Research Article

Alteration of the organic matter fractions in soil cultivated with sugarcane in the Cerrado-Amazon transition zone[1]

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ABSTRACT

The use of agroindustrial wastes, such as vinasse, may alter the soil chemical and physical characteristics. This study aimed to evaluate the total organic carbon and total nitrogen in a soil and the distribution of carbon and nitrogen in the sand and clay granulometric fractions, in three management systems (with and without vinasse application and with burning for harvest, in comparison with primary/native forest coverage), regarding fertilization and harvesting of sugarcane, in the Midwest region of Brazil. The use of organic wastes in the sugarcane production system may promote, even in a short time frame, conservation and improvement of the soil quality by the addition and maintenance of organic carbon. The use of vinasse favors the increase of the total organic carbon and total nitrogen in the soil, in the clay fraction, at all evaluated depths. The system with burning results in lower total carbon levels in the sand fraction, in comparison with the clay fraction, and, even with the sugarcane harvest employing burning, the most recalcitrant organic matter is associated with the clay fraction.

KEYWORDS: Bioenergy, soil carbon compartments, agricultural wastes.

RESUMO

Alteração das frações da matéria orgânica em solo cultivado com cana-de-açúcar na transição Cerrado-Amazônia

O uso de resíduos agroindustriais, como a vinhaça, pode alterar as características químicas e físicas do solo. Objetivou-se avaliar o carbono orgânico total e o nitrogênio total de um solo e a distribuição de carbono e nitrogênio nas frações granulométricas areia e argila, em três sistemas de manejo (com e sem aplicação de vinhaça e com uso de queimada para a colheita, em comparação à cobertura vegetal de floresta primária/mata nativa), quanto ao modo de colheita e adubação da cana-de-açúcar, na região Centro-Oeste do Brasil. O uso de resíduos orgânicos no sistema de produção da cana-de-açúcar pode proporcionar, mesmo em curto período, conservação e melhoria da qualidade do solo pela adição e manutenção de carbono orgânico. O uso de vinhaça favorece o aumento do carbono orgânico total e do nitrogênio total no solo, na fração argila, em todas profundidades avaliadas. O sistema com queima resulta em teores de carbono total menores na fração areia, em comparação à fração argila, e, mesmo com a colheita da cana após a queima, a matéria orgânica mais recalcitrante está associada à fração argila.

PALAVRAS-CHAVE: Bioenergia, compartimentos de carbono no solo, resíduos agrícolas.

INTRODUCTION

In areas with native vegetation, the biological components are complex, diversified, stratified and stable. Their removal to implement monoculture farming or grazing systems reduces the natural soil fertility, by altering the dynamics of soil organic matter and the biogeochemical cycles of the elements, mainly those considered to be essential plant nutrients.

In natural ecosystems, the organic matter in the soil is stable, i.e., in a humification stage. The use of land for agriculture causes a loss of carbon due to reduction of soil organic matter levels, altering the soil quality (Costa et al. 2015).

Native areas typically have soil organic matter levels ranging from 6 to 10 g kg^{-1}. When transforming these areas for farming or grazing without the use of burning, these levels start to decrease until reaching relative stability, with values between 3 and 4 g kg^{-1}. But when burning and reburning of agricultural wastes are performed, modifications occur in the soil physical, chemical and biological properties, particularly a decrease of organic matter and increased soil compaction, a pattern that occurs worldwide (Ascanio & Hernández 2004, Ascanio & Hernández 2006).

The intensive sugarcane cultivation without adequate recycling of the exported nutrients leads

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to a natural decline in the soil fertility (Luo et al. 2019), which tends to be intensified by straw burning (Scarpare et al. 2019). There is a scientific consensus about the negative environmental impacts of this burning, and that the transition from manual to mechanized harvesting may bring environmental benefits (Hadian & Madani 2015, Bellezoni et al. 2018, Cardoso et al. 2019).

In the Brazilian Mato Grosso State, since 2008, legislation requires that sugarcane growers reduce the planted areas subjected to burning by at least 6 % per year, to completely eliminate the practice by 2026 (Mato Grosso 2008). Therefore, the longstanding method of burning sugarcane straw before harvesting is on the way to extinction, due to the potential for polluting the atmosphere and degrading the soil.

In sugarcane plantations, the application of vinasse (a by-product of producing ethanol) can supply organic matter and nutrients such as potassium, calcium and magnesium (Reis et al. 2019, Yin et al. 2019). In addition, the presence of labile organic matter in large quantities may accelerate the decomposition of stabilized organic matter (priming effect), thus increasing the availability of nutrients (Oliveira Filho & Pereira 2020). Therefore, the use of vinasse on sugarcane fields is a strategy both to manage the wastes produced and improve the fertility of cultivated soils. This is particularly interesting in areas with naturally poor soils, as in the Brazilian Midwest region, or areas with soil depleted by inadequate agricultural practices.

Thus, this study aimed to evaluate the total organic carbon content and the organic matter fractions after a change in the soil use and management systems, in a region of transition between the Cerrado (Brazilian Savanna) and Amazon biomes.

MATERIAL AND METHODS

The study was carried out in Mirassol D'Oeste, Mato Grosso State, in the Midwest region of Brazil (15º42'48.6"S and 58º07'48.2"W), in May 2018. The climate in the region, according to the Köppen classification, is tropical Savanna, or hot semiarid, with a four-month dry season, with average temperatures between 24.1 and 25 ºC. The soil is classified as typical Latossolo Vermelho Distrófico (Santos et al. 2018) or Oxisol (USDA 2015).

The evaluations were performed in an area of 6 ha cultivated with sugarcane, to verify the gains and losses of organic matter in the soil when submitted to different harvest and fertilization systems: with vinasse application; without vinasse application; with burning before harvesting; and a reference area of native forest.

The area was cultivated with grass for cattle grazing until 2006, when it was converted to sugarcane cultivation with a conventional soil preparation system. In 2013, there was a change to a new cultivation method, with heavy and medium harrowing to incorporate crop residues into the soil, followed by planting of *Crotalaria spectabilis*. After three months, the area was mowed, and the plant mass was left on the soil surface.

For vinasse fertilization, 350 kg ha^{-1} of NPK (06-37-00) + 180 m^3 ha^{-1} of vinasse were applied. In the areas without vinasse and with burning, 350 kg ha^{-1} of NPK (07-38-08) were applied.

The sugarcane variety planted in all the areas was RB85545. The maintenance fertilization of the area with vinasse was performed after the first year (first harvest) with 600 kg ha^{-1} of NPK (20-00-00) + 180 m^3 ha^{-1} of vinasse, followed by 550 kg ha^{-1} of NPK (20-00-00) + 180 m^3 ha^{-1} of vinasse in the second year, 500 kg ha^{-1} of NPK (20-10-00) + 180 m^3 ha^{-1} of vinasse in the third year, and 500 kg ha^{-1} of NPK (20-05-00) + 180 m^3 ha^{-1} of vinasse in the fourth year.

In the areas without vinasse and with burning, 700 kg ha^{-1} of NPK (19-00-22) were applied after the first year, 680 kg ha^{-1} of the same formula were applied after the second year, 330 kg ha^{-1} of NPK (15-15-15) + 400 kg ha^{-1} of NPK (19-00-22) after the third year, and 550 kg ha^{-1} of NPK (18-04-24) after the fourth year.

After the third harvest, subsoiling was performed in all the areas to an approximate depth of 40 cm, to uncompact the soil between the rows.

Semi-preserved and deformed soil samples were collected after the fourth year of planting sugarcane, in May 2018, in the layers 0.00-0.05, 0.05-010 and 0.10-0.20 m, in five mini-trenches in each treatment area. The soil samples were dried in a forced-air oven at 60 ºC, disintegrated and passed through a 2-mm sieve, to prepare them for physical and chemical analyses (Teixeira et al. 2017) (Table 1).

The physical fractioning of the soil organic matter was performed according to Cambardella & Elliot (1993), with 20 g of each soil sample being placed in a beaker along with 20 mL of deionized water. The solution was submitted to ultrasound

Table 1. Chemical and physical characteristics of the soil after four sugarcane harvests in areas submitted or not to vinasse and harvested with and without burning.

Systems*	Layer	pH	P	K^+	Mg^{2+}	Ca^{2+}	Al^{3+}	$H + Al^{3+}$	Sand	Silt	Clay
	m	H_2O	mg dm^{-3}	cmol$_c$ dm^{-3}					g kg^{-1}		
NF	0.00-0.05	5.9	39.23	0.22	3.26	7.10	0.00	9.83	598	33	369
	0.05-0.10	5.5	9.34	0.13	2.82	5.36	0.00	7.85			
	0.10-0.20	5.6	4.54	0.07	2.60	4.44	0.00	7.62			
WV	0.00-0.05	6.3	64.08	0.58	4.26	6.60	0.00	5.45	531	100	369
	0.05-0.10	6.1	52.90	0.45	2.48	6.50	0.00	6.77			
	0.10-0.20	6.4	23.47	0.36	2.80	6.74	0.00	4.82			
WoV	0.00-0.05	5.6	19.42	0.27	2.88	6.80	0.00	4.72	598	66	336
	0.05-0.10	5.7	18.55	0.16	2.34	6.46	0.00	5.41			
	0.10-0.20	5.5	4.54	0.11	2.28	6.48	0.00	5.15			
WB	0.00-0.05	6.3	68.81	0.28	2.54	7.38	0.00	3.23	631	100	269
	0.05-0.10	6.4	50.82	0.13	2.08	8.30	0.00	4.19			
	0.10-0.20	6.7	17.64	0.07	2.06	7.80	0.00	3.37			

* NF: native forest; WV: with vinasse application; WoV: without vinasse application; WB: with burning before harvesting.

treatment for 20 min, followed by sifting through a sieve with 53 μm mesh, to separate the organic matter associated with the sand fraction and the silt + clay fraction. The dry weight of the fractions was determined after drying in a forced-air oven at 60 ºC, for 72 hours, and weighing on an analytic scale. After separation of the organic matter fractions, the soil total organic matter was determined according to Teixeira et al. (2017), by combustion in a muffle furnace. To measure the total organic carbon and total nitrogen, 0.5 g of each granulometric fraction was digested in an acid medium with sodium dichromate, followed by application of the method described by Yeomans & Bremner (1988), to quantify the total organic carbon content, with results expressed in g kg^{-1}. The total nitrogen content was determined by the Kjeldahl method (Bremner & Mulvaney 1982), using 0.05 g of the fraction associated with silt/clay.

The labile carbon (LC) was quantified by oxidation with $KMnO_4$ (333 mmol L^{-1}) and reading with a spectrophotometer (Shang & Tiessen 1997). In turn, the non-labile carbon (NLC), which is the carbon not oxidized by $KMnO_4$, was determined by the difference with the total organic carbon. Based on the differences in the total organic carbon (TOC) between the reference system and the cultivated system, the carbon compartment index (CCI) was calculated, as it follows: CCI = cultivated TOC/reference TOC. The carbon lability index (LI) was calculated based on the proportion of LC in the soil: LI = cultivated LC/reference LC. These two indices (CCI and LI) were then used to calculate the carbon management index (CMI) (Blair et al. 1995): CMI = CCI x LI x 100.

The data were analyzed with the nonparametric Kruskal-Wallis test of the Agricolae package (Mendiburu 2019), to compare the means of the evaluated variables for the different treatments at each soil depth, at 5 % of significance, using the R software (R Core Team 2019).

To evaluate the relationship among the different areas with the organic matter granulometric fractions and the soil chemical attributes, the principal component analysis (PCA) was applied, calculated with the R software.

RESULTS AND DISCUSSION

The particles larger and smaller than 53 μm were considered to be the sand and silt/clay fractions, respectively (Figure 1). From the initial mass of 20 g of soil used in the physical fractioning, more than 90 % were recovered in the samples from all the cultivation systems and all evaluated depths. The silt/clay fraction (henceforth just called clay fraction) accounted for more than 50 % of this mass in the native forest, with and without vinasse, and the smallest recovered mass of this fraction was found in the system with burning.

The proportion of total organic carbon associated with the sand fraction (> 53 μm) was smaller than the total organic carbon associated with the clay fraction (< 53 μm), varying from 28 to 56 %

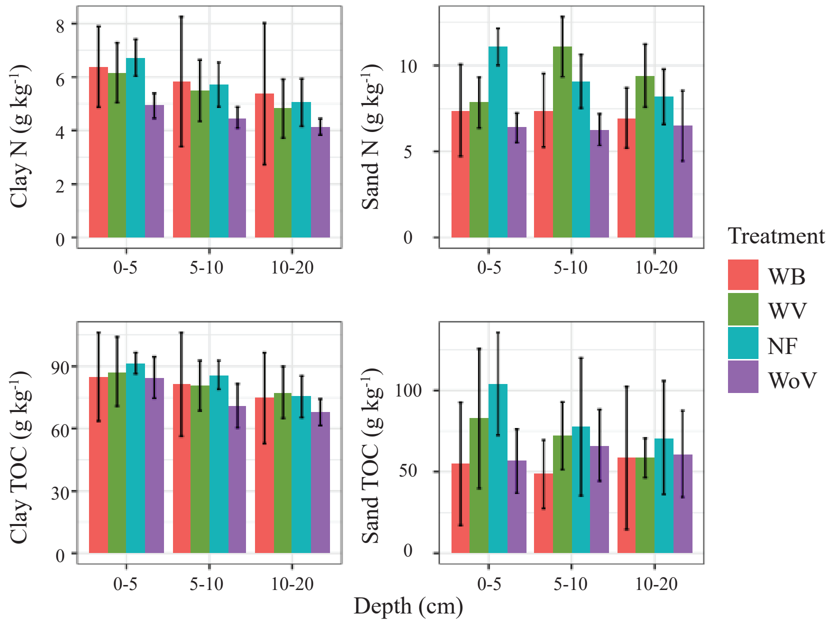

Figure 1. Total organic carbon (TOC) and total nitrogen (TN) in the sand fraction (> 53 μm) and clay fraction (< 53 μm) of the organic matter, at different soil depths and sugarcane cultivation systems (WB: with burning; WV: with vinasse; NF: native forest; WoV: without vinasse).

for the systems with and without vinasse application, respectively.

The systems with vinasse application and without burning had lower levels of total organic carbon and total nitrogen, possibly due to the presence of the labile substrate, which was more susceptible to oxidation and disintegration of the plant wastes by surface microorganisms (Varanda et al. 2018). In this respect, the system without vinasse presented the lowest levels of total organic carbon at all the analyzed depths.

The highest levels of total organic carbon and total nitrogen in the > 53 μm fraction were found in the native forest system. Soils in primary forest areas generally receive constant input of plant residues on the surface, and are less prone to perturbation, allowing a greater accumulation of carbon associated with the sand fraction (Das et al. 2019). However, the tendency here was for this fraction to be more sensitive to short-term alterations (Figure 1). Therefore, the efficient cycling of nutrients that occurs in this habitat is important for the development and conservation of the system (Conceição et al. 2014).

For the sugarcane cultivation system with burning, lower levels of carbon were expected, in comparison to the system with mechanized harvesting (without burning), due to the lower input of organic matter (Kunde et al. 2016). The results found probably reflect the short period (four years) of burning after the start of the sugarcane cultivation.

Despite the importance of organic carbon to the soil quality and climate regulation, the mechanisms responsible for its long-term storage in the soil are insufficiently understood (Stockmann et al. 2013). Recent studies have suggested that the persistence of organic carbon is less defined by its chemical composition and recalcitrance than previously thought (Lehmann & Kleber 2015, Kallenbach et al. 2016). According to the new conception, the chemical composition of organic inputs influences the short-term carbon dynamics, while the long-term persistence of carbon is mainly defined by its interactions with the mineral matrix and environmental constraints (Coward et al. 2018), mainly water availability.

The results of the present study showed that the average content of organic carbon in the clay fraction was 42.5 %, reflecting the soil type (Oxisol), climate conditions (Cerrado biome), quality and magnitude of the input of crop residues, and intensity of the soil turnover. The studied region has soils that are subjected to periods of intense leaching of nutrients and weathering of primary minerals, associated with periods of heavy rainfall. At the time of this study, however, the studied area had experienced 4 to 6 months of water restriction.

Few studies have analyzed the sorption and redox reactivity of minerals in the soil and the associated reactions for transformation of the associated organic matter. Experiments with organic molecules have shown that oxides of Fe (III) and Mn (III or IV) are able to oxidize carbon compounds in abiotic systems (Suter et al. 1991), but the heterogeneity of the soil organic matter has prevented the detailed investigation of its transformation after the reaction with surface minerals (Hering & Stumm 1990). This indicates that new studies with new methods need to be carried out for a complete understanding of the behavior of the carbon associated with the various soil granulometric fractions.

In the clay fraction, the organic carbon content decreased with depth in all the systems, what may be related to the accumulation of carbon, preferentially in the upper soil layers. On the surface, organic matter accumulates in the non-labile state, which is more difficult for microorganisms to decompose.

The greatest content of organic carbon in the clay fraction in the topmost layer (0.00-0.05 m) was observed in the system with vinasse. Although the application of vinasse favors the accumulation in the deep layers, the carbon levels found may be explained by the input of carbon from the cultivation of C4 plants like sugarcane (Mitton et al. 2017).

The system with burning had lower carbon contents in the sand fraction than in the clay fraction, demonstrating that the burning contributed to maintain the more recalcitrant structures associated with sand by means of hydrophobic interactions (Garcia et al. 2016).

For total nitrogen in the topmost layer (0.00-0.05 m), the highest quantities were associated with the control area (native forest) in both the evaluated fractions. The system without vinasse had the lowest nitrogen levels in both fractions and at all the evaluated depths. The system with vinasse had a higher nitrogen content, if compared to the system without vinasse, both for the sand and clay fractions, at all depths.

Concerning nitrogen, different mechanisms have been suggested to explain how the physical protection of organic compounds is related to nitrogen mineralization in different soil types. Among these are adsorption of compounds to the surface of clays, or the coating of these compounds by clays (Tisdall & Oades 1982), and the trapping of organic compounds in the small pores of the aggregates, making them inaccessible to the microorganisms in the soil (Hassink et al. 1993). In the present study, both these processes might have occurred, because, with the application of a liquid residue, the penetration of the compounds in the smaller pores might have been facilitated.

A pattern of nitrogen levels was not observed for the system with burning. Once again, contents higher than expected were found, possibly related to the time that the area had been cultivated with the use of fire. For other systems, Heid et al. (2009) reported that the higher quantity of carbon and nitrogen in the fraction < 53 µm is an indication of the greater stability of the organic matter by the formation of an organo-mineral complex.

The highest levels of labile carbon were observed in the system without vinasse, and the smallest levels in the systems with burning and the native forest, at all depths (Figure 2).

The lower levels of labile carbon in the system with burning was expected, because, according to Kunde et al. (2016), the burning of straw before harvest considerably reduces the input of organic matter in the soil and accelerates the decomposition of the labile compartment.

The non-labile carbon consists of the macromolecules that are hard for microorganisms to decompose, thus, it is subjected to slower cycling than labile carbon (Zech et al. 1997). The non-labile carbon decreased in the systems with increasing depth, except for the system with burning. In turn, the total organic carbon had the highest levels in the native forest and the system with vinasse and decreased with depth. This decrease of total organic carbon content with a greater depth was also reported by Gazzolla et al. (2015), who stated that this reduction could be explained by the slow decomposition of recalcitrant substances, including humic substances, due to the low microbial activity.

As reported by Santos et al. (2020), vinasse has the potential to replenish the organic carbon in sugarcane fields managed with burning. This explains the higher levels of total organic carbon in the treatments with burning and without vinasse.

The carbon management index (CMI) is a measure of the alterations caused by soil

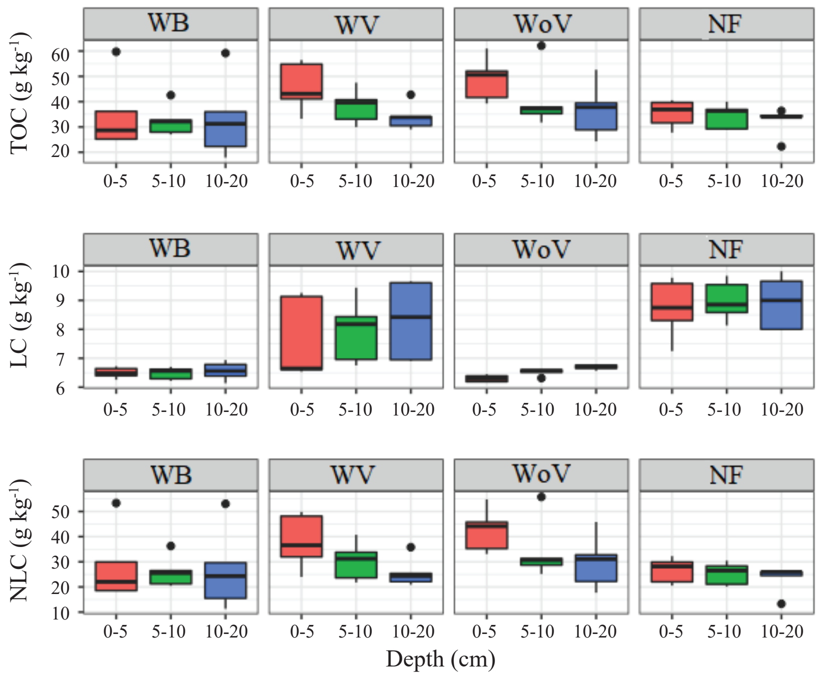

Figure 2. Soil labile carbon (LC), non-labile carbon (NLC) and total organic carbon (TOC), at different depths, with different use systems (WB: with burning; WV: with vinasse; WoV: without vinasse; NF: native forest).

management, in comparison with an original or ideal soil configuration. According to Conceição et al. (2014), it may be used to jointly evaluate the effect of management systems on the quantity and quality (lability) of the organic matter in the soil (Figure 3).

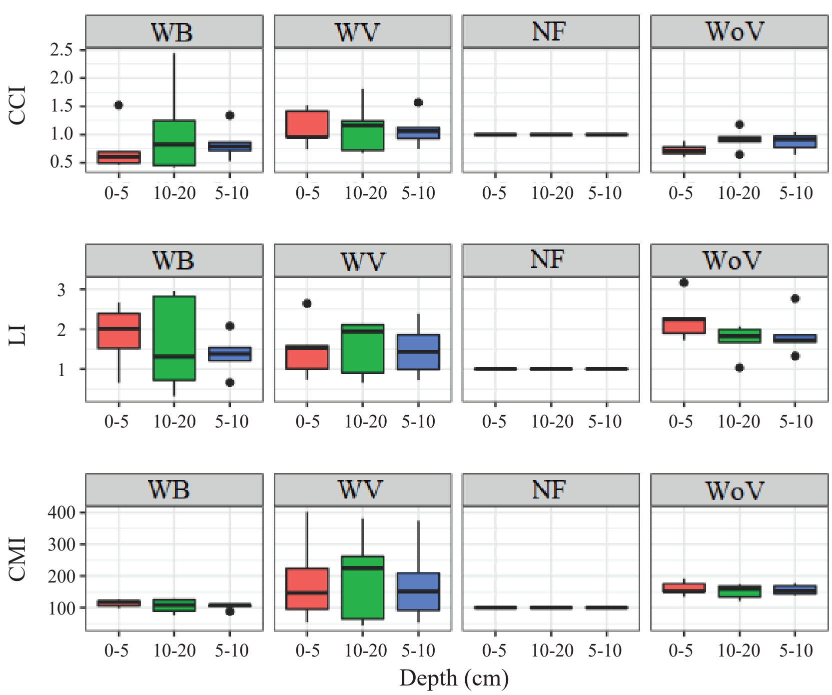

Figure 3. Carbon compartment index (CCI), lability index (LI) and carbon management index (CMI) in different soil use systems (WB: with burning; WV: with vinasse; NF: native forest; WoV: without vinasse).

The highest CMI was found in the system with vinasse. The index in the 0.10-0.20 m layer was 95.47 % greater than in the native forest area, while the smallest one (4.21 %) was observed in the system with burning, in the 0.05-0.10 m layer.

Based on the CMI in this study, the areas cultivated with sugarcane did not suffer a negative environmental impact. These results differ from those found by Kunde et al. (2016), in other regions, who have observed values lower than 100 % in areas cultivated with sugarcane in Argisols.

According to the carbon compartment index, values greater than 1.0 in the area with vinasse application indicate the proximity of the total organic carbon, in relation to the reference value. This shows the potential to increase the quantity of carbon in the soil of the cultivated areas, even in the short period of adoption of the system (4 years), promoted by the deposition of wastes, resulting in incorporation of the more functional structures in the soil, which may enable a greater participation in the humification process (Rangel et al. 2008, Santos et al. 2020).

The principal component analysis (PCA) was applied to visualize how the parameters previously mentioned were influenced by the different treatments. The PC1 and PC2 explained 32.9 and 19.8 % of the total variation, respectively (Figure 4).

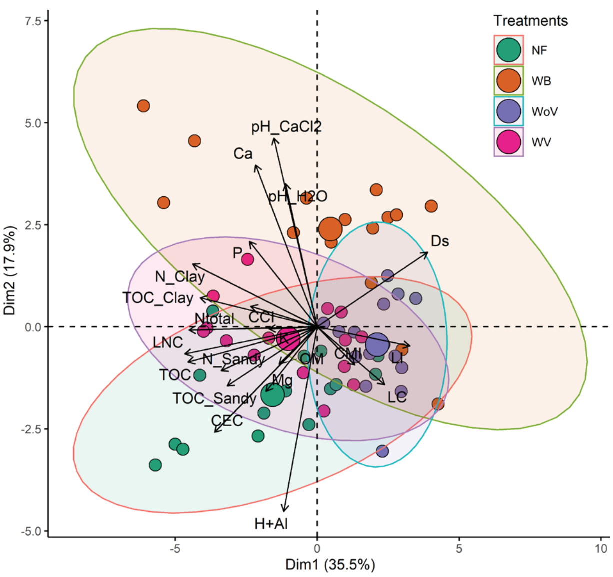

Figure 4. Principal component (PC) analysis for soil parameters, as a function of land use systems (NF: native forest; WB: with burning; WoV: without vinasse; WV: with vinasse).

The change in the land management with cultivation of sugarcane in the Cerrado-Amazon transition region has been affected by the chemical properties and the way that the organic matter is associated with the granulometric fractions. The tested variables had distinct influences, some more than others, depending on the treatments. The areas with burning and native forest were clearly separated in the principal component analysis, indicating the greater distinction of these treatments. The soil organic matter fractions, along with the fertility, were altered by the management systems, providing different levels of plant biomass inputs. Thus, the PCA may be used as a tool to evaluate the soil quality, especially after short periods of cultivation (Rossi et al. 2012). The results of the present study demonstrate efficiency also regarding the use of organic wastes from agroindustry.

Although the treatments with and without vinasse were in the middle of the principal component, variables such as total organic carbon, clay, total nitrogen and carbon compartment index were closely associated with the application of vinasse to the soil, as previously stated.

CONCLUSIONS

1. The total organic carbon and total nitrogen in the soil and their distribution in the sand and clay granulometric fractions are influenced by vinasse application;
2. The use of vinasse favors the increase of the total organic carbon and total nitrogen in the granulometric fraction < 53µm (clay);
3. The evaluated cultivation systems altered the carbon management index, with a higher value observed with vinasse application.

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