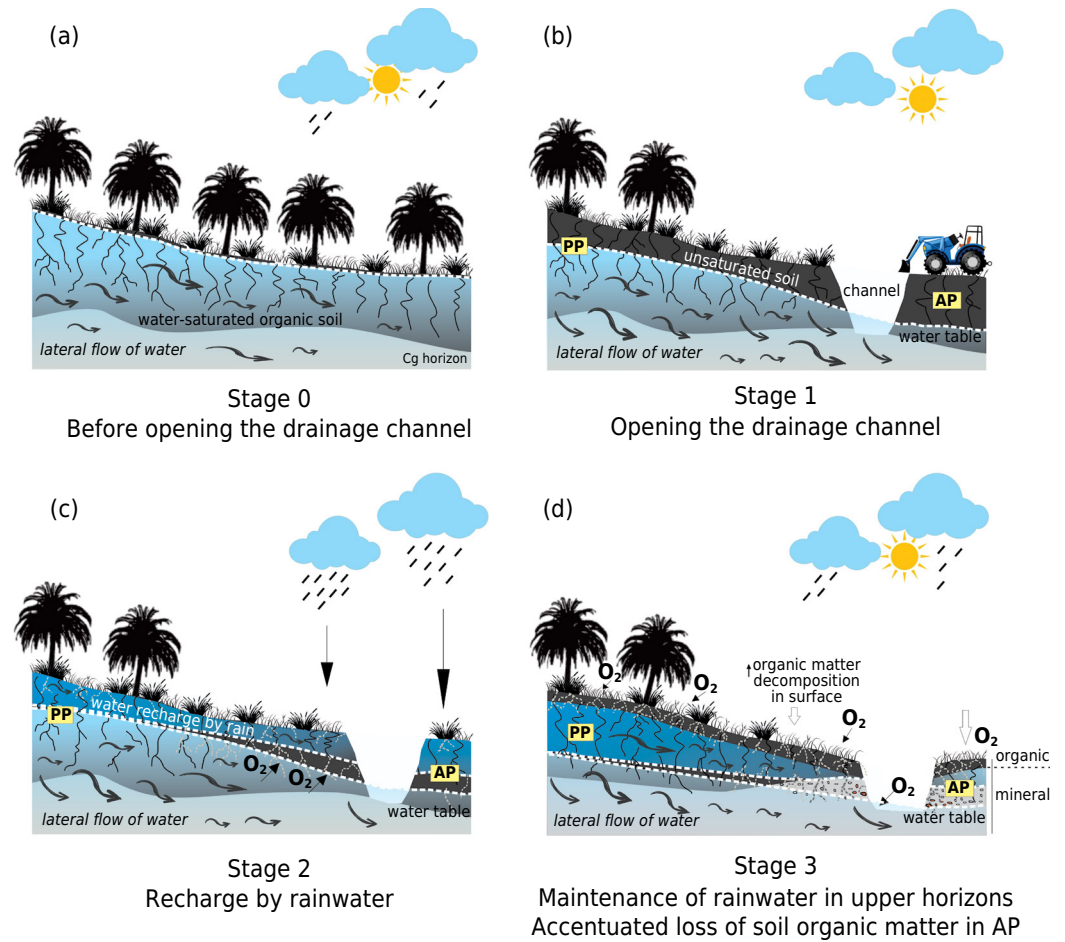
Figure 5. Representation of the suggested stages resulting from the opening of the drainage channel after 20 years.

and water table fluctuation is greater in downstream (AP), iron in minerals containing this element becomes oxidized (Fe^{3+}) and mottles begin to appear in a grayish soil matrix. Moreover, organic matter tends to decompose and degrade more quickly when there is a greater input of O_2, especially at intermediate depths. In upstream (PP), the soil organic and mineral properties are maintained more preserved because the distance is shorter.

Stage 3 (Figure 5d) shows the current situation obtained by continuing the processes that occurred in stage 2 over time (20 years). The intensification of the degradation/humification of organic matter is mainly seen downstream in almost the entire depth of AP, as well as in the surface horizons of the upstream profile (PP), which probably starts to go through the same pedogenetic process as AP, presenting evidence of degradation related to the indirect effects of the artificial drainage. In downstream, AP has horizons of the predominantly mineral constitution and grayish colors, due to the reduction and removal of iron. That degradation/humification of organic matter strongly impacts its ecosystem functions. Another important phenomenon is the subsidence occurring mainly in soils at the lowest levels of the Primavera *vereda* due to their reduced volume.

CONCLUSION

The two selected soil profiles of the Primavera *vereda* show distinct distribution patterns of their properties with depth, which is in agreement with their soil horizonation and their field situation. The anthropization through artificial drainage and original vegetation removal over the last twenty years involves and triggers different processes. The selected

physical, chemical and microbiological properties of the soil profiles are related to three main drivers: a) degradation/humification of organic matter and relative accumulation of mineral matter versus relative accumulation of organic matter; b) chemical reactivity; and c) mineralization of organic matter.

Our results confirm that *veredas* are complex and fragile ecosystems and suggest that they should be fully protected to maintain their ecosystem services. The anthropic action in question alters the water dynamics of the *vereda*, which causes organic carbon degradation, reducing it by about 22 % and promoting a significant decrease in carbon stock (~14 kg m^{-2}), reflecting the higher oxidation of organic materials contained in the studied soils.

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