




Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Impact of land use on Histosols properties in urban agriculture ecosystems of Rio de Janeiro, Brazil

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ABSTRACT: Histosols provide several ecosystem services, related mainly to their reserves of carbon and nitrogen. Management practices in these soils can increase the mineralization of organic matter and contribute to the emission of greenhouse gases. This study aimed to investigate the effect of tillage with plowing and drainage on Histosol properties in three land use systems located in the municipality of Rio de Janeiro, Brazil. Three areas subjected to different land use systems over the last twenty years were chosen: Area 1, secondary forest with natural regeneration; Area 2, conventional tillage of cassava with plowing; and Area 3, intercropped coconut + cassava with an artificial drainage system. The chemical characterization, von Post scale of organic matter decomposition, percentage of rubbed fiber, organic matter, percentage of mineral material, bulk density, electrical conductivity, soluble phosphate, total organic carbon (TOC) and nitrogen (NT), organic carbon fractions, and C and N stocks were analyzed. Our results showed the critical, nearly irreversible effects of agricultural practices comprising drainage and plowing of the soil. Over twenty years, in Area 2, the TOC and NT values decreased by 33 and 20 %, respectively in the histic horizon, and by about 17 and 8 %, respectively in the gley horizon. In Area 3, the TOC and NT values decreased by 31 and 18 %, respectively, in the histic horizon, and by 27 and 21 % in the gley horizon. Our findings also showed that the loss of C is related to the labile organic carbon, which is more sensitive to environmental changes, even at deeper depths. The plowing of the soil decreases the organic matter content due to the accelerated oxidation of organic matter, increasing the bulk density. Drainage, besides the loss of organic matter by subsidence, promotes the sulfidization of the soil with a high content of SO_4^{2-} , due to the oxidation of soil materials containing sulfides.

Keywords: Histosols, urban soils, subsidence, acid sulfate soils.

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INTRODUCTION

Soil is considered to contain the largest pool of carbon (C) in terrestrial ecosystems (Scharlemann et al., 2014). It is estimated that the global pool of C in the soil (~2500 Pg C) corresponds to nearly four times that in vegetation and 3.3 times that in the atmosphere, and is constituted mainly of organic carbon (~1500 Pg C) (Lal et al., 2004). Given this, peatland soils stand out, covering only 3 % of the terrestrial surfaces, but maintaining between 113 and 612 Pg of C (Köchy et al., 2015; Jackson et al., 2017). According to the Brazilian Soil Classification System, peatland soils (Histosols) are classified as *Organossolos* (Santos et al., 2018). It is estimated that Brazil has about 0.6–1.0 million hectares of Histosols distributed across tropical and subtropical areas, with an average of 204 Mg ha⁻¹ of organic carbon stock in the 1.00 m of topsoil (Valladares et al., 2016). Considering that the country has more than 12,200 km² of mangrove areas, distributed over 7,000 km of coast with likely presence of organic soils, the exact area of Histosols is still uncertain (Minasny et al., 2019).

In the municipality of Rio de Janeiro, the area of Histosols is estimated to be 3 % of the territory (Lumbreras and Gomes, 2004). The estimated average soil organic carbon in these soils ranges between 218.8 and 324.6 g kg⁻¹, indicating the greater capacity of these soils to store C (Lumbreras and Gomes, 2004). Most areas of Histosols are used by urban farmers who often do not receive adequate technical guidance on how to effectively manage these soils. Despite the urban expansion in the city, there are few studies assessing the impact of changes in land use on urban soil properties. These studies can contribute to the development of territorial planning tools at the local level, capable of preventing the aggravation of problems caused by the disordered expansion and occupation of land in the municipality of Rio de Janeiro.

The utilization of Histosols for agricultural purposes requires drainage. This practice causes several physical, chemical, and biological modifications to the soil, such as subsidence, the process of lowering the surface level of the soil (Pereira et al., 2005). This process leads to soil degradation with the collapse of the pores, increasing the rate of aeration and mineralization of organic matter, followed by the release of the C, which then becomes a source of greenhouse gases (Weissert and Disney, 2013; Soares et al., 2015).

Histosols in coastal environments can also have a pH lower than 3.5, typical of sulfuric horizons, due to sulfide oxidation, mainly of pyrite (Ferreira et al., 2007a,b). This horizon becomes a chemical barrier to the development of plant roots, limiting the soil volume to be explored, and reducing the plant's normal development. The selection of management methods and practices that are appropriate for sulfated acidic soils must take into account, beside edaphic factors, environmental characteristics such as weather (quantity and distribution of rainfall), hydrological factors (floods, irrigation methods, and water quality), and economic factors (Souza Júnior et al., 2001a,b).

Despite this high fragility, in several regions, farming in areas of Histosols is a source of income for many urban farmers. These farmers need information, tools, and training to find better soil management options for the efficient use of these soils. This study aimed to investigate the effect of tillage with plowing and drainage on Histosols properties in three land use systems located in the municipality of Rio de Janeiro, Brazil.

MATERIALS AND METHODS

Study area and sampling

The study was carried out in areas of Histosols in the municipality of Rio de Janeiro, Brazil (Figure 1). The soils are formed by sandy loam sediments, with high organic matter content, and they usually have high contents of salts and sulfur, showing a high risk of acidification when drained (Dantas et al., 2001).

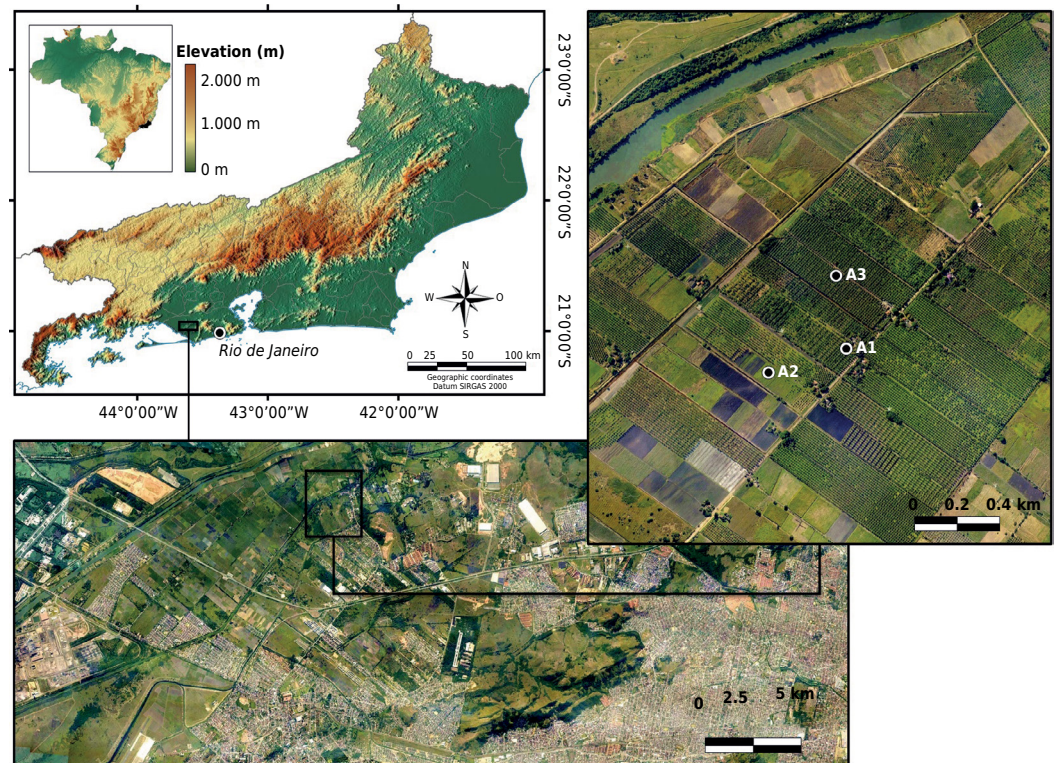


Figure 1. Location of study areas in the municipality of Rio de Janeiro, Brazil.

Regional climate is classified Aw, according to Köppen classification system, with annual average temperature and precipitation of 21 °C and 2,300 mm, respectively. Up to the first half of the twentieth century, this region used to be typically rural, with low rates of human occupation and extensive areas preserved. Between 1960 and 1970, the region went through an intense process of integration to the municipality of Rio de Janeiro for broadening the City's urbanized area.

Three areas subjected to different land use systems over the last twenty years were chosen. Area 1 (Secondary Forest) was a secondary tropical forest, where natural regeneration has been allowed for nearly 20 years, with species from the Myrtaceae, Lauraceae, Rubiaceae, and Fabaceae families. Area 2 (Cassava + plowing) was cultivated with cassava (*Manihot esculenta*, Euphorbiaceae) with conventional tillage, plowing to a depth of 0.20 m followed by harrowing, ridging, and planting in raised beds that were 0.30 m high. The row spacing and plant spacing were 1.0 and 0.6 m, respectively. Area 3 (intercropped coconut with cassava + drainage) was cultivated with coconut trees (*Cocos nucifera*) and cassava (*Manihot esculenta*), with a ditch-drainage system. The drains were open, rectangular shaped, with a depth of 0.7 m and a width of 1.0 m. The coconut trees were cultivated at a spacing of 5 m between rows and 5 m between plants. Cassava was planted at 1.0 and 0.6 m spacing, between the rows and plants, respectively. The three areas were located about 100 m from each other.

The study areas were part of a smallholder farm that was established in the 1940s. At first, these farmers received incentives from the government to start projects of olericulture. In subsequent years, due to the fall of natural fertility and soil degradation, the productivity of these areas decreased and the cultivation was replaced with coconut trees and cassava, a very rustic crop that grows well under conditions where few other crops survive (Table 1).

For obtaining the morphological description and sampling of soil profiles according to Santos et al. (2015), in each area, three trenches were opened, at approximately 20 m from each other. After the morphological description and physical and

Table 1. Profiles location and characteristics of the studied areas located in the municipality of Rio de Janeiro, Brazil

| Profile | Coordinates | Elevation m | Land use | Water table depth m |
|---|--------------------------------------|----------------|--|------------------------|
| Area 1 Secondary tropical forest (natural vegetation) | | | | |
| P1 | 22° 53' 27.34" S 43° 42' 38.15" O | 1 | | 0.60 |
| P2 | 22° 53' 27.25" S 43° 42' 37.31" O | 1 | Conventional tillage since 1940, Natural regeneration started in the last 20 years. | 0.62 |
| P3 | 22° 53' 27.89" S 43° 42' 37.20" O | 1 | | 0.60 |
| Area 2 Conventional tillage of cassava (<i>Manihot esculenta</i>) | | | | |
| P4 | 22° 53' 25.26" S 43° 42' 40.32" O | 1 | Conventional tillage since 1940. In the last 20 years, | 0.60 |
| P5 | 22° 53' 25.73" S 43° 42' 39.60" O | 1 | it was implemented the conventional tillage of | 0.57 |
| P6 | 22° 53' 26.15" S 43° 42' 38.94" O | 1 | cassava (<i>Manihot esculenta</i>) with soil plowing. | 0.51 |
| Area 3 Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | | | |
| P7 | 22° 53' 25.23" S 43° 42' 35.43" O | 1 | Conventional tillage since 1940. In the last 20 | 0.81 |
| P8 | 22° 53' 24.73" S 43° 42' 36.21" O | 1 | years, it was implemented intercropped coconut (<i>Cocos</i> | 0.70 |
| P9 | 22° 53' 24.10" S 43° 42' 37.16" O | 1 | <i>nucifera</i>) with cassava (<i>Manihot esculenta</i>), with ditch-drainage system. | 0.65 |

chemical characterization, the profiles were taxonomically classified according to the Brazilian Soil Classification System (Santos et al., 2018). Additionally, the equivalent classification consistent with WRB System (IUSS Working Group WRB, 2014) is presented in figure 2.

Physical and chemical analyses

The soil was characterized and classified following the analytical methods described by Teixeira et al. (2017). These included determination of pH(H₂O), pH(CaCl₂), and pH(KCl) at a soil:solution ratio of 1:2.5; contents of exchangeable cations (Ca²⁺, Mg²⁺, Na⁺, and K⁺); interchangeable aluminum (Al³⁺); potential acidity (Al+H); and the available phosphorus (P) content using the Mehlich-1 method. The following indices were calculated: sum of bases (S), cation-exchange capacity (T), and bases saturation (V, %). The electrical conductivity of saturated soil-paste extract (ECe) was determined according to the method proposed by Teixeira et al. (2017), in which the electrical conductivity (dS m⁻¹) was determined with a conductivity meter, and from the same extract, the values for Na⁺ and K⁺ were determined with a flame photometer. The soluble phosphate content was measured according to van Raij et al. (2001): briefly, 10 cm⁻³ of soil was submitted to extraction by calcium phosphate [Ca(H₂PO₄)₂, 0.01 mol L⁻¹]; the analyte was homogenized for 30 min and was then filtered. Part of it was removed and mixed to an acidic solution (S-SO₄²⁻, 20 mg L⁻¹) and 0.5 g barium chloride (BaCl₂·2H₂O). The content of soluble sulfate was determined using a spectrophotometer at 420 nm.

The characterization of the organic layers was determined following Lynn et al. (1974). The following aspects were assessed: von Post scale, rubbed fiber content (RF), organic matter (OM), mineral material content (MM), and bulk density (Bd). The von Post decomposition scale consists of squeezing a portion of wet sample with a high content of organic matter to observe the color of the extracted fluid, the characteristics of the plant fibers, and the residual proportion of the original sample held back in hand. Classes (1) to (4) are

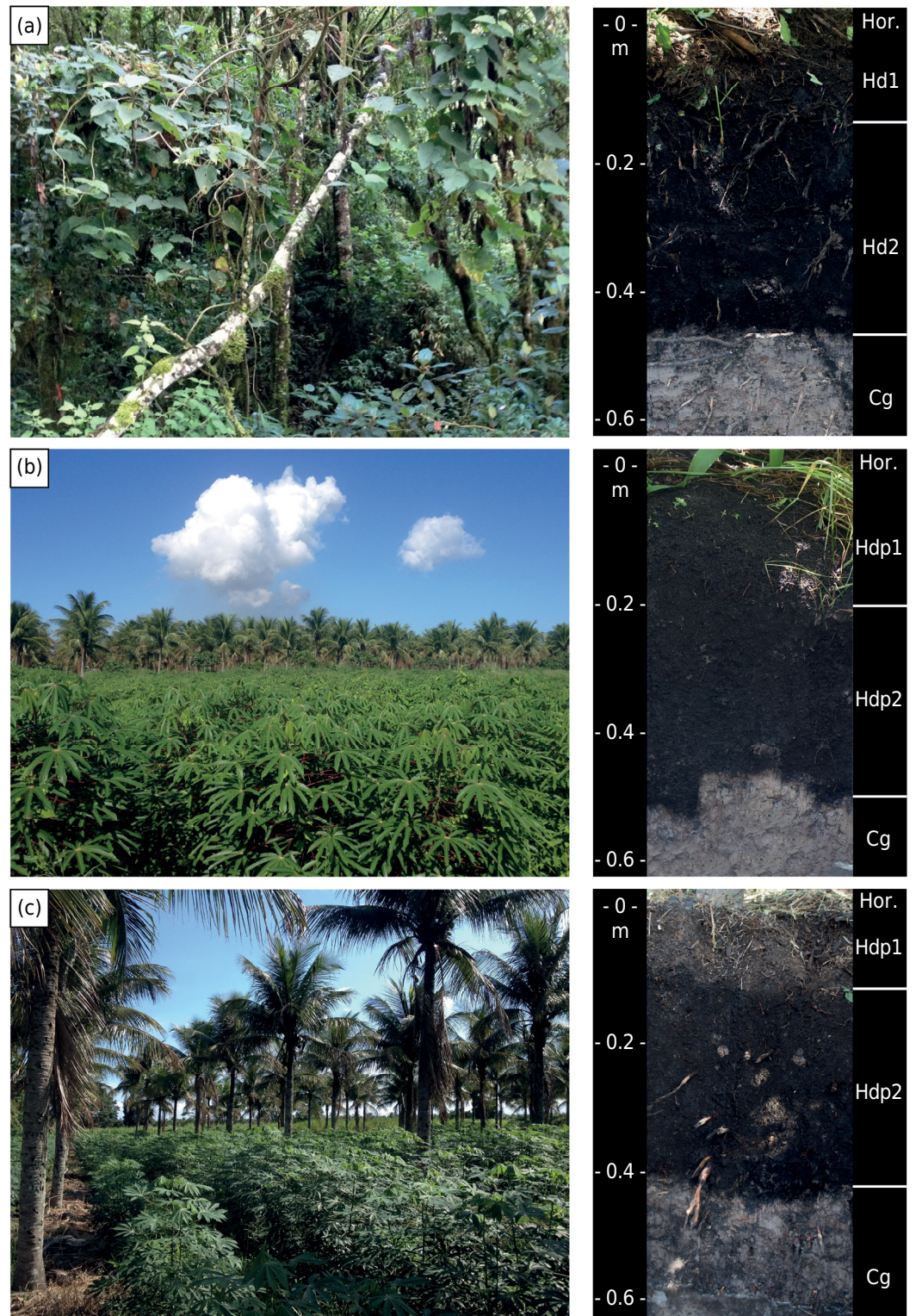


Figure 2. Histosol profiles under different land use systems in the municipality of Rio de Janeiro, Brazil. Secondary tropical forest (natural vegetation) (a); conventional tillage of cassava (*Manihot esculenta*) (b); and intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*) (c).

classified as organic matter of fibric soil; classes (5) and (6) as organic matter of hemic soil; and classes (7) to (10) as organic matter of sapric soil (Silva Neto et al., 2019).

The rubbed fibers (RF) were determined with a 100 mesh sieve, rubbing the matter between the thumb and the index finger, under a water gun, until the effluent was clear. The organic matter and the content of mineral material were obtained by combustion in a furnace. All the methods used here are described by Santos et al. (2018).

Total organic carbon and nitrogen, organic carbon fractions, and C and N stocks

The total organic carbon (TOC) content was quantified by oxidation with $K_2Cr_2O_7$ in a sulfuric medium, according to Teixeira et al. (2017). The fractionation of the organic carbon was accomplished based on the resistance to oxidation (Loginow et al., 1987). Briefly, 2 g of soil samples were put in 50 mL Falcon tubes with 25 mL $KMnO_4$ 0.3 mol L^{-1} . The tubes were stirred and centrifuged for 5 min at 2000 rpm. The fraction of labile organic carbon (LOC) was measured by the change in the concentration of $KMnO_4$, using a spectrophotometer at 565 nm; the results were expressed in g kg^{-1} . The fraction of organic matter associated with minerals (MOC) was separated by acidic hydrolysis (Wang et al., 2017) and measured by humid oxidation with $K_2Cr_2O_7$ 0.167 mol L^{-1} (Yeomans and Bremner, 1988).

The fractionation of the C based on its lability allows the enhanced monitoring of the short-term changes in the organic matter of the soil, leading to a better correlation between the fractions and the alterations in the soil chemical and physical fertility. The sum of these fractions (LOC and MOC) in organic soils (recovery percentile) can vary between 74 and 94 % of the TOC (Valladares et al., 2007).

The organic carbon stock (OCS) in the horizons was calculated according to equation 1:

$$OCS = (TOC \times Bd \times h)/10 \quad \text{Eq. 1}$$

in which OCS is the stock of organic carbon (Mg ha^{-1}) in the respective horizons; TOC is the total organic carbon content at the depth at which the sample was collected from (g kg^{-1}); Bd (bulk density) is the density of the soil of that horizon (Mg m^{-3}); and h is the thickness of the layer under study (m).

Total nitrogen (NT) was determined by sulfuric digestion followed by Kjeldahl distillation (Teixeira et al., 2017). From these results, the ratio C/N was obtained.

Statistical analysis

Multivariate statistical methods were applied, aiming to verify the similarity between the profiles surveyed based on the variables analyzed. We used the CANOCO statistics package (ter Braak and Smilauer, 2002). All variables were standardized, according to Gniazdowski (2017), before including them in the analyses. The analyses of the main components were based on the correlation matrix of these variables, using Ward's algorithm to obtain similar groupings. The result from this analysis is presented graphically (dendrogram) for the identification of the groupings.

RESULTS

Soil morphology and general characteristics

The soil profiles presented a sequence of horizons H-Cg (Table 2). The thickness of H horizon varied between the areas, with an average value of 0.46 m in Area 1, 0.44 m in Area 2, and 0.55 m in Area 3. All profiles presented a massive structure in the sub-superficial horizon (Cg) and were granular in the superficial horizon (H) with size and degree of development varying among the areas. In Area 1, the soil under natural vegetation presented a more cohesive structure, with strong grade (development degree) in all profiles. In Area 2, under conventional tillage of cassava, the soil structure was fine sized, and the grade was moderate to strong. In Area 3, where coconut was intercropped with cassava, the size of the structural units varied from very fine to fine and the grade varied from weak to strong. Further, the prevalence of dark colors in H horizons and grayish in C horizons was verified (Table 2).

The bulk density in the organic horizons was $0.74 \pm 0.11 \text{ Mg m}^{-3}$ in Area 1, $0.80 \pm 0.10 \text{ Mg m}^{-3}$ in Area 2, and $0.71 \pm 0.13 \text{ Mg m}^{-3}$ in Area 3 (Table 2). The percentage of organic matter was higher in Area 1 with an average of $303.8 \pm 15 \text{ g kg}^{-1}$, followed by Area 3 with an average of $214.8 \pm 9 \text{ g kg}^{-1}$, and Area 2 with an average of $209.1 \pm 7 \text{ g kg}^{-1}$. In all profiles, the properties related to the degree of organic matter decomposition showed low percentage of rubbed fibers and values between 8 and 10 on the von Post decomposition scale (Stanek and Silc, 1977), while the organic matter of the organic horizons was classified as sapric.

Chemical properties

In all profiles, the $\text{pH}(\text{H}_2\text{O})$ values were higher in the superficial horizons, with an average of 4.87 ± 0.21 in Area 1, 4.68 ± 0.16 in Area 2, and 3.96 ± 0.38 in Area 3. In sub-superficial horizons (Cg), the values were between 3.42 ± 0.12 in Area 1, 3.72 ± 0.05 in Area 2, and 3.40 ± 0.10 in Area 3 (Table 3). A similar pattern was observed for the $\text{pH}(\text{CaCl}_2)$ and $\text{pH}(\text{KCl})$; however, it must be highlighted that the lowest values were obtained using a saline solution of $\text{KCl } 1 \text{ mol L}^{-1}$. The sum of bases (S) was higher in Area 1 ($15.67 \pm 3.11 \text{ cmol}_c \text{ kg}^{-1}$) followed by Area 2 ($11.45 \pm 1.23 \text{ cmol}_c \text{ kg}^{-1}$), and then Area 3 ($7.20 \pm 4.18 \text{ cmol}_c \text{ kg}^{-1}$) with the prevalence of Mg^{2+} and Ca^{2+} that decreased with an increase in the soil depth. A similar pattern of decrease with increasing soil depth was observed for K^+ and Na^+ . In superficial horizons, Al^{3+} values were higher in Area 3 ($3.57 \pm 1.99 \text{ cmol}_c \text{ kg}^{-1}$) and lower in Area 1 ($0.91 \pm 0.58 \text{ cmol}_c \text{ kg}^{-1}$). In sub-superficial horizons, an expressive increase of Al^{3+} in all profiles was observed (Table 3), which was in contrast to what was observed for H^+ , which showed higher values in Area 3 ($4.57 \pm 2.65 \text{ mg dm}^{-3}$), and it increased with decrease in soil depth.

The soil salinity, estimated by the electrical conductivity in the extract of saturated paste, increased with the depth, with values between 2 and 6 dS m^{-1} (Table 4). According to the Brazilian Soil Classification System (Santos et al., 2018), soils in which saturated extracts show electrical conductivity between 4 to 7 dS m^{-1} may present a “saline character”, utilized in the fourth category level of Histosols. However, the ECe value of the studied soil profiles was not related to soil salinity but was probably related to hydrogen and sulfate ions, which also increased with the depth, as indicated by the pH and SO_4^{2-} values. The low values of Na^+ and K^+ in all profiles confirm this interpretation.

Soil classification

The morphological characteristics and chemical and analytical data from the selected profiles were used to classify the soils according to the Brazilian Soil Classification System (Santos et al., 2018). All profiles presented a histic H as superficial diagnostic horizon, which consists of a horizon formed from materials deposited under waterlogged conditions, with a thickness of $\geq 0.20 \text{ m}$. The sub-superficial horizons were classified as gley horizon characterized by iron reduction and strongly influenced by the water table, as evidenced by the grayish colors in the horizon matrix, with a thickness of $\geq 0.15 \text{ m}$. Thus, at the first level (order), soils were classified as *Organossolos* (Histosols). With the presence of sulfidic materials (soil materials that contain oxidizable sulfur compounds in waterlogged areas) in the 1.00 m of topsoil and the high degree of organic matter decomposition (sapric), the profiles were classified as *Organossolos Tiomórficos Sápricos típicos* (Sapric Thionic Histosol, WRB) (IUSS Working Group WRB, 2014). In the denomination of the horizons, the suffix “d” indicates the highly decomposed organic material, “p” indicates morphological modifications in the superficial horizons due to cultivation, and “g” means stagnic conditions.

Total organic carbon and nitrogen

The TOC values in the organic horizons were higher in Area 1 ($\text{TOC} = 162.65 \pm 11.18 \text{ g kg}^{-1}$), followed by Area 3 ($\text{TOC} = 112.04 \pm 5.88 \text{ g kg}^{-1}$), and Area 2 ($\text{TOC} = 108.92 \pm 3.49 \text{ g kg}^{-1}$) (Table 5). In the mineral horizons (Cg), values observed were between 56.76 and

Table 2. Morphological properties description and selected features of the studied Histosol profiles

| Hor | Layer | Munsell color | Bd | Soil structure ⁽¹⁾ | OM | MM | RF | von Post | |
|---|-----------|---------------|--------------------|-------------------------------|--------------------|-------|----|----------|----------|
| | m | | Mg m ⁻³ | | g kg ⁻¹ | | % | index | material |
| Area 1 - Secondary tropical forest (natural vegetation) | | | | | | | | | |
| P1 | | | | | | | | | |
| Hd1 | 0.00-0.16 | 10YR 2/1 | 0.69 | str, f, gr | 304.2 | 695.8 | 16 | 9 | sapric |
| Hd2 | 0.16-0.43 | 10YR 2/1 | 0.75 | str, f, gr | 274.3 | 725.7 | 10 | 9 | sapric |
| Cg | 0.43-0.81 | 10YR 5/1 | 0.82 | massive | 154.5 | 845.5 | | | |
| P2 | | | | | | | | | |
| Hd1 | 0.00-0.20 | 10YR 2/1 | 0.46 | str, f, gr | 327.5 | 672.5 | 10 | 8 | sapric |
| Hd2 | 0.20-0.32 | 10YR 2/1 | 0.87 | str, f, gr | 313.9 | 686.1 | 12 | 9 | sapric |
| Hd3 | 0.32-0.50 | 10YR 2/1 | 0.86 | str, f, gr | 291.7 | 708.3 | 6 | 10 | Sapric |
| Cg | 0.50-0.79 | 2.5Y 4/1 | 0.87 | massive | 152.9 | 847.1 | | | |
| P3 | | | | | | | | | |
| Hd1 | 0.00-0.14 | 10YR 2/1 | 0.70 | str, f, gr | 322.1 | 677.9 | 12 | 9 | sapric |
| Hd2 | 0.14-0.44 | 10YR 2/1 | 0.86 | str, f, gr | 292.7 | 707.3 | 4 | 9 | sapric |
| Cg | 0.44-0.63 | 2.5Y 4/1 | 0.86 | massive | 148.3 | 851.7 | | | |
| Area 2 - Conventional tillage of cassava (<i>Manihot esculenta</i>) | | | | | | | | | |
| P4 | | | | | | | | | |
| Hdp1 | 0.00-0.15 | 10YR 2/1 | 0.70 | str, f, gr | 231.3 | 768.7 | 8 | 8 | sapric |
| Hdp2 | 0.15-0.40 | 10YR 2/1 | 0.75 | str, f, gr | 224.7 | 775.3 | 4 | 9 | sapric |
| Cg | 0.40-0.67 | 2.5Y 4/1 | 0.89 | massive | 120.8 | 879.2 | | | |
| P5 | | | | | | | | | |
| Hdp1 | 0.00-0.13 | 10YR 2/1 | 0.60 | mod, f, gr | 223.1 | 776.9 | 6 | 8 | sapric |
| Hdp2 | 0.13-0.27 | 10YR 2/1 | 0.87 | str, f, gr | 213.2 | 786.8 | 4 | 9 | sapric |
| Hd | 0.27-0.47 | 10YR 2/1 | 0.76 | str, f, gr | 211.3 | 788.7 | 8 | 9 | sapric |
| Cg | 0.47-0.65 | 2.5Y 4/1 | 0.72 | massive | 121.6 | 878.4 | | | |
| P6 | | | | | | | | | |
| Hdp1 | 0.00-0.12 | 10YR 2/1 | 0.84 | mod, f, gr | 214.7 | 785.3 | 8 | 8 | sapric |
| Hdp2 | 0.12-0.20 | 10YR 2/1 | 0.93 | str, f, gr | 205.8 | 794.2 | 4 | 10 | sapric |
| Hd | 0.20-0.44 | 10YR 2/1 | 0.95 | str, f, gr | 193.9 | 806.1 | 6 | 9 | sapric |
| Cg | 0.44-0.76 | 2.5Y 4/1 | 0.93 | massive | 119.4 | 880.6 | | | |
| Area 3 - Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | | | | | | | | |
| P7 | | | | | | | | | |
| Hdp1 | 0.00-0.16 | 10YR 3/1 | 1.01 | wea, vf, gr | 212.8 | 787.2 | 20 | 8 | sapric |
| Hdp2 | 0.16-0.57 | 10YR 2/1 | 0.78 | mo, f, gr | 201.3 | 798.7 | 8 | 8 | sapric |
| Cg | 0.57-0.75 | 10YR 5/1 | 0.81 | massive | 107.6 | 892.4 | | | |
| P8 | | | | | | | | | |
| Hdp1 | 0.00-0.18 | 10YR 2/1 | 0.71 | mo, f, gr | 211.7 | 788.3 | 6 | 8 | sapric |
| Hdp2 | 0.18-0.47 | 10YR 2/1 | 0.80 | str, f, gr | 191.7 | 808.3 | 12 | 8 | sapric |
| Cg | 0.47-0.73 | 2.5Y 4/1 | 0.94 | massive | 100.2 | 899.8 | | | |
| P9 | | | | | | | | | |
| Hdp1 | 0.00-0.13 | 10YR 2/1 | 0.44 | mo, f, gr | 223.7 | 776.3 | 20 | 8 | sapric |
| Hdp2 | 0.13-0.38 | 10YR 2/1 | 0.68 | str, f, gr | 207.2 | 792.8 | 10 | 9 | sapric |
| Hd | 0.38-0.60 | 10YR 2/1 | 0.57 | str, f, gr | 215.4 | 784.6 | 2 | 10 | sapric |
| Cg | 0.60-0.83 | 2.5Y 4/1 | 0.74 | massive | 114.5 | 885.5 | | | |

⁽¹⁾ Degree (wea: weak; mod: moderate; str: strong); Size (vf: very fine; f: fine); Type (gr: granular); Hor: horizon; Bd: bulk density; OM: organic matter; MM: mineral material; RF: rubbed fibers. OM, MM, and RF were analyzed according to the methods proposed by Lynn et al. (1974) and Santos et al. (2013). P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

Table 3. Chemical properties of the studied Histosol profiles

| Hor | pH | | | Ca ²⁺ | Mg ²⁺ | K ⁺ | Na ⁺ | S | Al ³⁺ | H ⁺ | T | V | P | |
|---|------------------|-------------------|------|------------------|------------------|----------------|-----------------|-------|------------------|----------------|-------|----|----|---------------------|
| | H ₂ O | CaCl ₂ | KCl | | | | | | | | | | | |
| cmol _c kg ⁻¹ | | | | | | | | | | | | | % | mg dm ⁻³ |
| Area 1 - Secondary tropical forest (natural vegetation) | | | | | | | | | | | | | | |
| P1 | | | | | | | | | | | | | | |
| Hd1 | 4.89 | 4.76 | 4.37 | 4.7 | 13.1 | 0.09 | 0.01 | 17.91 | 0.2 | 13.55 | 31.66 | 57 | 28 | |
| Hd2 | 4.55 | 4.43 | 4.00 | 5.2 | 7.0 | 0.03 | 0.01 | 12.25 | 1.0 | 12.15 | 25.40 | 48 | 21 | |
| Cg | 3.30 | 3.41 | 3.29 | 1.7 | 2.5 | 0.01 | 0.01 | 4.22 | 9.4 | 1.25 | 14.87 | 28 | 3 | |
| P2 | | | | | | | | | | | | | | |
| Hd1 | 5.42 | 5.03 | 4.71 | 5.3 | 14.8 | 0.06 | 0.01 | 20.17 | 0.6 | 12.15 | 32.92 | 61 | 25 | |
| Hd2 | 4.98 | 4.83 | 4.41 | 4.4 | 12.9 | 0.03 | 0.01 | 17.35 | 0.4 | 18.75 | 36.50 | 48 | 21 | |
| Hd3 | 4.94 | 4.20 | 3.84 | 3.6 | 10.0 | 0.02 | 0.02 | 13.64 | 1.8 | 11.85 | 27.29 | 50 | 24 | |
| Cg | 3.36 | 3.34 | 3.22 | 1.3 | 4.5 | 0.01 | 0.01 | 5.82 | 10.1 | 4.05 | 19.97 | 29 | 2 | |
| P3 | | | | | | | | | | | | | | |
| Hd1 | 4.74 | 4.77 | 4.42 | 5.5 | 12.6 | 0.04 | 0.01 | 18.15 | 0.4 | 19.75 | 38.30 | 47 | 30 | |
| Hd2 | 4.59 | 4.08 | 3.76 | 4.7 | 5.5 | 0.01 | 0.01 | 10.22 | 2.0 | 12.65 | 24.87 | 41 | 21 | |
| Cg | 3.62 | 3.31 | 3.25 | 1.3 | 4.3 | 0.00 | 0.07 | 5.67 | 9.3 | 5.25 | 20.22 | 28 | 1 | |
| Area 2 - Conventional tillage of cassava (<i>Manihot esculenta</i>) | | | | | | | | | | | | | | |
| P4 | | | | | | | | | | | | | | |
| Hdp1 | 4.76 | 4.52 | 3.90 | 4.1 | 9.1 | 0.05 | 0.01 | 13.27 | 1.1 | 16.05 | 30.42 | 44 | 29 | |
| Hdp2 | 4.56 | 4.28 | 3.80 | 3.3 | 7.4 | 0.02 | 0.01 | 10.73 | 1.5 | 15.45 | 27.68 | 39 | 24 | |
| Cg | 3.78 | 3.33 | 3.24 | 1.6 | 4.6 | 0.01 | 0.01 | 6.22 | 7.6 | 5.85 | 19.67 | 32 | 1 | |
| P5 | | | | | | | | | | | | | | |
| Hdp1 | 4.87 | 4.38 | 3.89 | 5.5 | 6.5 | 0.03 | 0.04 | 12.07 | 1.0 | 17.05 | 30.12 | 40 | 26 | |
| Hdp2 | 4.77 | 4.39 | 3.86 | 4.8 | 6.3 | 0.01 | 0.01 | 11.12 | 1.1 | 16.55 | 28.77 | 39 | 28 | |
| Hd | 4.40 | 4.20 | 3.75 | 3.9 | 5.2 | 0.00 | 0.01 | 9.11 | 2.0 | 17.65 | 28.76 | 32 | 23 | |
| Cg | 3.64 | 3.35 | 3.21 | 1.3 | 1.8 | 0.00 | 0.01 | 3.11 | 10.2 | 4.05 | 17.36 | 18 | 1 | |
| P6 | | | | | | | | | | | | | | |
| Hdp1 | 4.72 | 4.58 | 4.10 | 4.5 | 9.0 | 0.04 | 0.01 | 13.55 | 0.6 | 15.05 | 29.20 | 46 | 22 | |
| Hdp2 | 4.94 | 4.44 | 3.96 | 4.1 | 7.7 | 0.04 | 0.01 | 11.84 | 0.9 | 14.85 | 27.59 | 43 | 25 | |
| Hd | 4.40 | 4.22 | 3.78 | 3.4 | 6.5 | 0.01 | 0.01 | 9.92 | 1.5 | 13.55 | 24.97 | 40 | 22 | |
| Cg | 3.75 | 3.49 | 3.32 | 1.6 | 4.5 | 0.00 | 0.01 | 6.11 | 7.9 | 3.75 | 17.76 | 34 | 1 | |
| Area 3 - Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | | | | | | | | | | | | | |
| P7 | | | | | | | | | | | | | | |
| Hdp1 | 3.67 | 4.42 | 4.11 | 3.3 | 11.9 | 0.05 | 0.01 | 15.26 | 0.5 | 19.15 | 34.91 | 44 | 8 | |
| Hdp2 | 3.89 | 3.54 | 3.59 | 0.8 | 2.1 | 0.09 | 0.04 | 3.02 | 4.9 | 12.25 | 20.17 | 15 | 3 | |
| Cg | 3.39 | 3.09 | 3.20 | 0.4 | 0.4 | 0.04 | 0.02 | 0.05 | 0.4 | 18.05 | 18.10 | 0 | 1 | |
| P8 | | | | | | | | | | | | | | |
| Hdp1 | 4.14 | 3.88 | 3.74 | 2.1 | 8.3 | 0.18 | 0.02 | 10.60 | 2.3 | 16.75 | 29.65 | 36 | 7 | |
| Hdp2 | 3.80 | 3.41 | 3.62 | 0.7 | 2.8 | 0.02 | 0.01 | 3.53 | 5.2 | 14.15 | 22.88 | 15 | 4 | |
| Cg | 3.55 | 3.15 | 3.29 | 1.0 | 1.3 | 0.01 | 0.01 | 2.32 | 10.7 | 2.35 | 15.37 | 15 | 0 | |
| P9 | | | | | | | | | | | | | | |
| Hdp1 | 5.12 | 3.99 | 3.82 | 3.5 | 6.7 | 0.18 | 0.01 | 10.39 | 1.4 | 16.05 | 27.84 | 37 | 8 | |
| Hdp2 | 3.67 | 3.70 | 3.74 | 2.4 | 2.8 | 0.11 | 0.04 | 5.35 | 3.1 | 17.05 | 25.50 | 21 | 1 | |
| Hd | 3.43 | 3.21 | 3.50 | 0.7 | 1.5 | 0.03 | 0.02 | 2.25 | 7.6 | 25.55 | 35.40 | 6 | 1 | |
| Cg | 3.26 | 3.12 | 3.31 | 0.4 | 0.4 | 0.03 | 0.02 | 0.05 | 0.4 | 18.45 | 18.50 | 0 | 2 | |

Hor: Horizons; S: sum of bases; T: cation exchange capacity; V: base saturation. pH(H₂O), pH(CaCl₂), and pH(KCl) at a soil:solution ratio of 1:2.5; Ca²⁺, Mg²⁺, and Al³⁺ were extracted by KCl 1 mol L⁻¹; P, Na⁺, and K⁺ were extracted with Mehlich-1; H⁺ (extractant calcium acetate 0.5 mol L⁻¹ and pH 7.0). P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

Table 4. Electrical conductivity, pH, Na, K, and soluble sulfate in the saturated soil-paste extract of the studied Histosol profiles

| Hor ⁽¹⁾ | Saturation extract | | | | Soluble sulfate (SO ₄ ²⁻) mg dm ⁻³ |
|---|--|----------------------|-----------------|----------------|---|
| | ECe ⁽²⁾ dS m ⁻¹ | pH(H ₂ O) | Na ⁺ | K ⁺ | |
| cmol _c dm ⁻³ | | | | | |
| Area 1 - Secondary tropical forest (natural vegetation) | | | | | |
| P1 | | | | | |
| Hd1 | 3 | 6.19 | 0.059 | 0.068 | 42.97 |
| Hd2 | 2 | 6.09 | 0.052 | 0.027 | 39.23 |
| Cg | 5 | 4.83 | 0.122 | 0.028 | 104.17 |
| P2 | | | | | |
| Hd1 | 4 | 6.04 | 0.060 | 0.110 | 51.06 |
| Hd2 | 3 | 6.10 | 0.055 | 0.022 | 39.85 |
| Hd3 | 5 | 5.72 | 0.107 | 0.031 | 109.36 |
| Cg | 5 | 4.54 | 0.120 | 0.026 | 157.72 |
| P3 | | | | | |
| Hd1 | 4 | 5.38 | 0.081 | 0.059 | 45.25 |
| Hd2 | 3 | 5.57 | 0.092 | 0.011 | 68.90 |
| Cg | 5 | 5.19 | 0.104 | 0.012 | 85.50 |
| Area 2 - Conventional tillage of cassava (<i>Manihot esculenta</i>) | | | | | |
| P4 | | | | | |
| Hdp1 | 3 | 6.03 | 0.059 | 0.066 | 39.44 |
| Hdp2 | 2 | 5.83 | 0.052 | 0.029 | 41.31 |
| Cg | 4 | 5.35 | 0.067 | 0.019 | 75.95 |
| P5 | | | | | |
| Hdp1 | 3 | 5.34 | 0.077 | 0.014 | 33.22 |
| Hdp2 | 2 | 5.93 | 0.060 | 0.017 | 18.28 |
| Hd | 2 | 5.80 | 0.039 | 0.006 | 24.09 |
| Cg | 4 | 4.98 | 0.065 | 0.019 | 75.12 |
| P6 | | | | | |
| Hdp1 | 2 | 5.59 | 0.035 | 0.019 | 16.41 |
| Hdp2 | 2 | 5.77 | 0.032 | 0.014 | 26.16 |
| Hd | 2 | 5.75 | 0.046 | 0.012 | 24.50 |
| Cg | 3 | 5.61 | 0.058 | 0.005 | 57.28 |
| Area 3 - Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | | | | |
| P7 | | | | | |
| Hdp1 | 5 | 5.41 | 0.141 | 0.083 | 87.16 |
| Hdp2 | 5 | 5.18 | 0.110 | 0.007 | 56.87 |
| Cg | 6 | 4.17 | 0.113 | 0.055 | 135.73 |
| P8 | | | | | |
| Hdp1 | 4 | 5.00 | 0.046 | 0.077 | 35.71 |
| Hdp2 | 5 | 4.75 | 0.055 | 0.023 | 59.4 |
| Cg | 6 | 5.25 | 0.059 | 0.018 | 110.19 |
| P9 | | | | | |
| Hdp1 | 4 | 5.30 | 0.096 | 0.134 | 57.07 |
| Hdp2 | 4 | 5.39 | 0.075 | 0.041 | 63.30 |
| Hd | 6 | 4.15 | 0.127 | 0.047 | 134.90 |
| Cg | 7 | 4.15 | 0.096 | 0.017 | 138.63 |

Hor: horizons; pH in water, 1:2.5 (v/v); ECe: electrical conductivity of saturated soil-paste extract determined with conductivity meter; Na⁺ and K⁺ determined with a flame photometer; and SO₄²⁻ determined by extraction with calcium phosphate [Ca(H₂PO₄)₂ 0.01 mol L⁻¹]. P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

Table 5. Total organic carbon (TOC), total nitrogen (TN), and C/N ratios of the studied Histosol profiles

| Horizon | TOC | TN | C/N |
|---|--------|------|-----|
| g kg ⁻¹ | | | |
| Area 1 - Secondary tropical forest (natural vegetation) | | | |
| P1 | | | |
| Hd1 | 165.47 | 7.18 | 25 |
| Hd2 | 143.66 | 7.43 | 23 |
| Cg | 78.57 | 5.69 | 11 |
| P2 | | | |
| Hd1 | 184.02 | 7.15 | 26 |
| Hd2 | 165.19 | 6.20 | 23 |
| Hd3 | 153.12 | 6.34 | 24 |
| Cg | 77.71 | 5.11 | 11 |
| P3 | | | |
| Hd1 | 175.07 | 6.93 | 25 |
| Hd2 | 152.03 | 6.30 | 24 |
| Cg | 75.19 | 5.29 | 10 |
| Area 2 - Conventional tillage of cassava (<i>Manihot esculenta</i>) | | | |
| P4 | | | |
| Hdp1 | 109.54 | 5.42 | 20 |
| Hdp2 | 104.05 | 5.34 | 19 |
| Cg | 61.81 | 5.73 | 8 |
| P5 | | | |
| Hdp1 | 112.51 | 5.48 | 21 |
| Hdp2 | 115.92 | 5.56 | 21 |
| Hd | 108.12 | 5.46 | 20 |
| Cg | 66.23 | 4.73 | 9 |
| P6 | | | |
| Hdp1 | 108.34 | 5.38 | 20 |
| Hdp2 | 111.67 | 5.47 | 20 |
| Hd | 101.18 | 5.31 | 19 |
| Cg | 65.27 | 4.30 | 9 |
| Area 3 - Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | | |
| P7 | | | |
| Hdp1 | 115.70 | 5.76 | 20 |
| Hdp2 | 104.02 | 5.52 | 19 |
| Cg | 56.36 | 4.02 | 9 |
| P8 | | | |
| Hdp1 | 114.55 | 5.52 | 21 |
| Hdp2 | 101.68 | 5.47 | 19 |
| Cg | 50.00 | 4.46 | 9 |
| P9 | | | |
| Hdp1 | 121.46 | 5.68 | 21 |
| Hdp2 | 109.83 | 5.47 | 20 |
| Hd | 117.08 | 5.59 | 21 |
| Cg | 62.24 | 4.23 | 10 |

TOC: determined according to the Walkley-Black method; and TN: determined according Kjeldahl Method. P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

77.71 g kg⁻¹, with a higher average value in Area 1 (77.16±1.31 g kg⁻¹). The observed NT values were between 4.23 and 7.43 g kg⁻¹, with a higher average value in Area 1 (6.36±0.64 g kg⁻¹). The agricultural areas had similar averages, with 5.29±0.28 g kg⁻¹ in Area 2 and 5.17±0.56 g kg⁻¹ in Area 3. The same pattern was observed for the C/N ratio, with a higher average observed in Area 2 (C/N = 20±5), and similar values in the agricultural areas (C/N = 17±4).

Carbon and nitrogen stocks

The organic carbon stocks (OCS) and nitrogen stocks (NS) were expressively higher in Area 1, with an average OCS of 217.99±58.60 Mg ha⁻¹ and an average NS of 10.81±3.73 Mg ha⁻¹ (Figure 3a). In the agricultural areas, the average OCS and NS values in Area 2 were 141.36±41.10 and 8.12±2.97 Mg ha⁻¹, respectively, while in Area 3 they were 161.52±59.22 and 9.02±2.94 Mg ha⁻¹, respectively (Figure 3a).

In all areas, the carbon and nitrogen stocks were more related to the horizon thickness than to the TOC and NT (Figure 4). When the areas were compared, the correlation between horizon thickness and carbon stocks was greater in Areas 2 and 3, due to lower TOC values observed there. In the correlation between the nitrogen stock and horizon thickness, the high values of R² observed in all areas indicate the direct relation between horizon thickness and NS.

Soil organic carbon fractions

The organic carbon fraction more accessible to microbial action is called labile organic carbon (LOC) (Blair et al., 1995). In this study, we considered the C oxidable by KMnO₄ as labile, the C oxidation by KMnO₄ may reflect the enzymatic decomposition in situ of the labile organic matter of the soil (Loginow et al., 1987; Wang et al., 2012, 2017). In the studied soils, the LOC values were between 8.74 and 76.59 g kg⁻¹, with averages between 62.17±8.44 g kg⁻¹ in Area 1, 39.32±2.86 g kg⁻¹ in Area 2, and 38.26±6.29 g kg⁻¹ in Area 3 (Figure 5).

For the organic carbon fraction associated with the minerals (MOC), the values observed were between 11.38 and 32.36 g kg⁻¹, with an average of 29.79±0.44 g kg⁻¹ in Area 1, 28.83±0.74 g kg⁻¹ in Area 2, and 29.63±1.12 g kg⁻¹ in Area 3. In all organic horizons of the studied profiles, the MOC values were lower than the LOC values. In the mineral horizons (Cg), the inverse pattern was observed, with higher values of MOC for all profiles. The MOC fraction is an important compartment of recalcitrant organic matter, mainly

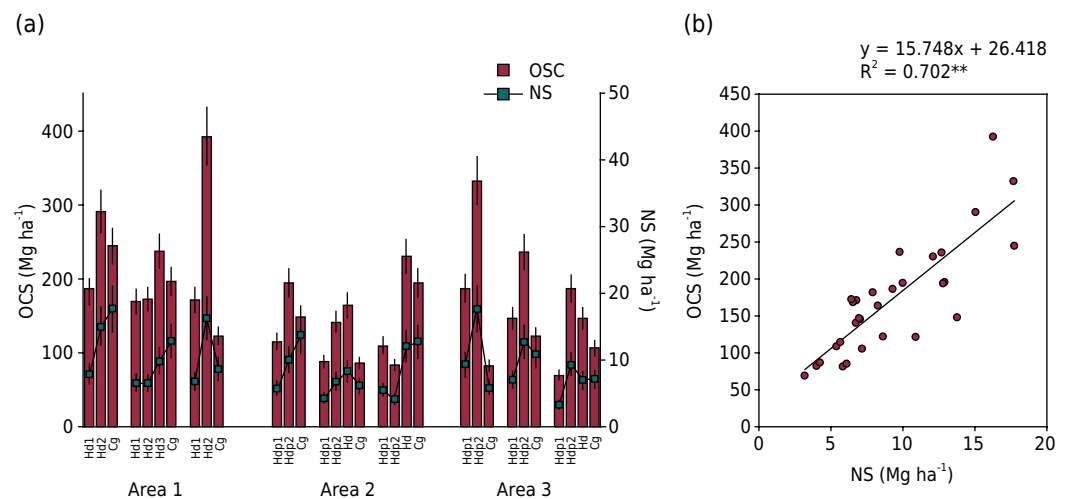


Figure 3. Carbon and nitrogen stocks of the studied Histosol profiles. Area 1: secondary tropical forest (natural vegetation); Area 2: conventional tillage of cassava (*Manihot esculenta*); and Area 3: Intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

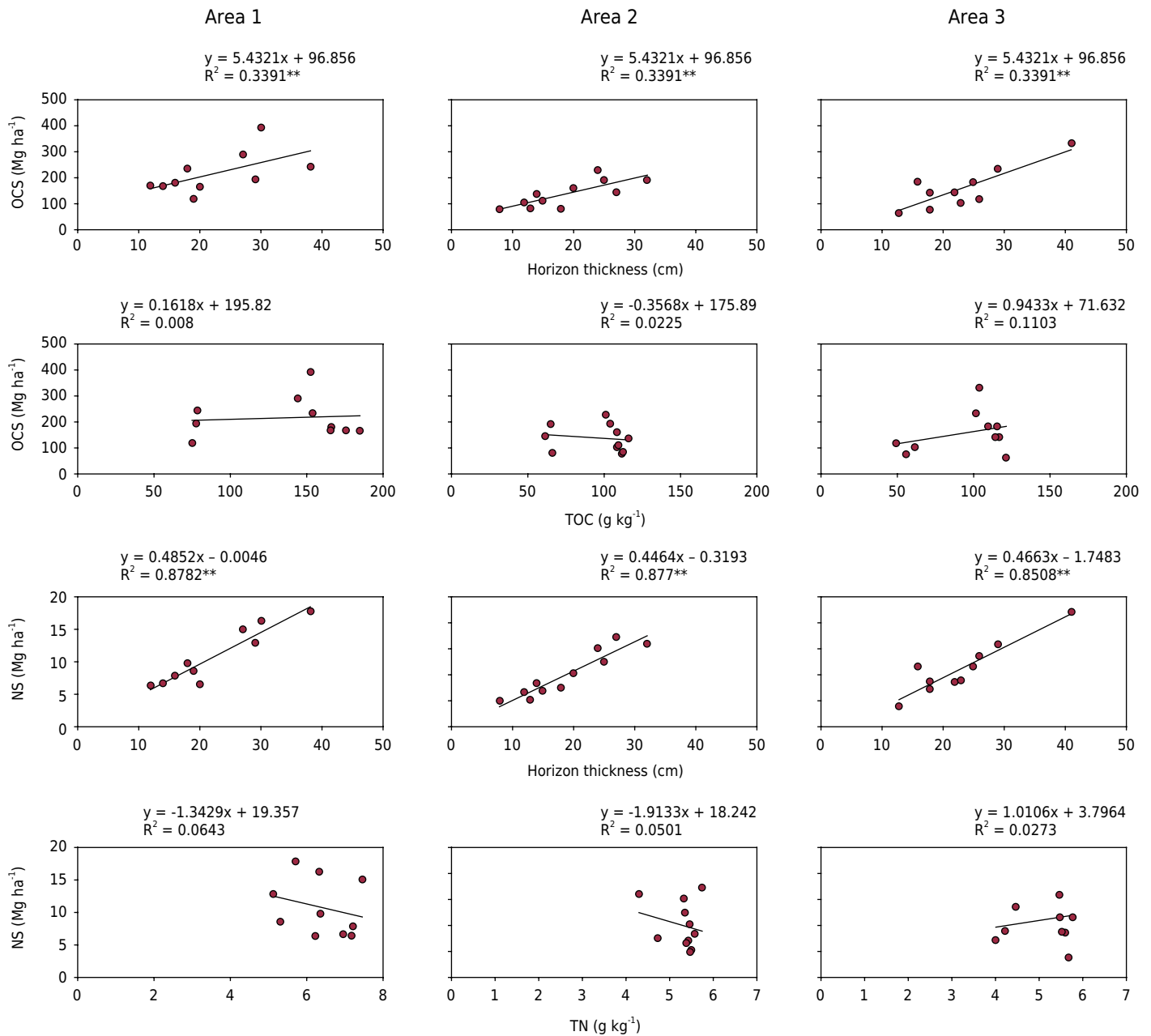


Figure 4. Relations between carbon and nitrogen stocks (OCS and NS) and horizons thickness and total carbon and nitrogen contents (TOC and TN). P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

in tropical environments, due to the intermolecular interactions with the surface of clay minerals and oxides of iron and aluminum (Bruun et al., 2010).

The ratio between the organic carbon fractions and the TOC also differed between the areas. All profiles of Area 1 presented higher averages for the LOC/TOC ratio and lower for the MOC/TOC ratio (Table 6). Between the agricultural areas (Areas 1 and 3), no significant differences were observed for any of the ratios. The LOC/TOC and MOC/TOC values varied between the horizons in the profiles, showing a pattern of decrease in the value of both ratios with soil depth.

Multivariate analysis

In the principal components analysis (PCA), the PC1 explained 47.17 % of the total variance, and the PC2 explained 25.91 %. Together, they explained 73.08 % of the variance in the original data (Figure 6). Three groups were identified in the PCA and clustering analysis,

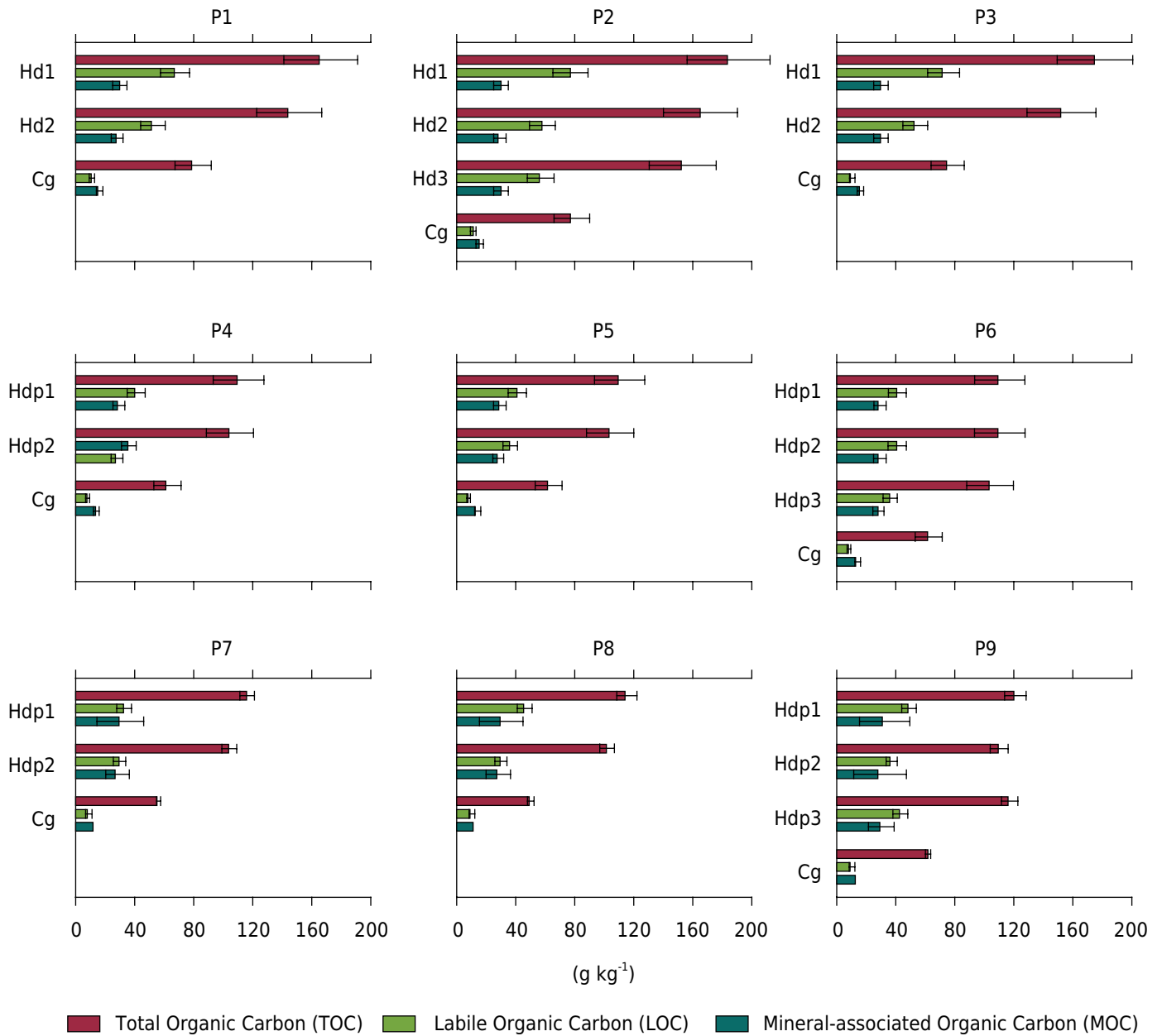


Figure 5. Total organic carbon and organic carbon fractions of the studied Histosol profiles. P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

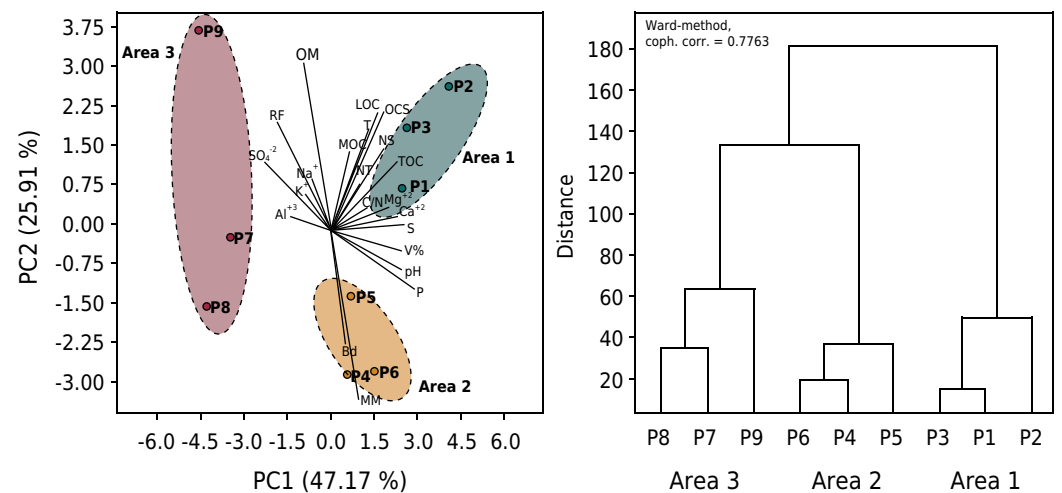
which separate the studied profiles according to the land use systems. These results indicate that conventional tillage with plowing and artificial drainage strongly influenced the properties of the Histosols.

The OCS, NS, TOC, NT, and parameters related to the fertility (S and V%) were defined by positive values in the PC1, which indicate soil conservation in Area 1, under natural vegetation. The negative axis of the PC1 is defined by the soluble sulfate (SO_4^{2-}), rubbed fibers, Al^{3+} , and salts soluble in the extract of the saturated paste (Na^+ and K^+). Some of these parameters may be related to modifications caused by the process of subsidence, with increased oxidation of the labile organic matter and increased fiber content. Also, this process may have triggered the process of sulfidization, which explains the observed values of SO_4^{2-} . The PC2 is clearly defined by the organic matter (OM) and fractions of the organic carbon (LOC and MOC) in the positive axis, and by the mineral material (MM) and bulk density (Bd) in the negative axis. This component indicates the decrease in the

Table 6. Ratios of labile organic carbon (LOC) and mineral-associated organic carbon (MOC) over total organic carbon (TOC)

| Prof | LOC/TOC | MOC/TOC |
|---|------------|------------|
| % | | |
| Area 1 Secondary tropical forest (natural vegetation) | | |
| P1 | 38.35±2.23 | 19.12±0.71 |
| P2 | 39.44±1.69 | 18.78±1.62 |
| P3 | 38.06±3.24 | 18.39±1.29 |
| Area 2 Conventional tillage of cassava (<i>Manihot esculenta</i>) | | |
| P4 | 36.15±1.41 | 26.65±0.16 |
| P5 | 35.65±1.51 | 26.19±0.15 |
| P6 | 36.42±1.69 | 26.66±0.19 |
| Area 3 Intercropped coconut (<i>Cocos nucifera</i>) with cassava (<i>Manihot esculenta</i>) | | |
| P7 | 28.89±0.41 | 26.84±0.44 |
| P8 | 34.78±5.14 | 26.84±0.45 |
| P9 | 36.81±2.12 | 26.20±0.42 |

Prof: profile. LOC: labile organic carbon; MOC: mineral-associated organic. LOC was determined using KMnO_4 0.3 mol L^{-1} and MOC was determined by humid oxidation with $\text{K}_2\text{Cr}_2\text{O}_7$ 0.167 mol L^{-1} . P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).


Figure 6. Principal component analysis and clustering analysis of the studied Histosol profiles. P1, P2, and P3: Area 1 - secondary tropical forest (natural vegetation); P4, P5, and P6: Area 2 - Conventional tillage of cassava (*Manihot esculenta*); P7, P8, and P9: Area 3 - intercropped coconut (*Cocos nucifera*) with cassava (*Manihot esculenta*).

organic matter content along with the increase in the bulk density in Area 2, which are also signals of the process of subsidence.

DISCUSSION

The results indicate that the properties of the Histosols are strongly modified by tillage with plowing and drainage. In the study areas, conditions promote the accumulation of sulfidic materials: flat landforms, waterlogged soils, lack of oxygen, provision of dissolved sulfate by marine water, and abundant organic matter. Persistent anaerobic conditions in soils result in precipitation of FeS . This process is an intermediate step in S diagenesis and an important part of the S biogeochemical cycle. The FeS is formed due to the abundance of SO_4^{2-} , high degree (frequency and duration) of soil saturation,

and high TOC contents supporting anaerobic microbial respiration (Rabenhorst et al., 2010; Duball et al., 2020). With drainage and plowing, the soils are exposed to oxygen, and sulfides (usually iron sulfides or mineral pyrite) are oxidized to sulfuric acid leading to acidification. In our study, this process is demonstrated by the high correlations between the SO_4^{2-} content, pH values, and ECe (Figure 7). The observed low soil pH values and the soluble sulfate contents (SO_4^{2-}) also indicated acid-sulfate soil potential (Vegas-Vilarrúbia et al., 2008).

The results demonstrate that the increase in the electrical conductivity in the studied profiles is not related to salinity, but are to the hydrogen and sulfate in solution, released by the oxidation of the pyrite with the formation of sulfuric acid, as observed by Souza Júnior et al. (2001a,b). This pattern is due to the drainage system installed in Area 3 (Figure 8a), which altered the natural conditions of the soil and may have triggered the sulfurization process. With the soil being drained, the pyrite oxidation leads to the development of mottles of yellow-brown color, probably from jarosite, which characterizes the process of sulfurization (Figure 8b). Thus, as observed by Souza Júnior et al. (2001b), for thionic soils, the high electrical conductivity cannot be used as the only criterion to identify salinity.

The drainage of Histosols also leads to the process of subsidence, which involves the reduction of soil bulk, by the oxidation of organic matter (Cipriano-Silva et al., 2014). In the studied soils, this process is highlighted by the lower contents of TOC and NT in the agricultural areas (Areas 2 and 3; Table 5). In Area 2, the TOC and NT values decreased by 33 and 20 %, respectively in the histic horizon, and about 17 and 8 % in the gley horizon. In area 3, the TOC and NT values decreased by 31 and 18 %, respectively in the histic horizon, and by about 27 and 21 % in the gley horizon, respectively. Although it does not have a drainage system as in Area 3, the soil in Area 2 was constantly

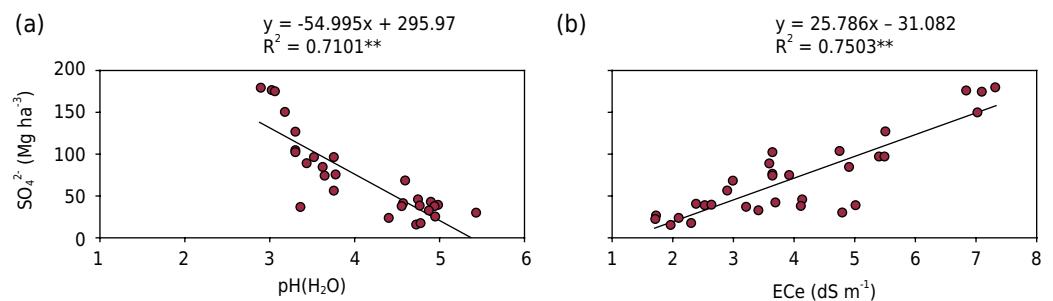


Figure 7. Relations between soluble sulfate (SO_4^{2-}) and $\text{pH}(\text{H}_2\text{O})$ and electrical conductivity of saturated soil-paste extract (ECe).

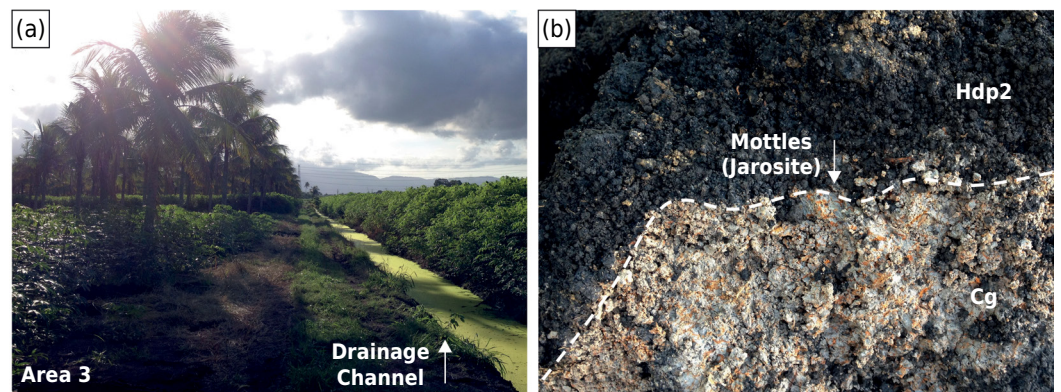


Figure 8. Drainage channel in Area 3 (a) and transition between superficial (Hdp2) and subsurface (Cg).

plowed, which explains the lower levels for C and N in comparison to Area 1. The rate of subsidence of peatland depends not only on the kind of peat, its bulk density, and drainage intensity but also on its usage and management practices (Gnatowski et al., 2010). With the plowing of the soil, besides the reduction of the organic matter content, it is possible that, when the peatland dries out, it becomes hydrophobic and, thus, is unable to return to the earlier levels of moisture, which then intensifies the loss of C and N (Holden et al., 2006; Grzywna, 2017).

Regarding the stocks of C and N, we verified that the thickness of the horizons is more correlated with the stock values than with the local C and N content in the agricultural areas (Areas 2 and 3; Figure 4). This can be explained by the losses of C and N by oxidation, the drainage in Area 3, and the plowing of the soil in Area 1. Besides that, our results indicate that the dynamics of the C stock is closely related to that of the N stock, as indicated by the correlations between the changes in the C and N stocks (Figure 3b). This demonstrates that the dynamics of C-N interactions is very important for the regulation of the C stock in the long term, as nitrogen is necessary to support the accumulation of C as a result of the stoichiometric ratios in the vegetation and the soil (Hungate et al., 2003; Luo et al., 2004; Li et al., 2012).

The drainage and cultivation of organic soils increase the TOC mineralization and the emission of CO₂ (Lal et al., 2004; Couwenberg et al., 2010; Wang et al., 2017). In the current study, it can be observed by the reduction of labile organic carbon in the agricultural areas (Figure 5) and lower values of the LOC/TOC ratio (Table 3). These results suggest that the reduction in the TOC content is linked to the loss of LOC. The labile organic carbon in the soil is the most active fraction of the TOC with a fast turnover rate and can be degraded by microorganisms. Therefore, it is more sensitive to environmental impacts, mainly in the superficial soil (Zou et al., 2005; Zhang et al., 2006). Our findings showed that the TOC and LOC content in the deeper organic horizons are also affected by the cultivation. Similar results have been reported by Wang et al. (2017) when assessing the impact of change in land usage on the patterns of distribution of organic carbon in peatlands and mineral soils in Northeastern China.

The low C/N ratio in Areas 2 and 3 also reflects a more intense decomposition process. The C/N ratio may reflect the quality of the organic matter and the processes of microbial transformation. High values for C/N ratio are associated with slow transformation and cycling of organic matter, while low values imply a high degree of decomposition of organic matter (Rumpel et al., 2006; Kindler et al., 2011; Wang et al., 2017). Therefore, the lower C/N ratios observed in the agricultural areas (Areas 2 and 3) in comparison to Area 1 suggest a high decomposition rate for the organic matter in the agricultural areas, leading to losses in LOC and, consequently, lower TOC content.

Regarding the organic carbon fraction associated with minerals (MOC), no expressive changes were observed among the studied profiles. In Area 2, the MOC/TOC ratios were lower than those of the agricultural areas. These results suggest that the loss of C in the agricultural areas comprise only the most labile fraction of the LOC. The MOC represents the organic carbon that obtains stability by physical sorption to the minerals and, later, chemical bonding to the surface, constituting an important mechanism to stabilize the organic matter (Kaiser et al., 2007; Wang et al., 2014).

The multivariate analysis of the physical and chemical properties of the soils under study showed a clear distinction between the profiles (Figure 6), grouping them according to the studied areas. This separation is an indicator of the effects of the cultivation practices on the Histosols. For example, the plowing in Area 2 that promotes an increase of mineral material contents (MM) by the loss of organic matter by mineralization/oxidation and increasing bulk density (Bd). In Area 3, the drainage of the soils with a high content of SO₄²⁻ promotes sulfurization, which occurs when materials containing sulfide (as pyrite, FeS) are exposed to oxidizing conditions (Fanning, 2017). In Area 1, where the soils were

maintained with natural vegetation, the profiles present higher total content and stock content for C and N, higher content of carbon for the LOC fraction, and higher fertility (S and V%). Thus, the values of the PCA analysis confirmed the results from the other analyses undertaken in this study.

Although most studies of C loss in peatlands are focused on non-agricultural soils, wetland organic soils that are intensely cultivated may also present great losses of C and N through the emission of greenhouse gases (e.g., CH₄, N₂O) (Taft et al., 2017). In cases of peatlands with acid sulfate soils, the best management of land must comprise a series of activities both to minimize the increase in acidity resulting from the oxidation of sulfide minerals and the management of the already existing acidity in the landscape (Melville et al., 2017). Unsuitable management practices in these soils can cause irreversible changes. In this study, we have demonstrated that such practices may contribute to the emission of greenhouse gases, producing a fast loss of C reserves that have been accumulated through many million years (Kløve et al., 2017). However, despite this high fragility, in several regions similar to the study area, the Histosols are a good source of income to many urban farmers. Such farmers need information, tools, and training to find better options to use the soil.

CONCLUSION




Cultivation practices comprising drainage and plowing of the soil affect the Histosols properties negatively. The implementation of such practices in the soil management over two decades has depleted carbon and nitrogen stocks, mainly in the histic horizon, but also in the gley horizon. The loss of C is related to the reduction of labile organic carbon, which is more sensitive to environmental changes, even at deeper depths.



The plowing of the soil decreases the organic matter content due to the accelerated oxidation of organic matter, increasing the bulk density. Drainage, besides the loss of organic matter by subsidence, promotes the sulfidization of the soil with a high content of SO₄²⁻, due to the oxidation of soil materials containing sulfides.



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