Floresta e Ambiente 2022; 29(1): e20210091
https://doi.org/10.1590/2179-8087-FLORAM-2021-0091
ISSN 2179-8087 (online)

Floram
Floresta e Ambiente

ORIGINAL ARTICLE – Silviculture

Organic Matter in Soils with Anthropic Horizons in The Eastern Amazon, Pará (Brazil)

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Abstract

The aim of this study was to evaluate the distribution of chemical and physical fractions of soil organic matter (SOM) in anthropic horizons of soil profiles in the west of Pará. The highest total organic carbon values were observed in the superficial horizons, especially in the antrópico LAd and antrópico CHd (45.0g kg^{-1}). Were observed predominance of recalcitrant organic material. It appears that most of the C found in the SOM fractions is associated with C stabilization mechanisms such as the recalcitrance provided by the presence of pyrogenic coal, in addition to its ability to present carboxylic groups that increase its interaction with the mineral fraction of the soil, characterizing the mechanism of chemical protection. It is observed that the SOM fractions can function as indicators that contribute to better understanding of the soil carbon dynamics in soils with antrópico horizons.

Keywords: total organic carbon, physical fractionation of SOM, chemical fractionation of SOM, anthropic horizons.

1. INTRODUCTION AND OBJECTIVES

Around 2000 years ago, indigenous civilizations turned soils with low storage capacity for C and low fertility into large and extremely fertile reservoirs of this element (Neves et al., 2004). According to Fraser et al. (2011) these types of soils can cover from 1% to 3% of different Brazilian biomes, occurring on a larger scale in the Amazon region.

In general, the soils found naturally in the Amazon have high acidity, high aluminum saturation, low cation exchange capacity (CEC), few nutrients, and a factor that limits the storage of C, with emphasis on the rapid decomposition of the deposited organic matter. Ancestral indigenous civilizations were able to transform these soils, through the addition of organic material in different forms, into extremely fertile soil patches called Archaeological Black Earth (ABE) or Indian Black Earth (IBE) (Schellekens et al., 2017). There is great variability of attributes within these spots due to the uneven deposition of organic residues by the indigenous peoples (Lehmann et al., 2003; Barros et al., 2012).

In places where anthropic horizons are identified today, micro-ecosystems resilient to environmental conditions over time and to agricultural use were formed (Teixeira et al., 2009). The practices adopted by indigenous civilizations on these soils were able to positively modify their properties, even though it was not intentional, and the result provided excellent soil quality (Glazer et al., 2001).

In Brazil, IBE is characterized by having surface diagnostic horizons denominated anthropic A (Santos et al., 2018), identified by having a minimum thickness of 20 cm and extractable P content with Melich-1 solution with values greater than or equal to 30 mg kg^{-1} (Santos et al., 2018). Additionally, variable levels of total organic carbon (TOC) and calcium can be observed (Ca^{2+}) (Bernardes et al., 2017).

In these soils, the participation of organic matter is fundamental in the expression of the intrinsic characteristics attributed to ABEs. The permanence of this organic matter in these soils may be related to the presence of compounds with high recalcitrance, especially pyrogenic carbon (Liang et al., 2006; Novotny et al., 2009; Mao et al., 2012). Carbon in the form of pyrogenic charcoal can reach 35% of the soil TOC (Glaser et al., 2000), playing an important role in the biogeochemical cycle of C and its storage in the soil. The origin of this charcoal in these soils is attributed to the residues of charcoal from the fires frequently used by the indigenous people.

Furthermore, the permanence of carbon in these soils may also be related to the interaction of the mineral matrix of the soil with organic components. This interaction can favor or reduce the access of microorganisms to organic material, and this material is extremely important as an energy source for these microorganisms. When using organic materials, microorganisms transform them, making them more recalcitrant (Sollins et al., 1996). Despite this finding, there are few studies evaluating the different fractions of organic matter in these soils. The aim of the current study was to evaluate the distribution of chemical and physical fractions of organic matter in anthropic horizons of soil profiles described in Western Pará.

2. MATERIALS AND METHODS

The studied area is located in the municipality of Santarém, in the west of the State of Pará, with a predominance of primary vegetation characterized as Subevergreen Tropical Forest and a humid tropical climate (Am according to Köppen) (Figure 1). Precipitation and mean annual temperature are around 2150 mm and 25.9 ºC, respectively. For the study, six trenches were opened at selected points on which there was information on the occurrence of ABEs, located in the Experimental Unit of the Campus of the Federal University of Oeste do Pará and in the Tapajós National Forest (Flona). Five profiles were defined in upland areas and one in a lowland area. The soils were classified according to the Brazilian Soil Classification System (SiBCS) up to the fourth level (Santos et al., 2018) and according to the World Reference Base for Soil Resources (WRB) (IUSS Working Group, 2015).

With respect to the classification of the profiles, they were identified as follows: three profiles belonging to the Latossolo Amarelo Distrófico (Ferralsol) (LAd). These profiles differ in their fourth categorical level, namely: argissólico LAd, antrópico LAd, and típico LAd. Two Cambissolos (Cambisol) that differed from the second categorical level (suborder), being Cambissolos Húmicos Distróficos Antrópicos (antrópico CHd) and Cambissolo Háplico tb Distrófico latossólico Antrópico (antrópico latóssolico CXbd). A profile was classified as Gleissolo Melânico Tb Distrófico cambissólico (Entisol) (cambisólico GMbd) (Almada et al., 2021).

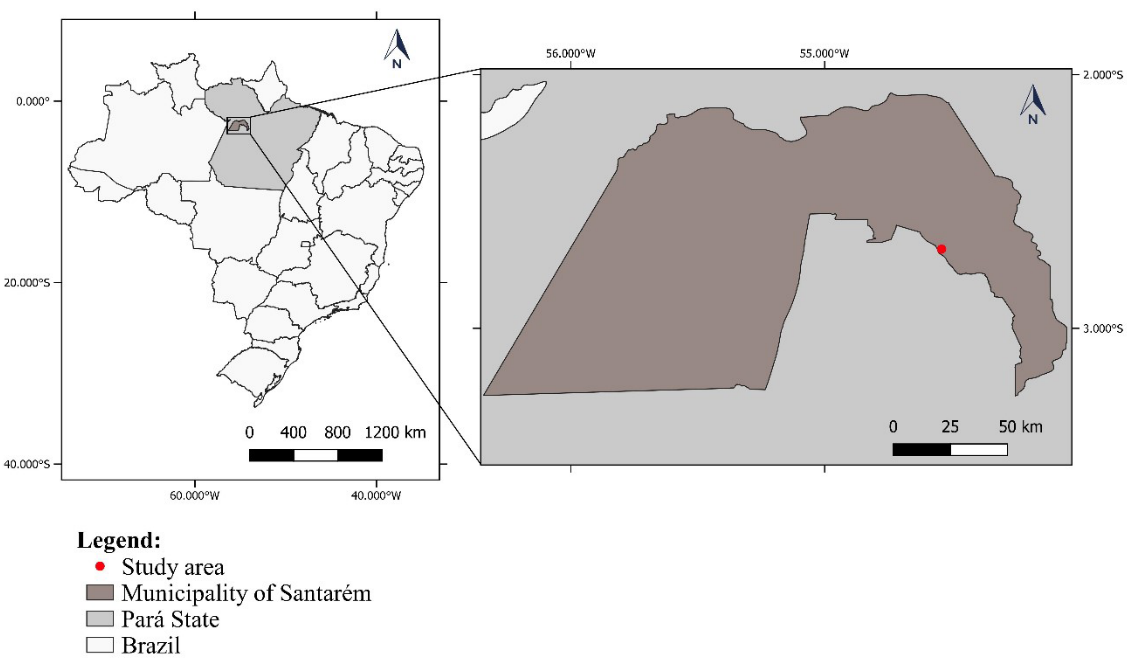

Figure 1. Localization of study area, Santarém, Pará.

Samples were collected from each horizon, air-dried, and then crushed and passed through sieves with an opening mesh of 2.0 mm, thus obtaining the air-dried fine earth (ADFE), from which the quantification was performed. of the total organic carbon (TOC) (TEIXEIRA et al., 2017) and the permanganate oxidizable carbon (POXC) which represents the most labile portion of the SOM (Culman et al., 2012). Nitrogen (N) and phosphorus (P) contents were also quantified according to Tedesco et al. (1995).

Through physical fractionation (Cambardella & Elliott, 1992) the particulate organic carbon fractions were obtained (POC) and mineral-associated organic carbon (MOC). Chemical fractionation was also performed, established by the International Society of Humic Substances - IHSS - and adapted by Benites et al. (2003), obtaining the humic fractions of SOM, fulvic acid fraction (FAF), humic acid fraction (HAF), and humin fraction (HUMF) in addition to the alkaline extract (AE) which is composed of HA and FA. Subsequently, the HA/FA and AE/HUM ratios were calculated.

The statistical procedures for data analysis were performed using the free access program R (The R Foundation, 2013) through the Algorithm for Quantitative Pedology (AQP) package, developed by Beaudette et al. (2013).

3. RESULTS

3.1. Total organic carbon and labile carbon

The TOC contents in each horizon are shown in Figure 1. In the profiles classified as LAd, there are decreases in the TOC contents with depth. The quantities found in the LAd horizons were higher in the anthropic horizons Au1, Au2, and Au3 of the antrópico LAd profile, reaching 45.0 g kg^{-1} in the Au1 horizon, in which the highest TOC content was quantified.

In antrópico CHd, higher TOC contents were found when compared to antrópico latossólico CXTbd. The highest TOC values found in the horizons of the antrópico CHd profile were approximately 25 g kg^{-1} in the Au1 horizon, 15.0 g kg^{-1} in the Au2 horizon, and AB, and 35.0 g kg^{-1} in horizon Au3. In this profile, there is an increase in the contents of the TOC with depth. Differing from the pattern observed in antrópico CHd, in the latossólico CXbd profile the TOC contents decreased with depth. In this profile, anthropic horizons (Au1, Au2, and Au3) are also observed, with the highest content of TOC (15.0 g kg^{-1}) being quantified in the Au1 horizon. In the cambissólico GMbd profile, composed of only two horizons, A and Bg, the TOC values were 25.0 g kg^{-1} and 5.0 g kg^{-1}, respectively.

The POXC contents, in all horizons, ranged from 0.10 g kg^{-1} to 1.0 g kg $soil^{-1}$, approximately. As with the TOC, the highest POXC values were quantified in the surface horizons, with emphasis on the anthropic horizons. Among the LAd, in the antrópico LAd there was a more effective contribution of labile carbon both in depth and quantity. The horizons Au1 (1.0 g kg^{-1}) and Au2 (0.8 g kg^{-1}) had the largest contents found in this profile.

The contribution of POXC in the surface horizons of the profiles classified as Cambisols varied between 0.8 g kg^{-1} of soil (Au2) and 0.4 g kg^{-1} of soil (AB) in the antrópico CHd. In the anthropic latossólico CXbd profile, there was a variation of POXC from 0.2 g kg^{-1} to 0.5 g kg^{-1} of soil between the surface horizons (Figure 2). In the cambissólico GMbd, POXC contents of approximately 0.7 g kg^{-1} in the A horizon and 0.3 g kg^{-1} in the Bg horizon were found.

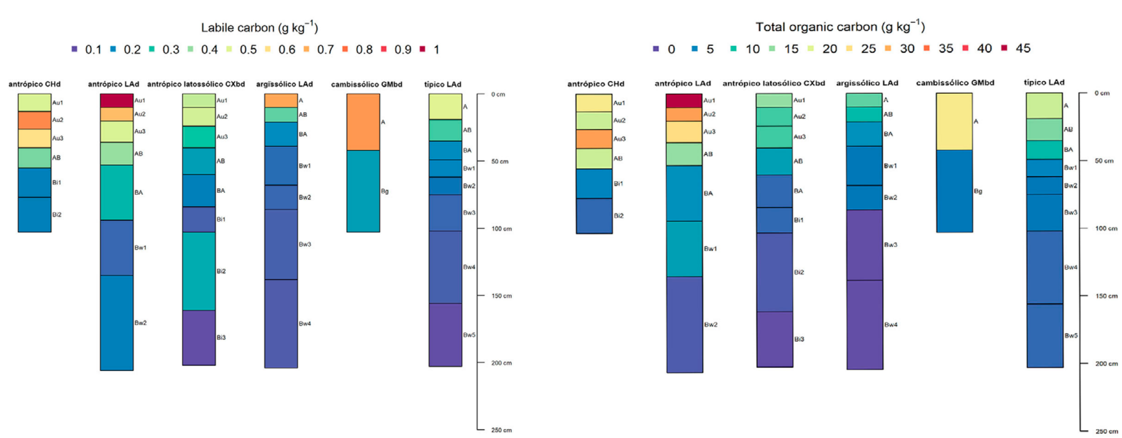

Figure 2. Total organic carbon (TOC) contents and labile carbon (POXC) in g kg^{-1} in the horizons of the profiles described in the Eastern Amazon. argissólico LAd: Latossolo Amarelo Distrófico argissólico; antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

3.2. Phosphorus and nitrogen

The P contents are shown in Figure 3. In general, it can be verified that the profiles with anthropic horizons (antrópico LAd, antrópico CHd, and antrópico latossólico CXbd) have the highest P contents available, while in cambissolo GMbd, argissólico Lad, and típico LAd profiles, values above 2 mg kg^{-1} of soil were not observed in any horizon.

The available P values in soils with anthropic horizons were greater than 2 mg kg^{-1} in all horizons, with the highest contents among all anthropic horizons being verified in the antrópico LAd, with values of up to 11 mg kg^{-1} in the Au2 horizon.

In smaller quantities, for the total N contents, patterns similar to those verified for the TOC contents were observed, with higher values in the surface horizons. Among all the horizon profiles, the quantities ranged from 0.5 g kg^{-1} in the Bw4 horizon of the argissólico LAd profile to 5.5 g kg^{-1} in the Au1 horizon of the antrópico LAd profile.

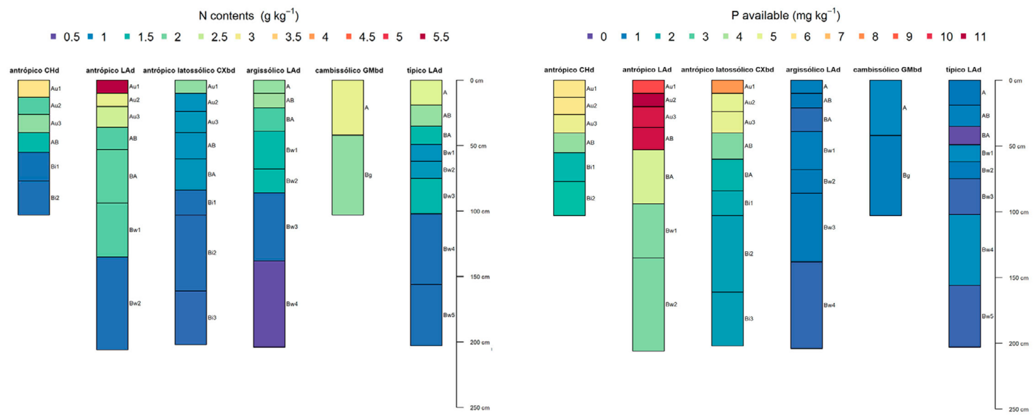

Figure 3. Values of P available (mg kg^{-1}) and N contents (g kg^{-1}) in the horizons of the profiles described in the Eastern Amazon. argissólico LAd: Latossolo Amarelo Distrófico argissólico; antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

3.3. SOM fractionation

The values of POC and MOC determined through particle size fractionation are shown in Figure 4. Analyzing these two compartments, the values of MOC are higher than those of POC in all profiles, indicating that the organic material is more recalcitrant. In LAd the highest POC values (5.0 g kg^{-1}) were found in the two surface horizons Au1 and A of the antrópico LAd and argissólico LAd profiles. In the anthropic horizons of the antrópico LAd profile, high values of MOC were quantified, reaching 40 g kg^{-1} in the Au1 horizon.

Analyzing POC and MOC values in Cambisols, the antrópico CHd profile shows the highest POC value (approximately 9.0 g kg^{-1} in the Au1 horizon). In this same profile, the highest MOC value is also observed in the Au3 horizon (approximately 30 g kg^{-1} soil).

In the cambissólico GMbd profile, POC values of 6.0 g kg^{-1} in the A horizon and 2.0 g kg^{-1} in the Bg horizon were verified. Similar to what was observed in the other profiles, most of the C stored in the physical fractions is associated with minerals, with values close to 20.0 g kg^{-1} in the A horizon and 5.0 g kg^{-1} in the Bg horizon.

The chemical fractions of SOM are shown in Figure 5. In general, the C contents of HUMF were higher than those of the other chemical fractions (C-FAF and C-HAF) in all horizons of the profiles evaluated. The C contents of HUMF reached approximately 13.0 g kg^{-1}, mainly in the anthropic horizons of the antrópico LAd, antrópico CHd, and antrópico latossólico CXbd profiles.

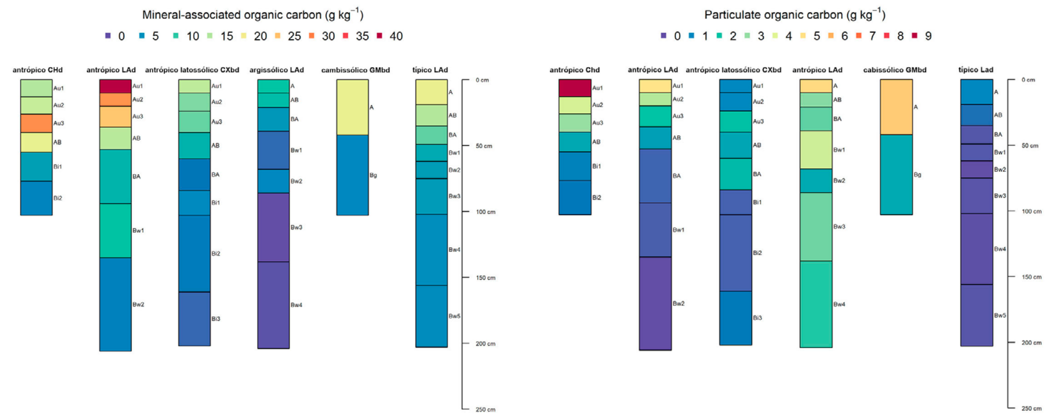

Figure 4. Physical particle size fractionation of soil organic matter in the horizons found in soil profiles described in the Eastern Amazon. POC – particulate organic carbon; MOC – mineral-associated organic carbon; argissólico LAd: Latossolo Amarelo Distrófico argissólico antrópico; LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

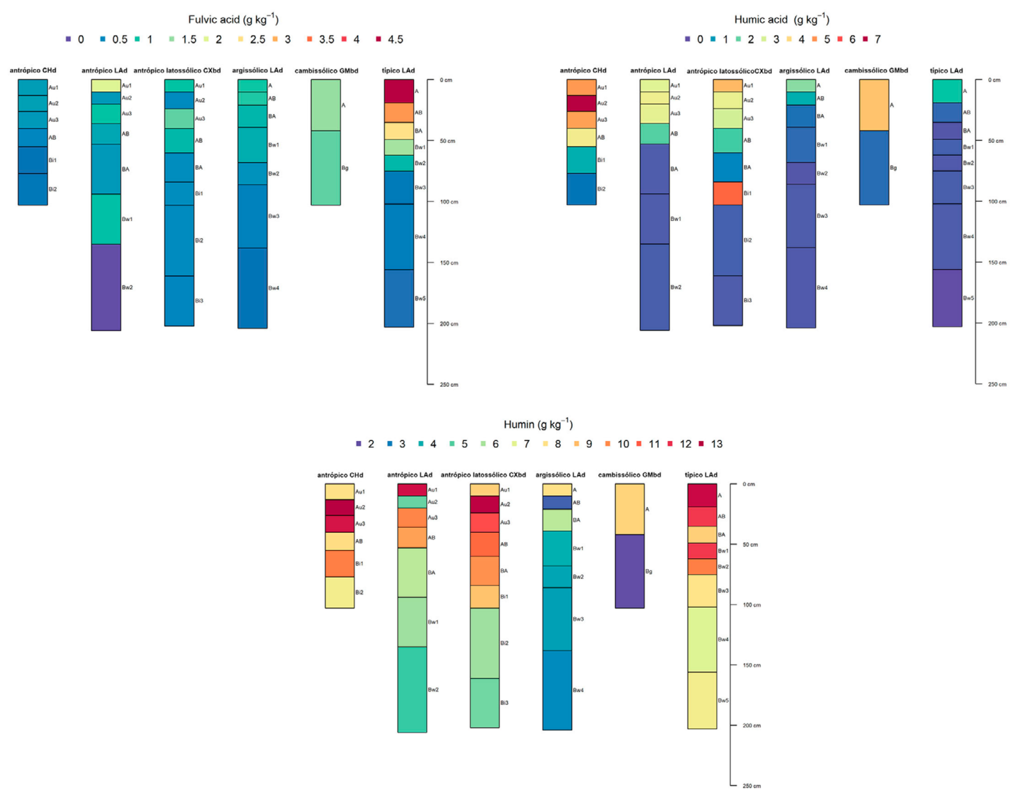

Figure 5. Chemical fractions of soil organic matter in the horizons of soil profiles described in the Eastern Amazon. argissólico LAd: Latossolo Amarelo Distrófico argissólico antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

In the anthropic LAd profile, it is observed in the first three horizons, Au1, Au2 and Au3, amounts of C-FAF close to 4.0 g kg^{-1} while in the other LAd profiles these values did not exceed 2.0 g kg^{-1} in all horizons. Among the profiles, the values of C-FAF were higher than those found in C-HAF only in the típico LAd (Figure 5) with values close to 4.5 g kg^{-1} soil.

The relations between the humic fractions of the SOM are shown in Figure 6. The relation between HUM and the sum of the FA and HA ranged from 0 to 16, approximately, with an increase in this relation with increasing depth. This pattern is opposite to that observed for the AE/HUM ratio of soil profiles. The típico LAd profile was the only profile in which the AE/HUM ratio decreased in depth, ranging from 0.5 in the A horizon to values close to 0.0 in the Bwg horizon in a uniform and decreasing manner. In the antrópico latossólico GMbd profile, an increase in the AE/HUM ratio was observed in depth, with approximate values of 0.7 in the A horizon and 0.9 in the Bg horizon. For the other profiles, antrópico CHd, latossólico CXbd, antrópico LAd, and argissólico LAd, decreases in the AE/HUM ratio in depth were also observed, however, this decrease was not uniform as observed in the típico LAd profile. In these profiles, with depth, irregular variation (increase or decrease) in the AE/HUM ratio was verified.

To facilitate the synthesis of all results obtained, through the mean and median, the percentage values of all studied variables were calculated (HUM, FA, HA, HA/FA, AE/HUM, HUM(HA+FA), POC, MOC, POXC, TOC, N, and P) (Figure 7). The profiles were grouped and presented in graphs with median values of 50 cm deep slices delimited on both sides by the 25[th] and 75[th] percentiles. Values along the y-axis (right side of Figure 7) describe the proportion of data that contributes to aggregate values at this depth. In general, the evaluation of the variables was carried out up to a depth of 100 cm.

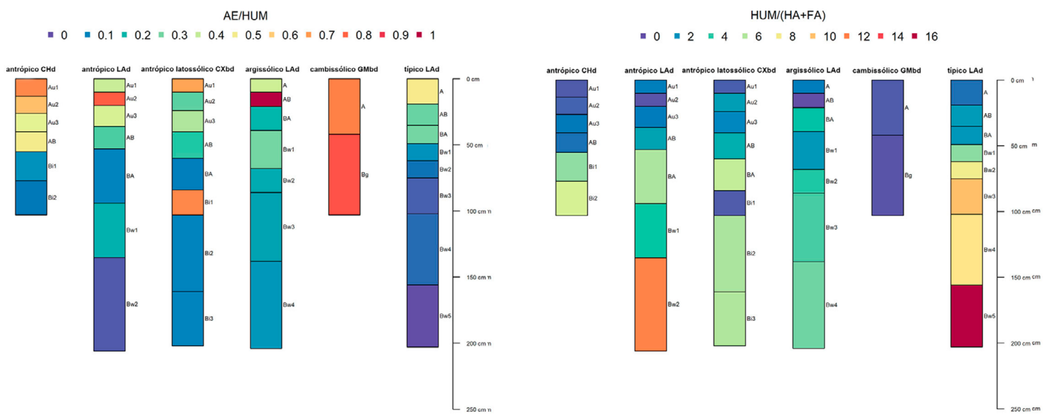

Figure 6. Relations between humic fractions, AE/HUM and HUM/(HAF+FAF) of the SOM of the horizons of soil profiles in the Eastern Amazon. argissólico LAd: Latossolo Amarelo Distrófico argissólico antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

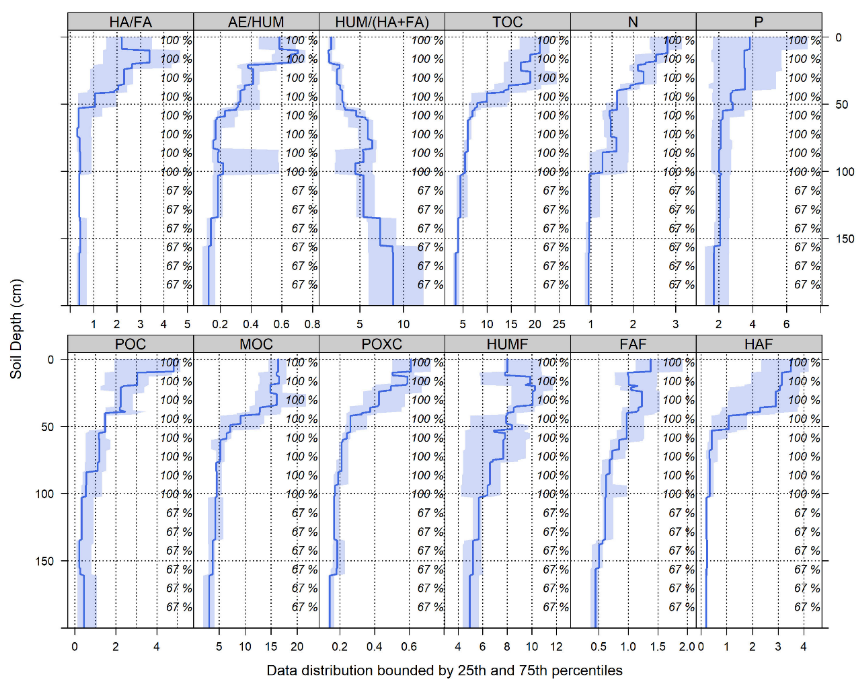

Figure 7. Depth distribution of the variables HUM, FA, HA, HA/FA, AE/HUM, HUM(HA+FA), POC, MOC, POXC, TOC, N, and P as a function of the 25[th] and 75[th] percentiles of the series of six profiles with anthropic horizons found in the Eastern Amazon.
HUM: humin fraction; FA: fulvic acid fraction; HA: humic acid fraction; POC: particulate organic carbon; MOC: organic carbon associated with minerals; POXC: labile carbon; TOC: total organic carbon; N: total nitrogen; P: phosphorus. argissólico LAd: Latossolo Amarelo Distrófico argissólico; antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

The soil profiles were grouped in a dendrogram where the x axis represents the similarity between the variables HUM, FA, HA, HA/FA, AE/HUM, HUM(HA+FA), POC, MOC, POXC, TOC, N, and P (Figure 8). The y-axis represents the depths at which these profiles were collected. The dendrogram, which has the function of describing the dissimilarity between pairs (Beaudette et al., 2013), allowed the separation of the profiles that were most similar according to the variables described. The profiles that were most similar were antrópico CHd and cambissólico GMbd, due to the smaller dissimilarity distance that differentiated them. These two profiles represented a distinct group from the other profiles studied (antrópico latossólico CXbd, typical LAd, argissólico LAd and antrópico LAd).

In the second group of soils, the latossólico CXbd profile and típico LAd represented the profiles that were most similar according to the studied variables. The similarity of these two profiles and the other two profiles belonging to this same group (argissólico LAd and antrópico LAd) occurred in a hierarchical way, where the antrópico LAd represented the most different profile within the group with a greater dissimilarity distance of its separation.

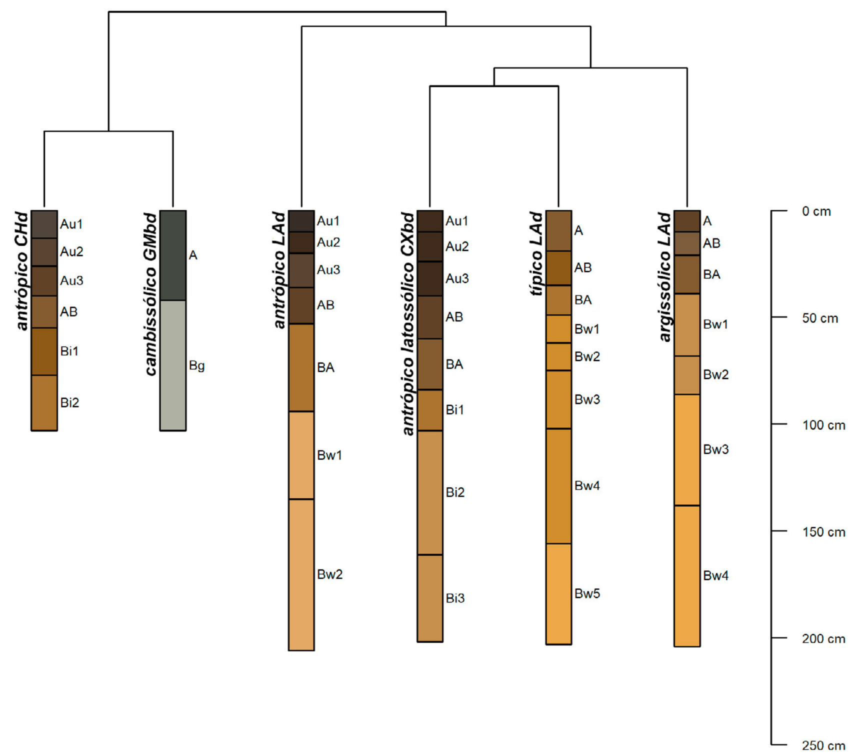

Figure 8. Representation of soil profiles through colors according to Munsell and dissimilarity between soil profiles with anthropic horizons found in the Eastern Amazon.

argissólico LAd: Latossolo Amarelo Distrófico argissólico; antrópico LAd: Latossolo Amarelo Distrófico antrópico; típico LAd: Latossolo Amarelo Distrófico típico; antrópico CHd: Cambissolo Húmico Distrófico antrópico; antrópico latossólico CXbd: Cambissolo Háplico Tb Distrófico latossólico antrópico; cambissólico GMbd: Gleissolo Melânico Tb Distrófico cambissólico.

4. DISCUSSION

Soil carbon dynamics are controlled by factors that can contribute to the increase or decrease of its content. C stabilization or destabilization factors are similar to soil formation factors (Jenny, 1941), namely: organisms, climate, relief, source material, and time. Additionally, there are also C stabilization mechanisms in the soil that include i) recalcitrance of organic material; ii) physical protection of organic material inside soil aggregates; and iii) chemical protection through the formation of organo-mineral complexes (Sollins et al., 1996).

It is important to highlight the influence of humans on the carbon stabilization process in soils with anthropic horizons. The presence of ancestral indigenous populations in areas close to the rivers resulted in soils with rich and resilient organic material composition (Teixeira et al., 2009). Therefore, soil C accumulation factors directly affect the SOM stabilization mechanisms and the dynamics of other soil nutrients.

For soils with anthropic horizons, Lehmann et al. (2003), in general, observed that N concentrations were higher when compared to soils without the occurrence of anthropic horizons. The N contents in all soil profiles studied were higher in the anthropic horizons of the LAd. Lehmann et al. (2003) found that there is a low concentration of N-NO_3 in soils with anthropic horizons when compared to non-anthropic horizons in adjacent soils. That is, even with satisfactory amounts of total N, it may not be in a readily available form for assimilation by plants, resulting in deficiency.

The highest values of total P were determined in the anthropic horizons of the antrópico LAd, antrópico latossólico CXbd, and antrópico CHd profiles when compared to the other horizons of the profiles in which this type of horizon was not observed. The deposition of bones from fish and other animals (Fraser & Clement, 2008) may be the explanation for the considerable levels of P observed in works on anthropic horizons (Lima et al., 2002; Campos et al., 2011) and in the current study.

The presence of anthropic horizons in the antrópico LAd, antrópico CHd, and antrópico latossólico CXbd profiles indicates the human action in the formation of the soils with anthropic horizons studied. However, these anthropic horizons can occur in other classes besides those presented.

In all three profiles that have anthropic horizons (antrópico LAd, antrópico CHd, and antrópico latossólico CXbd) three of these horizons (Au1, Au2, and Au3) were observed, at practically the same depths, with considerable amounts of TOC when compared to other surface horizons of the other profiles. The thickness of anthropic horizons may be related to the time of occupation of these soils by indigenous populations. In their study of Indian Black Earth in the Médio Madeira region of Amazonas, Campos et al. (2011) found carbon contents between 43.70 g kg^{-1} and 80.30 g kg^{-1} of soil, values higher than those verified in the current study. This diversified pattern of large TOC contents can be explained by the great variability of attributes within the anthropic soil patches, in addition to the possible uneven deposition of residues by the indigenous people (Lehmann et al., 2003; Barros et al., 2012). In places where anthropic horizons are identified today, according to Teixeira et al. (2009), micro-ecosystems resilient to environmental conditions over time and agricultural use were formed.

It is noticed that the effect of deposition of various residues on the soil carried out by indigenous communities over a long period can considerably increase the contents of TOC, this pattern being observed with greater expression in the antrópico LAd compared to the other two profiles classified as LAd. Similar to what was seen in the current study, Chagas et al. (2017) found that the deposition of these residues also contributed to the increase in TOC content in anthropic horizons of LA.

The cambissólico GMbd profile is located in an environment of poor drainage in an area of vegetation composed of grasses, which distinguishes it from the other profiles. The TOC content found in the A horizon of this profile is related to the differentiated dynamics that the SOM is subjected to in this environment. The anaerobic environment reduces the activity of aerobic microorganisms in the process of transforming organic material in the soil (Sousa et al., 2019), and thus decomposition occurs more slowly.

The practices adopted by indigenous civilizations on these soils were able to positively modify their properties, even if this practice was not intentional, the result provided excellent soil quality (Glazer at al., 2001). It is believed that all residues produced by ancient populations were deposited on the soil, including plant and animal residues and also ash from their fires, resulting in an increase in organic matter in the soil. These carbonized residues are considered the great differential of anthropogenic soils found in the Amazon region.

Labile C (POXC) represents organic material that is easily oxidized and consumed by microorganisms and consequently lost more quickly. When considering it as part of the TOC, it turns out that the amounts of labile C are small. Most of the TOC is composed of more humified organic material, which is proven by the physical and chemical fractionation of SOM.

In soils with anthropic horizons, the different fractions of SOM show some differences when compared to soils with non-anthropic horizons. It is verified through the physical fractionation of SOM that most of the C is found associated with minerals (MOC), which is the most recalcitrant fraction of SOM. The participation of the POC is small and this fraction corresponds to labile C, corroborating the data mentioned above.

Through the quantification of the C contents of the humic fractions, it is possible to evaluate the most recalcitrant and persistent fractions of the SOM, that is, those that have already undergone transformations in the soil, the humic fractions. Among the humic fractions, for C-HUMF the highest C contents were observed, especially in soils with anthropic horizons. There was also considerable C-HAF participation in these solos. These data are similar to those reported in other studies Cunha et al. (2009); Cunha et al. (2007); Lima et al. (2002); Barros et al. (2012), since in soils with anthropic horizons, there is a tendency for the predominance of humic fractions, humic acid, and humin, considered more stable.

As already mentioned, in the three profiles, antrópico LAd, antrópico CHd, and antrópico latossólico CXbd, horizons constituted of a more recalcitrant organic matter were verified. This recalcitrance is a result of the presence of pyrogenic

C left from the bonfires of past indigenous populations. (Teixeira et al., 2009). Soils that have this type of carbon are able to contribute to better natural fertility, favoring increased agricultural production or even lush vegetation.

In pyrogenic charcoal, the presence of aromatic groups with a higher degree of polymerization and greater recalcitrance is observed, represented by the increase in the HUM fraction. In general, this fraction is not used by microorganisms (Teixeira et al., 2009), due to its great stability. Pyrogenic carbon, in addition to presenting condensed aromatic structures (aromatic rings) such as aryl carbon, also has oxidized carboxylic groups attached to these structures, allowing stability of this C and increasing the CEC of the soil and its fertility (Liang et al., 2006; Novotny et al., 2009; Madari et al., 2009).

Additionally, the stability of C found in soils with anthropic horizons in the Amazon region can also be correlated with calcium content, which, as a flocculant ion, can form fulvates and humates that make the C more stable (Cunha et al., 2009). In soils that do not have anthropic horizons, in places with high SOM transformation rates such as the Amazon, there is a trend towards higher values of C-FAF since they are influenced by the entry of new C into the soil and, consequently, more labile. The relation between pyrogenic C and the environment involves mechanisms that are not yet well established by the scientific community. In addition to all the effects on the chemical, physical, and biological properties of the soil, pyrogenic C can favor the accumulation and synthesis of other highly stable organic compounds, further contributing to the increase in soil C contents (Liang et al., 2010).

The known C stabilization mechanisms that act on SOM fractions in soils with anthropic horizons in Amazonia are associated with SOM recalcitrance provided by the presence of pyrogenic coal, in addition to its tendency to present carboxylic groups that increase its ability to interact with the fraction mineral, characterizing the mechanism of chemical protection. This results in better soil aggregation, allowing some SOM fractions to be stored and protected from microorganisms inside the aggregates, favoring the physical protection of these fractions. Therefore, the mineralogical composition of soils is considered a limiting attribute in the capacity of a soil to store C in the form of SOM fractions (Sollins et al., 1996). However, in soils with anthropic horizons, this capacity is increased due to the structural chemical composition of pyrogenic coal (Mao et al., 2012) which makes it more recalcitrant and more able to remain in the soil for longer.

5. CONCLUSIONS

The highest C contents were observed in the MOC and C-HUMF fractions, indicating that the main form of carbon stabilization is associated with chemical protection from SOM and the recalcitrance of organic material provided by pyrogenic coal.

ACKNOWLEDGEMENTS

We thank the research funding agencies FAPERJ, CAPES and CNPq.

SUBMISSION STATUS

Received: 14 Nov. 2021
Accepted: 01 Feb. 2022
Associate editor: Eduardo Vinicius da Silva

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