Revista Brasileira de Ciência do Solo

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

Forest harvest management systems and residual phytomass affecting physical properties of a sandy soil

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ABSTRACT: Organic carbon introduced in soils, mainly through organic matter, has a relevant role in various soil properties and is particularly important in sandy soils. In these soils, the input of organic material is necessary to ensure the sustainability of production systems. This study aimed to investigate the changes in total organic carbon content and its effect on physical properties in areas under different harvest management systems (HMS) after the harvest of eucalyptus. The study was performed in December 2017 in a *Eucalyptus urograndis* (clone E13) commercial plantation, in the municipality of Água Clara, Mato Grosso do Sul State, Brazil. The soil of this area was classified as a sandy-textured *Neossolo quartzarênico*, which corresponds to *Quartzipsamments*. Soil samples were taken from the 0.00-0.05, 0.05-0.10 and 0.10-0.20 m layers for determinations of aggregate stability, soil bulk density (BD), macroporosity (Macro), microporosity (Micro), total porosity (TP) and total organic carbon (TOC); and for calculation of carbon stock (CS). Total organic carbon and CS continued down into the 0.20-0.40, 0.40-0.60, 0.60-0.80, and 0.80-1.00 m layers. Soil mechanical penetration resistance (PR) was determined to the 0.40 m depth in 0.10 m intervals. Carbon content was evaluated in the aggregates of the 0.00-0.05 m layer after wet sieving in 2000, 1000, 250 and 53 μm diameter sieves. Statistical evaluation consisted of analysis of variance, the Tukey test, and regression for the sources of variation that showed significance at 5 %. The data suggest that keeping the residual phytomass on the soil surface can positively impact total organic carbon, with a smaller reduction under the cut-to-length harvest management system. However, carbon stock is greater at the layer of 0.20-0.60 m; as the soil has a sandy texture, carbon moves through the soil profile, which has lower soil mechanical penetration resistance at the surface layers (0.00-0.10 m), once more under the cut-to-length system. Maintaining crop residual phytomass on the soil surface in the cut-to-length harvest management system provides better soil physical conditions, with greater macroporosity (0.00-0.05 m), aggregates with more carbon, and lower soil mechanical penetration resistance compared to systems that maintain only part of the harvest residual phytomass or no residual phytomass on the surface.

Keywords: carbon stock, aggregates, physical quality, *Eucalyptus* sp., organic matter.

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Received: January 04, 2021
Approved: June 09, 2021

How to cite: Sena KN, Maltoni KL, Troleis MJB, Faria GA. Forest harvest management systems and residual phytomass affecting physical properties of a sandy soil. Rev Bras Cienc Solo. 2021;45:e0200190.
https://doi.org/10.36783/18069657rbcs20200190

Editors: José Miguel Reichert and Luciano da Silva Souza.

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INTRODUCTION

Brazil has 9.0 million hectares of planted forests, 6.97 million hectares of which are of eucalyptus, and the state of Mato Grosso do Sul has 1.12 million hectares of eucalyptus growing on sandy soils, which predominate in that region (IBÁ, 2020). Sandy soils often have weak structure, low water retention, high permeability and sensitivity to compaction, low field capacity, and low organic carbon content and cation exchange capacity (Laclau et al., 2010; Huang and Hartemink, 2020). For sustainable use of sandy soils, their physical and chemical properties must be preserved through reduced tillage or no-till systems, crop residue management, carbon inputs, decreases in losses of soil nutrients (carbon, nitrogen, phosphorus, etc), and increase in the amount of macroaggregates and total porosity (Laclau et al., 2010; Six and Paustian, 2014; Du et al., 2015).

Forest areas are important in the economic sector and play a key role in the global carbon cycle. Eucalyptus plantations have been indicated as a valuable practice for carbon sequestration when associated with conservationist silvicultural practices in which soil turnover is reduced, residual phytomass is maintained, and nutrient cycling is promoted (Du et al., 2015; Rocha et al., 2018). Carbon plays an essential function in soil formation and maintenance of soil properties when incorporated in the soil. Soil contains more carbon than the total amount present in plants and the atmosphere, thus constituting a significant carbon reserve and effective stabilizer (Schmidt et al., 2011; Guan et al., 2015), which contributes to the mitigation of the greenhouse gas effect.

The impacts of soil use and management on soil physical quality have been quantified through physical properties related to soil structural stability, such as, aggregate stability. This property is dependent on soil mineralogy, soil particle size, and the presence of organic matter. At the same time, aggregate stability performs a significant function in the physical protection of organic carbon by enabling its occlusion within structural units and reducing its microbiological decomposition or its biodegradation, thus preserving organic carbon in the soil (Six and Paustian, 2014; Rocha et al., 2018; Vicente et al., 2019).

In the West Central region of Brazil, eucalyptus is normally grown on areas of degraded pasture, where it contributes by providing organic material during cultivation and harvest, when plant residual phytomass is left on the soil surface. Harvesting methods may lead to considerable differences in the amounts of organic matter deposited on the soil surface. The methods most used in this region are tree-length and cut-to-length harvest systems (Machado, 2008). The tree-length (TL) system generates tree-length logs; that is, the tree is semi-processed (delimbing and topping) in the area where the tree is felled, and the trunk plus branches, of more than 7-meter length, is taken to the roadside, where the processing of the logs is concluded (Machado, 2008).

The cut-to-length (CTL) method is characterized by processing the tree at the location where it is felled; delimbing, bark removal, and cutting trees into logs of pre-defined size are carried out at that location, leaving plant residual phytomass on the area (Machado, 2008). When this residual phytomass remains on the surface, it ensures a certain soil cover and maintains a large amount of plant material on the surface, initially forming a mulch and then plant litter.

The nutrients in the forest are returned to the soil through plant litter, which will be transformed and incorporated into the soil in the form of mineralized organic matter; the nutrients are then released for plant uptake (Krishna and Mohan, 2017; Rocha et al., 2018). The increase in organic matter input promotes soil aggregation and reduces exposure of carbon, which remains within soil aggregates, contributing to the improvement of soil structural stability, increase in total porosity, and microbial activity, among other benefits (Six and Paustian, 2014; Rocha et al., 2018; Vicente et al., 2019).

The CTL harvest management system (HMS) leads to greater input of organic matter than other practices, suggesting that it may promote conservation of the physical properties of soils of low structural stability, such as sandy soils, through the cycling of nutrients by residual phytomass left on the soil after harvest. This hypothesis supposes that the CTL, with a greater amount of material left in the area, may reduce losses of carbon/organic matter and preserve soil physical properties due to the residual harvest phytomass maintained in the area.

This study aimed to evaluate changes in organic carbon content and stock, and the changes in some physical properties of a sandy soil in areas under different harvest management practices of eucalyptus in the east of the state of Mato Grosso do Sul, Brazil.

MATERIALS AND METHODS

Study area

The study was performed in a *Eucalyptus urograndis* (clone E13) commercial plantation in the municipality of Água Clara, Mato Grosso do Sul State, Brazil (Figure 1). The climate in the region is tropical with dry winter (Aw), according to the Köppen classification system (Alvares et al., 2013), with mean annual rainfall and temperature of 1370 mm and 24.4 °C. The site was originally *Cerrado stricto sensu* (Brazilian tropical savanna), with pasture introduced in the 1960s and the first cycle of eucalyptus initiated in 2011, which was harvested in 2017.

Initial soil characterization

The soil of this area was classified as a *Neossolo quartzarênico* (Santos et al., 2018), which corresponds to a *Quartzipsamments* (Soil Survey Staff, 2014) or *Arenosol* (IUSS working group WRB, 2015), with loamy sand textural class. The area under study was initially characterized (120 days after harvest of the eucalyptus of the first cycle and before soil preparation for the next eucalyptus cycle) in terms of soil particle size and chemical properties. Disturbed soil samples were collected randomly with three

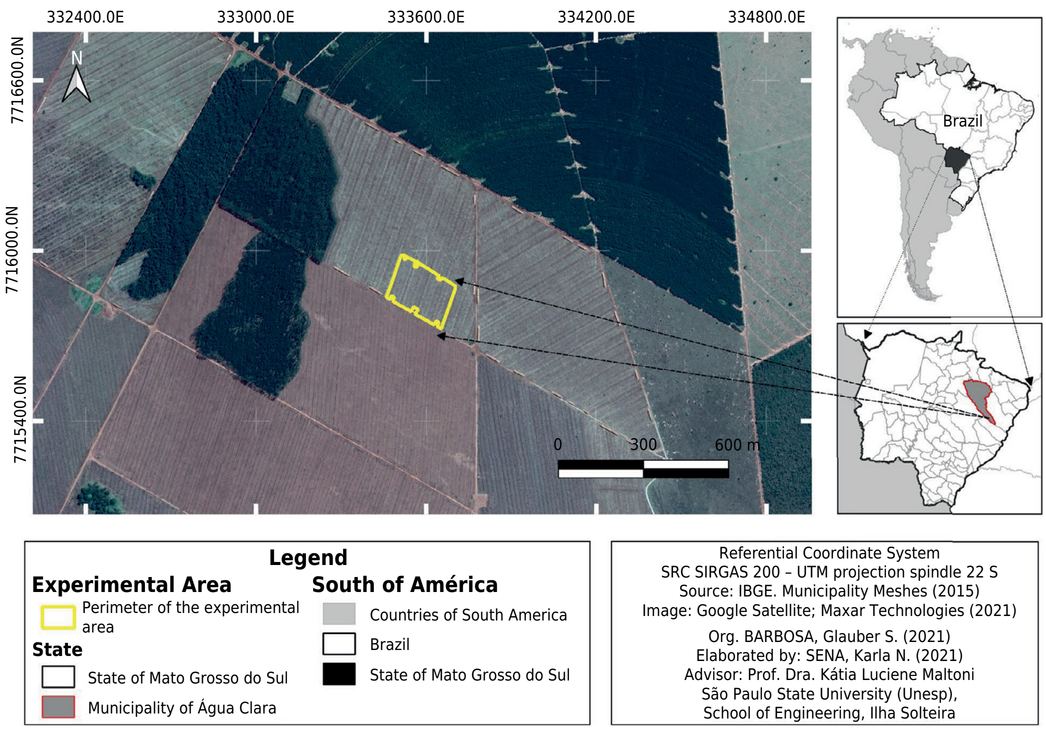

Figure 1. Location of the experimental area.

replications per plot from each HMS to make up a composite sample for the 0.00-0.20, 0.20-0.40, and 0.40-0.60 m soil layers.

This soil has loamy sandy texture, with sand, silt and clay content ranging from 843 to 878 g kg^{-1}, 91 to 54 g kg^{-1} and 83 to 61 g kg^{-1}, respectively; low fertility (with averages of P = 1.86 mg dm^{-3}, MO = 7.87 g dm^{-3}, pH($CaCl_2$) = 4.2, K^+ = 0.17 $mmol_c$ dm^{-3}, Ca^{2+} = 2.97 $mmol_c$ dm^{-3}, Mg^{2+} = 2.23 $mmol_c$ dm^{-3}, H+Al = 14.70 $mmol_c$ dm^{-3}, Al^{3+} = 6.22 $mmol_c$ dm^{-3}, total organic carbon (TOC) 14 g kg^{-1}, sum of basis 5.37 $mmol_c$ dm^{-3}, cation exchange capacity 20.07 $mmol_c$ dm^{-3}, base saturation 26.77 % and aluminum saturation 30.97 %.

Particle size was determined by the pipette method (Gee and Bauder, 1986). Total organic carbon (TOC) was determined by the weight loss on ignition method (Ben-Dor and Banin, 1989). Soil chemical analysis was determined at the beginning of the study, as described by Teixeira et al. (2017): exchangeable calcium (Ca), magnesium (Mg), and aluminum (Al) were extracted with ion exchange resin; available phosphorous (P) and potassium (K) determined through an anion exchange resin extractor; organic matter (OM) determined by the digestion method; pH determined in $CaCl_2$ 0.01 mol L^{-1} at a soil/solution ratio of 1:2.5; and potential acidity (H+Al) determined indirectly through SMP solution.

Experimental design

Harvest occurred at the beginning of June 2017, after six years of eucalyptus growth, according to the cut to length system. After 120 days (September, 2017) the plots were prepared to simulate the three different harvest management systems (HMS): (i) cut-to-length (CTL) – all residual phytomass was maintained (100 % of leaves, branches, bark, and litter) in the area, simulating the cut-to-length harvest system; **(ii)** bare (B) – removal of 100 % of the residual phytomass (leaves, branches, bark, and litter) and plant litter through the installation of Sombrite® protective netting to impede deposition of plant biomass from the current cycle on the soil surface; and (iii) tree-length (TL) – removal of the bark but maintaining the residual phytomass (leaves, branches, and litter were maintained in the area, but not the bark), simulating the tree-length harvest system.

These three harvest management systems (HMS) were established 120 days after harvest of the eucalyptus due to the need to reduce humidity; then, the logs were kept in place as in the commercial area. Field studies were conducted in a completely randomized experimental design, with four replications, and the soil layers (0.00-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80, and 0.80-1.00 m) were analyzed in a split-plot experimental arrangement.

The management systems were arranged in rectangular areas of 40.8 × 27.6 m, containing 12 plant rows at a spacing of 3.4 m between rows and 2.3 m between plants, for an area of 1126 m^2 (Figure 2). Within this area, the 8 central rows were considered for evaluations, thus constituting an area of 500.8 m^2, avoiding effects of field access roads and interference from neighboring areas.

Single soil samples were taken from the 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80 and 0.80-1.00 m soil layers with a spiral type auger from between the rows, with three replications per soil depths, to determine total organic carbon (TOC) by the weight loss on ignition method (Ben-Dor and Banin, 1989). The organic carbon stock (CS) was calculated from the organic carbon accumulated at each depth using equation 1 (Xie et al., 2007):

$$CS = \frac{(TOC \times BD \times e)}{10} \quad \text{Eq. 1}$$

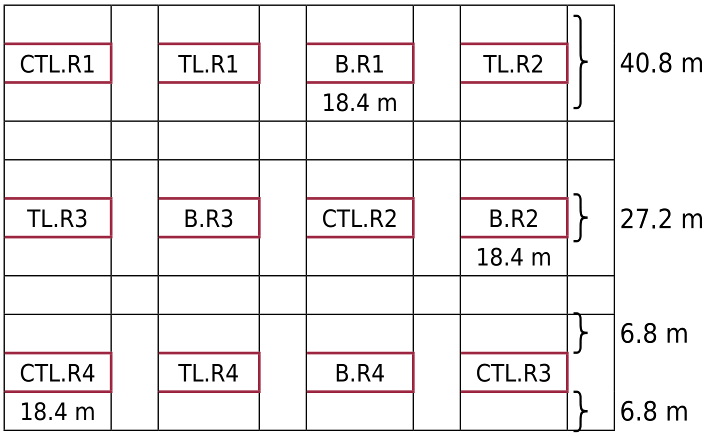

Figure 2. Schematic representation of the work area and respective management systems and replications.

in which CS is the organic carbon stock at a determined depth (Mg ha^{-1}); TOC is the total organic carbon content (g kg^{-1}); BD is the mean soil bulk density of the layer (Mg m^{-3}), determined from undisturbed samples; and *e* is the thickness of each layer (0.00-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60, 0.60-0.80, and 0.80-1.00 m) considered (cm).

Stability of aggregates in water (water-stable aggregates) was determined in undisturbed soil core samples taken in the row from each plot, according to the method of Nimmo and Perkins (2002) and using 2000, 1000, 250, and 53 µm sieves. These analyses were performed in each one of the four replications of each HMS in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m soil layers. The aggregates retained in the 2000, 1000, 250, and 53 µm sieves for the 0.00-0.05 m layers were selected for evaluation of TOC (Ben-Dor and Banin, 1989) because this soil layer directly received the residual phytomass.

Morphology of these aggregates in each HMS for the 0.00-0.05 m layer was analyzed in a scanning electron microscope, EVO-LS15- ZEIS® (White, 2008). The aggregates selected had diameters ranging from 4000 to 2000 µm, 2000 to 1000 µm, 1000 to 250 µm, and 250 to 53 µm. Semi-quantitative microanalyses were carried out using the energy dispersive X-ray analysis (EDX) system, for recognition of the chemical composition of the crystalline materials present in the aggregates smaller than 53 µm through the electron backscattered diffraction system.

Bulk density (BD), macroporosity (Macro), microporosity (Micro), and total porosity (TP) were evaluated in two undisturbed samples collected in rows from each plot with a Kopecky ring (height: 40 mm; diameter: 55 mm; volume: 95.03 cm^3) in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m soil layers. Bulk density was determined via the volumetric cylinder method, and macroporosity and microposity were determined using the tension table method (Grossman and Reinsch, 2002). Total porosity (TP) was calculated from the sum of macro- and micropores (Flint and Flint, 2002).

Mechanical penetration resistance (PR) was evaluated with an electronic penetrometer (Penetrolog – Falker - cone diameter 12.83 mm). The penetration resistance (PR) recordings were taken in the row, with three replications in each plot, for the 0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m layers. The data were automatically recorded for each 0.01 m increment of penetration to a maximum of 0.4 m, and the results for each 0.10 m layer is the average of 10 increments of the 0.01 m. The measurements were conducted at a moisture content of around 30 % of field capacity in summer 2017.

Statistical analysis

Analysis of variance was performed on the results obtained for soil properties (TOC, CS, aggregate stability, organic carbon of aggregates, bulk density, macroporosity, microporosity, total porosity, mechanical penetration resistance) and the F test was applied ($p<0.05$) when presuppositions (homogeneity of variance and data normality) were met.

When significant difference was found among the sources of variation, the means of the HMS were compared by the Tukey test ($p<0.05$) and polynomial regression for the soil layers. Since the model was checked based on the p value of the standard deviation of regression, the polynomial regression models were selected from the superior correlation coefficients (r^2) among the regressions significant by the F test, respecting the characteristics of each factor. The SISVAR program (Ferreira, 2019) was used for data analysis.

RESULTS

The TOC and CS content (Table 1) had significant differences for HMS; CTL and B had the highest values in a quadratic response for soil layers ($\hat{y}_{TOC}^{**} = 10.0705 + 0.1486x - 0.0020x^2$, $r^2 = 0.5706$, maximum point = 0.37 m; $\hat{y}_{CS}^{**} = 8.3235 + 1.2688x - 0.0125x^2$, $r^2 = 0.6217$, maximum point = 0.51 m.

The HMS × soil layer interaction for TOC (Table 1) had variations in the 0.20-0.60 m layer. A larger amount of TOC was found in the CTL, which indicates positive effects from preserving the harvest residual phytomass in relation to carbon content, even over a period of only 90 days. Total organic carbon increased significantly in the 0.20-0.60 m layer (Table 1) for the CTL and in the 0.40-0.60 m layer for B, both with quadratic responses ($\hat{y}_{CTL}^{**} = 9.1848 + 0.3811x - 0.0046x^2$, $r^2 = 0.6134$, maximum

Table 1. F values, coefficients of variation (CV) and determination (r^2), regression equations, decomposition (Dec.) of interaction, harvest management systems (HMS) × soil layer (L), for total organic carbon (TOC; g kg^{-1}) and carbon stock (CS; Mg ha^{-1}), after 90 days of Harvest Management System implantation

Property	F values			CV	HMS		
	HMS	L	HMS × D	%	CTL	B	TL
		m					
TOC (g kg^{-1})	15.993**	94.310**	4.302*	22	13.0 A	10.7 B	9.2 C
CS (Mg ha^{-1})	6.178**	33.868**	1.773ns	35	31.7 A	29.6 A	22.3 B
L (m)	0.00-0.10	0.10-0.20	0.20-0.40	0.40-0.60	0.60-0.80	0.80-1.00	
TOC (g kg^{-1})	12.2	9.7	13.5	16.0	8.7	8.5	
	$\hat{y}_{TOC}^{**} = 10.0705 + 0.1486x - 0.0020x^2$, $r^2 = 0.5706$, maximum point = 0.37 m						
CS (Mg ha^{-1})	18.2	14.8	40.6	47.4	25.3	24.8	
	$\hat{y}_{CS}^{**} = 8.3235 + 1.2688x - 0.0125x^2$, $r^2 = 0.6217$, maximum point = 0.51 m						
Dec.				TOC (g kg^{-1})			
HMS	0.00-0.10	0.10-0.20	0.20-0.40	0.40-0.60	0.60-0.80	0.80-1.00	F values
CTL	12.4 a	10.5 a	18.1 a	20.0 a	9.0 a	7.8 a	20.710 **
	$\hat{y}_{TOC(CTL)}^{**} = 9.1848 + 0.3811x - 0.0046x^2$, $r^2 = 0.6134$, maximum point = 0.41 m						
B	12.2 a	9.5 a	12.9 b	15.1 b	8.9 a	7.3 a	19.286 **
	$\hat{y}_{TOC(B)}^{**} = 9.8554 + 0.1417x - 0.0019x^2$, $r^2 = 0.4863$, maximum point = 0.37 m						
TL	12.0 a	9.8 a	9.5 b	9.5 c	7.5 a	6.8 a	2.791*
	$\hat{y}_{TOC(TL)}^{*} = 11.4488 - 0.0528x$, $r^2 = 0.8200$, range of variation = -0.528 g C kg^{-1} 0.10 m^{-1}						
F values	0.033 ns	0.299 ns	16.238 **	20.170 **	0.570 ns	0.192 ns	

Mean values followed by the same uppercase letters in the row (HMS) and lowercase letters in the column (TOC) do not differ statistically from each other by the Tukey test for $p<0.05$. ns: not significant; ** and * significant at 1 and 5 %, respectively. (1) CTL: cut-to-length (Maintaining 100 % of the residual phytomass in the area); B: bare (Removal of 100 % of the vegetation residual phytomass and setting up a net to collect all leaves, branches, etc); TL: tree-length (Removal of the bark and maintaining the other residual phytomass in the area).

point = 0.41 m; $\hat{y}_B^{**} = 9.8554 + 0.1417x - 0.0019x^2$, $r^2 = 0.4863$, maximum point = 0.37 m; $\hat{y}_{TL}^{*} = 11.4488 - 0.0528x$, $r^2 = 0.8200$, range of variation = -0.528 g C kg^{-1} 0.10 m^{-1}).

In the CTL, where the residual phytomass from the harvest was maintained, there are increases in TOC (Table 1) from this phytomass. However, in the B and TL, where the residual phytomass was removed (totally and partially), the TOC content already declines after a period of only 90 days in the HMS, in which TOC ranged from 12 to 16 g kg^{-1}. Macroaggregates (>250 μm) predominate in the distribution of the soil aggregates by

Table 2. F values and coefficient of variation (CV) for distribution of the aggregates (in %) in relation to the harvest management systems (HMS) and the soil layer (L)

Variable	Diameter					
	>2000 μm	2000-1000 μm	1000-500 μm	500-250 μm	250-102 μm	102-53 μm
			F values			
HMS	1.945^{ns}	0.051^{ns}	0.882^{ns}	1.694^{ns}	2.807^{ns}	0.640^{ns}
L (m)	45.350^{**}	25.770^{**}	29.399^{**}	30.030^{**}	34.707^{**}	1.580^{ns}
HMS × D	1.425^{ns}	0.514^{ns}	0.812^{ns}	0.641^{ns}	$2.810^{*\#}$	0.494^{ns}
CV (%)	10	75	71	64	53	101
HMS[(1)]			Mean (%)			
CTL	85.39a	1.89a	2.17a	3.71a	2.77a	0.45a
B	80.03a	2.00a	2.70a	5.71a	4.11a	0.57a
TL	79.96a	2.09a	3.21a	5.75a	4.69a	0.39a
L (m)						
0.00-0.05	89.79a	0.80b	1.30b	2.50b	2.07b	0.41a
0.05-0.10	87.00a	1.24b	1.41b	3.38b	2.69b	0.44a
0.10-0.20	67.47b	3.95a	5.38a	10.07a	7.11a	0.68a

Mean values followed by the same lowercase letters in the column do not differ statistically from each other by the Tukey test for p<0.05. ^{ns}: not significant; ** and * significant at 1 and 5 %, respectively. $^{\#}$: decomposition not presented. (1) HMS: harvest management systems. CTL: cut-to-length (Maintaining 100 % of the residual phytomass in the area); B: bare (Removal of 100 % of the residual vegetation phytomass and setting up a net to collect all leaves, branches, etc.); TL: tree-length (Removal of the bark and maintaining the other residual phytomass in the area).

Table 3. F values, coefficient of variation (CV), and decomposition (Dec.) of interaction, harvest management systems (HMS) × aggregates diameter (μm), for the carbon of the aggregates (g kg^{-1}) in the 0.00-0.05 soil layer (L), after 90 days of Harvest Management System implantation

Variable	F values			CV	HMS		
	HMS	Diameter	HMS × D	%	CTL[(1)]	B	TL
		μm					
C aggregates (g kg^{1})	0.08^{ns}	16.686^{**}	2.796^{*}	26	15.0	14.5	14.9
			Diameter (μm)				
	>2000	2000-1000	1000-250	250-53			
C aggregates (g kg^{1})	19.7A	17.2A	12.4B	9.9B			
Dec.			Diameter (μm)				
	>2000	2000-1000	1000-250	250-53	F values		
HMS			C aggregates (g kg^{1})				
CTL	18.5abA	18.1aA	14.0aAB	9.4aB	5.004^{**}		
B	15.8bA	17.6aA	12.2aA	12.3aA	1.966^{ns}		
TL	24.8aA	15.9aB	11.1aBC	7.8aC	15.307^{**}		
F values	6.020^{**}	0.381^{ns}	0.586^{ns}	1.482^{ns}			

Mean values followed by the same uppercase letters in the row and lowercase letters in the column do not differ statistically from each other by the Tukey test for p<0.05. ^{ns}: not significant; ** and *: significant at 1 and 5 %, respectively. (1) CTL: Cut-to-Length (Maintaining 100 % of the residual phytomass in the area); B: Bare (Removal of 100 % of the vegetation residual phytomass and setting up a net to collect all leaves, branches, etc); TL: Tree-Length (Removal of the bark and maintaining the other residual phytomass in the area).

diameter (Table 2) (Tisdall and Oades, 1982), especially the >2000 µm class, which is prevalent in all the HMS, constituting at least 80 % of the aggregates.

Aggregates >2000 µm are important in the 0.00-0.10 m soil layer, coinciding with the TOC content higher in this layer than in the 0.10-0.20 m layer due to its nearness to the residual phytomass left on the surface. Of the aggregates analyzed for TOC in the 0.00-0.05 m soil layer (Table 3), those of greater diameter (>2000 µm and >1000 µm) lead to the greatest retention of TOC in the soil, without differences among the HMS at 90 days. Nevertheless, it is important to note that microaggregates (<250 µm) also retain TOC within them, though in smaller amounts than in the larger aggregates.

The soil under the management systems studied has isolated particles of microaggregate dimension (Figure 3d). The silicon content identified in the isolated particles, combined with oxygen, indicates the presence of quartz, which is the predominant mineral in the isolated particles (Figures 4, 5, and 6).

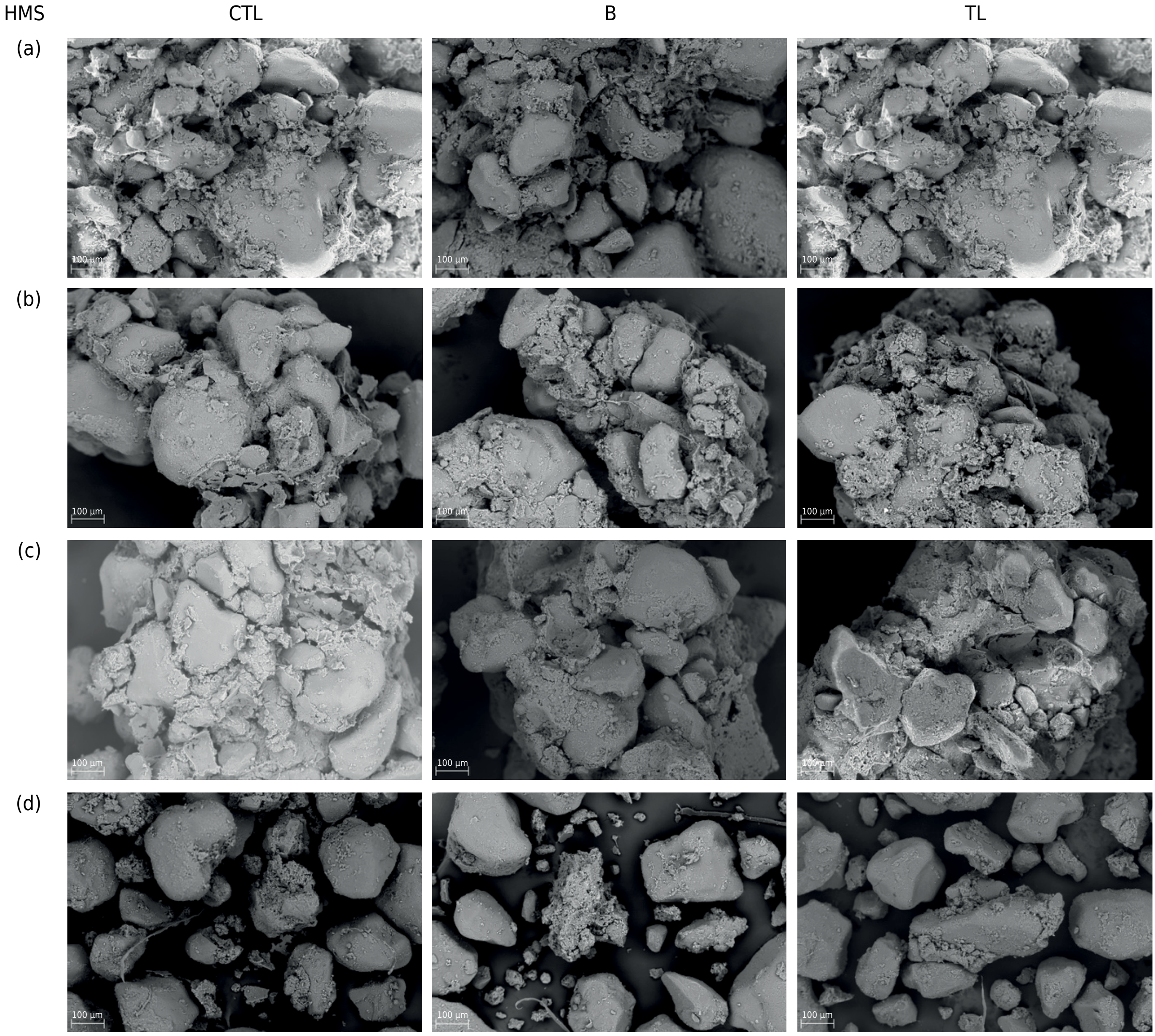

Figure 3. Images obtained in a scanning electron microscope (SEM; Magnitude = 250 X; EHT = 20.00 kV) of the aggregates with diameter from 4000 to 2000 µm (a), 2000 to 1000 µm (b), 1000 to 250 µm (c), and less than 250 µm (d), in the 0.00-0.05 m soil layer and different harvest management systems (HMS). [(1)] CTL: cut-to-length (maintaining 100 % of the residues in the area); B: bare (Removal of 100 % of the residues and setting up a net to collect all leaves, branches, etc.); TL: tree-length (Removal of the bark from the area and maintaining the other residues in the area).

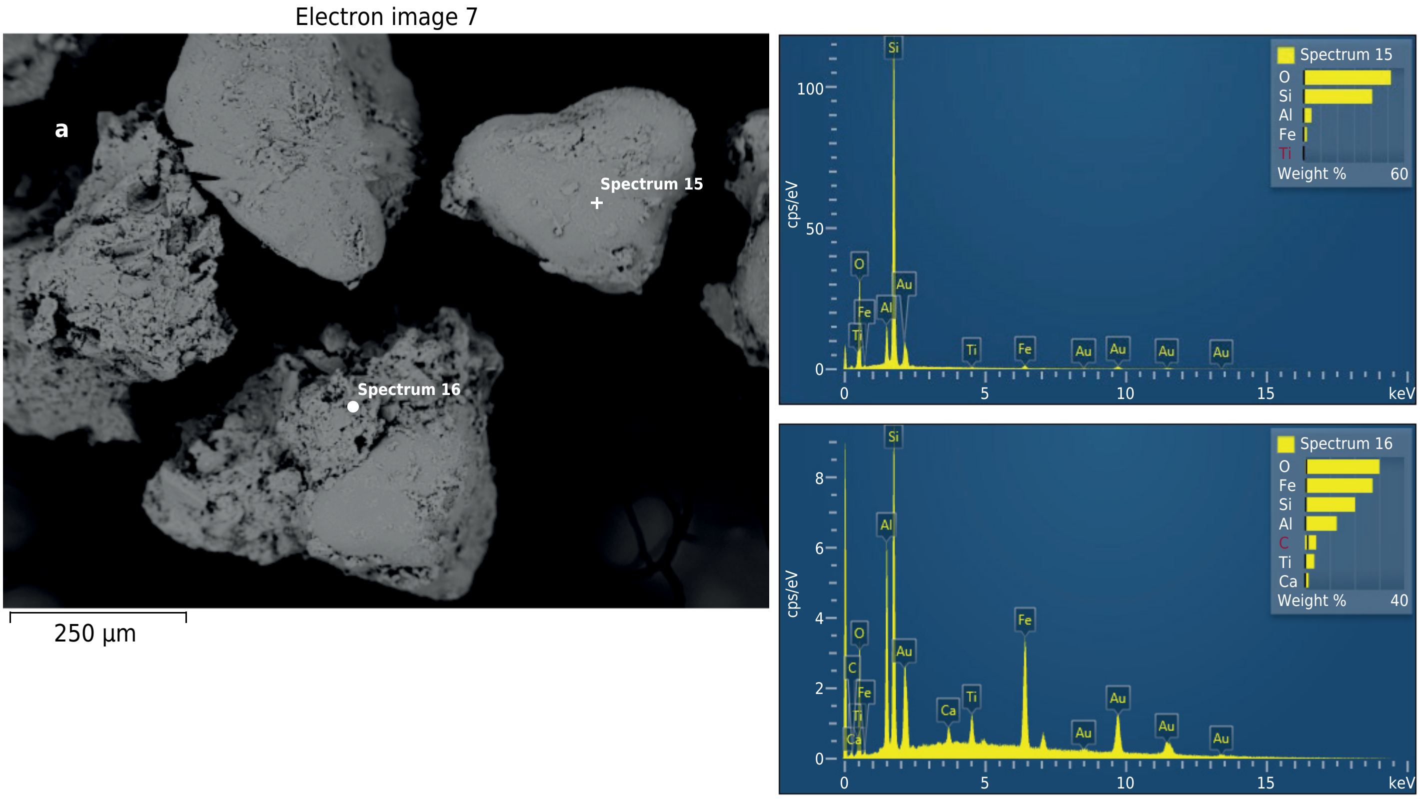

Figure 4. Images obtained in a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) of the aggregates with diameter from 0 to 53 µm (a) in the 0.00-0.05 m soil layer in the cut to length harvest management systems.

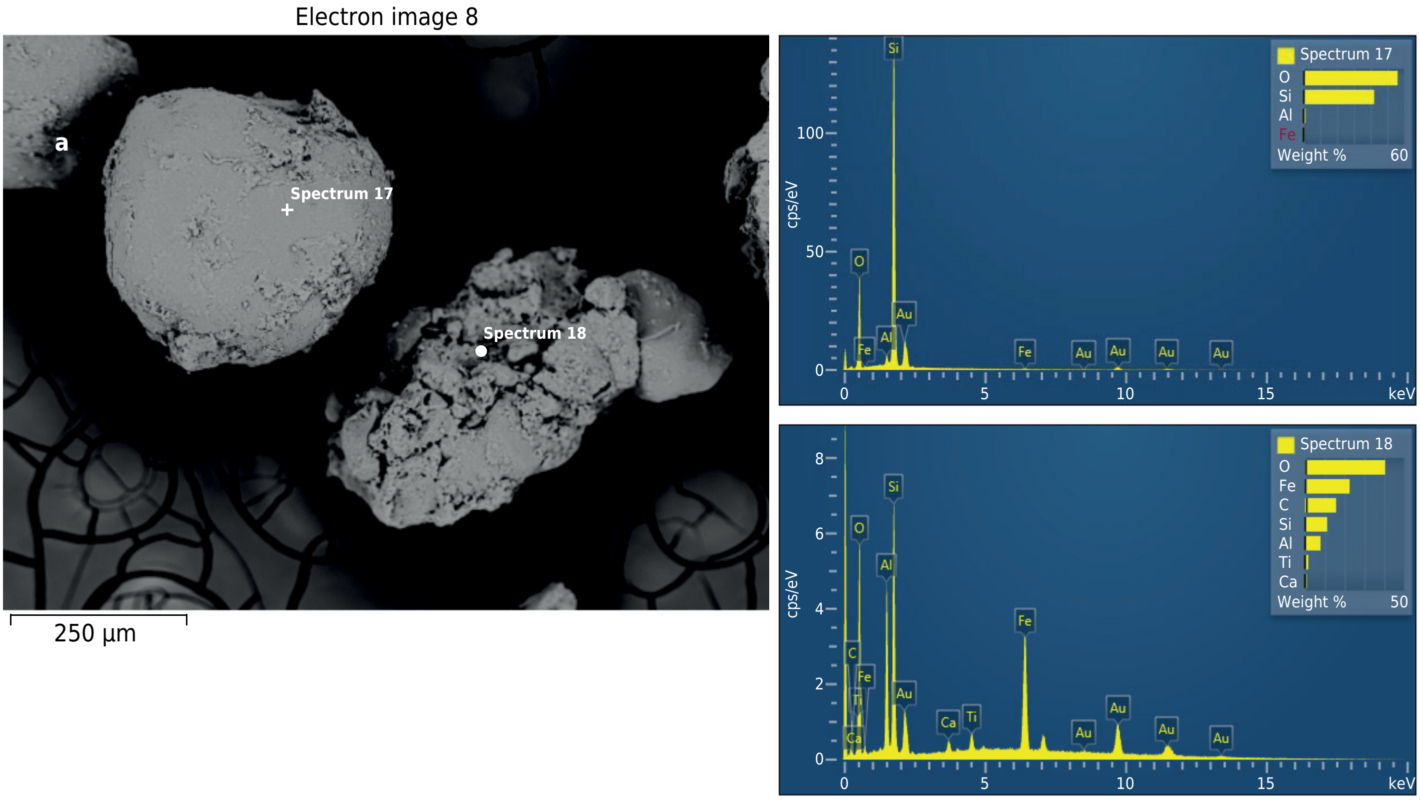

Figure 5. Images obtained in a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) of the aggregates with diameter from 0 to 53 µm (a) in the 0.00-0.05 m soil layer in the bare harvest management systems.

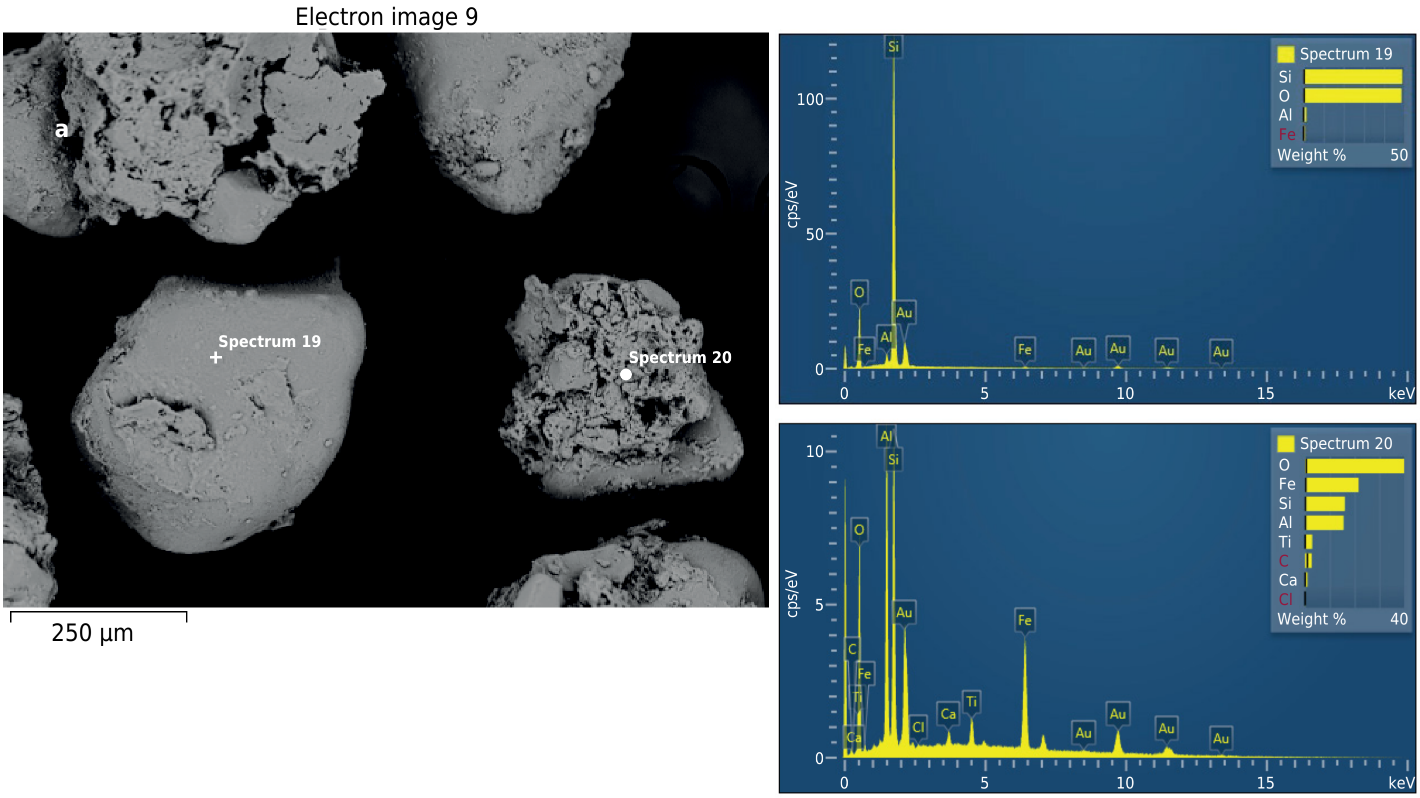

Figure 6. Images obtained in a scanning electron microscope (SEM) and energy dispersive X-ray (EDX) of the aggregates with diameter from 0 to 53 µm (a) in the 0.00-0.05 m soil layer in the tree length harvest management systems.

In the HMS × soil layer decomposition (Table 5), the Macro values remain near 3 %, now for the three HMS in the 0.10-0.20 m layer, and show that the CTL, which maintains all residual phytomass at the surface, has a higher mean value for Macro in the 0.00-0.05 m layer (11.84 %). The decomposition of the HMS × carbon of the aggregates interaction (Table 3) confirms the maintenance of TOC in the larger aggregates (Figure 3), particularly in the CTL and TL, both with maintenance (total and partial, respectively) of the residual phytomass from eucalyptus harvest. However, in the B, with the removal of 100 % of the residual phytomass, differences are not observed for TOC among aggregates of different diameters (Table 3).

The response observed in the B for carbon of the aggregates (Table 3) highlights the importance of the management system adopted, in which removal of the residual phytomass reduced the TOC content and, consequently, the stability of the aggregates of greater diameter (Table 2), without difference in carbon retention among the different diameters of aggregates that compose the soil in this HMS.

Although soil BD and Macro properties did not vary among the HMS, they varied among the layers evaluated. Macroporosity approaches 3 % in the 0.10-0.20 m layer, suggesting severe limitation of water infiltration in the soil (Table 4). The HMS did not significantly affect total porosity, exhibiting mean values for CTL, B and TL of 38.74, 37.11 and 38.14 %, respectively (Table 4). Mechanical penetration resistance Weight (PR) (Table 4 and Figure 7) had significant variations for the HMS and soil layers evaluated. The CTL led to the lowest PR, differing from the others, which are similar to each other.

In this study, the CTL has the lowest PR, lower at the surface, a direct and indirect effect of TOC, whereas under the surface, the benefits are not evident. As the depth of the profile increased, the PR values increased, with a quadratic response ($\hat{y}_{PR\#}^{**} = 0.668 + 2.008\ x - 0.3020\ x^2$; $r^2 = 0.9983$), and PR reached a maximum level in the 0.33 m depth.

Table 4. Mean values for macroporosity (Macro) and microporosity (Micro), total porosity (TP), soil bulk density (BD), mechanical penetration resistance (PR), F values, and coefficient of variation (CV) by harvest management system (HMS) and soil layer (L), after 90 days of Harvest Management System implantation

Source of variation	BD	Macro	Micro	TP	PR#	
	Mg m-3		%		MPa	
F values						
HMS	1.639^{ns}	1.800^{ns}	0.460^{ns}	2.359^{ns}	5.427^{**}	
L (m)	17.330^{**}	22.807^{**}	6.856^{**}	6.628^{**}	41.060^{**}	
HMS × L	1.682^{ns}	1.957^{ns}	0.318^{ns}	1.309^{ns}	0.127^{ns}	
CV (%)	3	45	8	7	25	
HMS[1]						
CTL	1.49a	7.22a	31.52a	38.74a	1.72a	
B	1.52a	5.54a	31.57a	37.11a	2.16b	
TL	1.49a	5.81a	32.33a	38.14a	2.24b	
Layer (m)					Layer (m)##	
0.00-0.05	1.46a	8.38a	30.52a	38.91a	0.00-0.10	1.03
0.05-0.10	1.51b	6.59a	31.28a	37.87ab	0.10-0.20	2.18
0.10-0.20	1.54b	2.81b	33.34b	36.16b	0.20-0.30	2.61
					0.30-0.40	2.55

Mean values followed by the same lowercase letters in the column do not differ statistically from each other by the Tukey test for $p<0.05$. ns: not significant; ** and *: significant at 1 and 5 %, respectively. (1) CTL: Cut-to-Length (Maintaining 100 % of the residual phytomass in the area); B: Bare (Removal of 100 % of the vegetation residual phytomass and setting up a net to collect all leaves, branches, etc.); TL: Tree-Length (Removal of the bark and maintaining the other residual phytomass in the area); #: soil humidity in field: 8-10 % (volume); water holding capacity: 27 % (volume) according to USDA (2014). ##: regression equation for PR in-layer $\hat{y}_{PR\#\#}^{**}$: $0.668 + 2.008x - 0.3020x^2$, $r^2 = 0.9983$.

Table 5. Decomposition of the interaction between harvest management systems (HMS) × soil layer (L) for macroporosity

Soil layer	HMS			F values
	CTL	B	TL	
m		Macropores (%)		
0.00-0.05	11.84aA	7.02aB	9.00aAB	5.046^{**}
0.05-0.10	7.32aA	6.76aA	5.34abA	0.617^{ns}
0.10-0.20	2.49bA	2.84bA	3.08bA	0.051^{ns}
F values	12.359^{**}	9.322^{**}	5.040^{**}	

Mean values followed by the same uppercase letters in the row and lowercase letters in the column do not differ statistically from each other by the Tukey test for $p<0.05$. ns: not significant; ** and * significant at 1 and 5 %, respectively. (1) CTL: Cut-to-Length (Maintaining 100 % of the residual phytomass in the area); B: Bare (Removal of 100 % of the vegetation residual phytomass and setting up a net to collect all leaves, branches, etc.); TL: Tree-Length (Removal of the bark and maintaining the other residual phytomass in the area).

DISCUSSION

The TOC and CS content found in the uppermost soil layer (Table 1) is related to the input of residual phytomass from eucalyptus harvest, a recurrent response frequently reported in the literature (Costa Jr et al., 2012; Guan et al., 2015; Jesus et al., 2015; Marques et al., 2016; Sena et al., 2017). Below the surface, the increases observed in TOC and CS in deeper layers (0.20-0.60 m – Table 1) for the CTL and B coincide with the layer of greatest abundance of the root system in eucalyptus. This increase may also be the result of the downward movement of TOC in sandy soil, as also reported by Marques et al. (2016) evaluating primary forest in the Amazon region under *Latossolos*

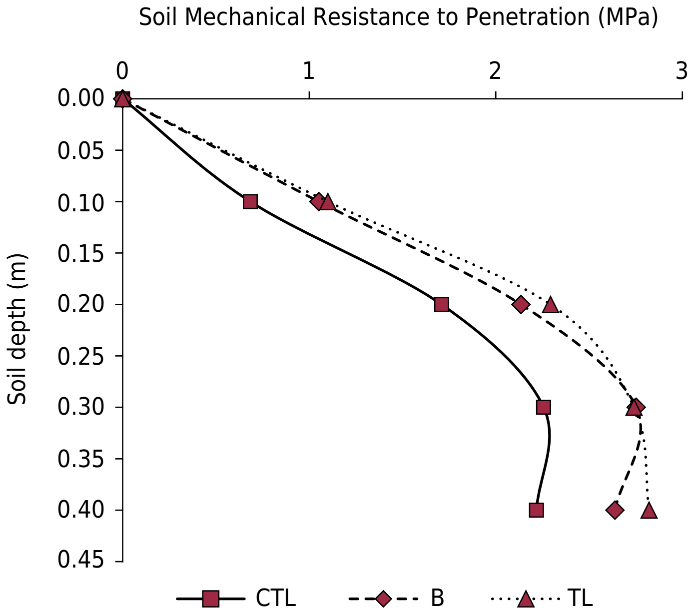

Figure 7. Soil mechanical resistance to penetration in the harvest management systems (HMS).

(plateau), *Argissolo* (slope), and *Espodossolo* (lowland). It may reflect effects from previous crops, though this is a less likely hypothesis due to climate conditions (hot and humid climate) and microbial activity (Costa Jr et al., 2012; Cunha et al., 2012), it is a question under analysis.

Commercial eucalyptus plantations can incorporate carbon in the soil due to the biomass deposited annually in the form of an organic covering and of dead roots (Silva et al., 2012), a fact observed in the CTL in which the residual harvest phytomass was maintained. However, in the B and TL, where residual phytomass was removed (totally and partially) over a period of 90 days, the TOC and CS content (Table 1) already manifests a decline at the layer of 0.20-0.40 m, indicating that removal of the litter that would accumulate over a period of 6 years could rapidly reduce the TOC in cultivated areas on sandy soil (Rocha et al., 2018). These results suggest that the residual harvest phytomass should be maintained in the area for more effective conservationist management.

Total organic carbon does not differ statistically between CTL and B, which have a higher content of TOC than in TL. However, the initial values for TOC in the 0.00-0.20 m soil layer indicate that this decreased in CTL from 14 to 12.4 g kg^{-1}, in B from 16 to 11 g kg^{-1}, and in TL from 16 to 11 g kg^{-1}, with smaller differences in the CTL (100 % residual phytomass at the surface) than in the TL or B HMS, where the residual phytomass was partially or totally removed.

In a study on sandy soil, Soares et al. (2017) found changes of greater magnitude in carbon stocks in the organic matter fractions in the 0.00-0.10 m soil layer due to the large contribution of the eucalyptus residual phytomass. The organic fraction of the soils do not have the same stability as the mineral fraction under agricultural use; thus, intensive use of the soil can contribute to its degradation (Six and Paustian, 2014; Sena et al., 2017), compromising the stability of its aggregates. Consequently, losses of TOC occur, which increases soil bulk density and reduces total porosity.

Macroaggregates (>2000 μm) are predominant in the 0.00-0.10 m soil layer and all HMS, as shown in (Table 2). This predominance occurs in areas with low soil movement, as these areas normally exhibit greater stability of aggregates and greater organic carbon content (Six and Paustian, 2014; Sena et al., 2017). This explains the occurrence of 80 % of aggregates >2000 μm in the sandy soil in the three HMS examined, indicating that the effects of total or partial (B or TL) litter removal over 90 days before sampling did not reduce aggregate stability. Greater quantity of macroaggregates stable in water (>2000 µm) in *Latossolos* under Cerrado was reported by Salton et al. (2008) in a study on different soil management systems with low soil movement, which was observed in other studies (An et al., 2010) as well, including a study on sandy soil (Sena et al., 2017).

The higher TOC content observed in the soil layer 0.00-0.10 m (Table 1) is associated with the higher stability of the aggregates >2000 µm (Table 2), shows the importance of this carbon on maintenance of the stability of the aggregates and, therefore, on the structural stability of the soil (Salton et al., 2008; Guan et al., 2015). The larger aggregates (>2000 µm) and those of lower stability tend to subdivide into smaller aggregates (Six et al., 2000), a process directly related to the reduction in TOC content (Nichols and Toro, 2011; Bast et al., 2014).

The loamy sandy soil (843 to 878 g kg^{-1} of sand in the soil) in the area evaluated may have produced macroaggregates of lower stability and stable microaggregates. An explanation for greater stability of the microaggregates is the presence of single quartz particles of sand size (Figures 3, 4, 5 and 6), which grants greater resistance and absence of response to the HMS. The quartz particles show indications of coating (Figure 3 – diameter <250 µm), suggesting that they were part of larger aggregates, and their greater stability also involves the amount of sand (quartz) they contain, which is greater than 80 % (Figures 4, 5 and 6).

Soil BD is not restrictive (1.46 to 1.54 Mg m^{-3}) to water infiltration in the soil or to root development of eucalyptus, and neither are Micro and TP (Table 4). Reports of BD in loamy sandy soil ranging from 1.40 to 1.80 Mg m^{-3} were considered restrictive when higher than 1.55 Mg m^{-3} (Reichert et al., 2003); 1.65 Mg m^{-3} for soils with less than 200 g kg^{-1} of clay (Reinert et al., 2001), and 1.60 Mg m^{-3} with macroporosity smaller than 10 % (Michelon, 2005).

Nevertheless, macroporosity has restrictive values (Table 5), near 3 % for the three HMS in the 0.10-0.20 m soil layer, indicating that the CTL, which maintains all the residual phytomass at the surface, has a higher mean value for Macro in the 0.00-0.05 m layer (11.84 %). However, the occurrence of Macro = 3 % in the layer immediately below can limit liquid and gas exchanges, as cited by Carter (2002), who considers macroporosity of around 10 % as adequate.

The presence of macroaggregates is positively associated with soil organic matter content (Costa Jr et al., 2012; Six and Paustian, 2014), as observed at the surface (Tables 1 and 3). The BD increased with the depth of the profile, coinciding with the reduction in TOC content, which is related to the aggregation of the soil (Salton et al., 2008; Sena et al., 2017). The Macro observed (Table 4) suggests that the reduced Macro is restricted to a narrow, compacted depth, which ended up not being represented in the BD samples; variations from 1.46 to 1.54 Mg m^{-3} in these samples are not compatible with a Macro of 3 %. Micro and TP did not vary for HMS and depths (Table 4). In an area growing eucalyptus (2 years) in sandy soil, a similar response was observed (Sena et al., 2017), low macroporosity (5 %) under the surface layer (0.10-0.30 m), with density lower than the limit established by Reichert et al. (2003), emphasizing the existence of a narrow, compacted depth. Jesus et al. (2015) evaluated physical properties after harvest activities and concluded that the aforementioned 0.10-0.20 m layer is most affected, which is shown in the BD, TP, and PR.

Total porosity (Table 4) was not significantly affected by the HMS and soil layers, with mean values near 40 %. The ideal TP of soil is 50 %, or 0.5 m^3 m^{-3} of its total volume (Kiehl, 1979); under these parameters, the HMS evaluated have limiting conditions for plant development.

Mechanical penetration resistance (PR) (Table 4), closely linked to properties like bulk density and total porosity, showed significant variations for the HMS and soil layers evaluated. Although BD, macro, microporosity and TP do not vary among HMS (Table 4), it is possible to relate the behavior of PR to macroporosity (Table 5), which in CTL is 40 % higher than B and 32 % higher than TL, the greater the PR and the lower is the macroporosity (Sena et al., 2017), as can be observed in the B and TL.

Lower PR (1.72 MPa) for CTL, compared to B and TL, which are higher and similar to each other (2.16 and 2.24 MPa, respectively), could be related to the maintenance of residual crop phytomass on the soil surface. However, this residual phytomass was removed only 90 days before, and that is not a period of sufficient length to affect soil PR in deeper layers, suggesting that these effects are still related to the process that was previously established in setting up the crop (6 years before) and mechanized activities at harvest (7 months before). These effects are also recorded in the CTL; however, they are diluted due to greater organic input at the surface. Jesus et al. (2015) observed that harvest under the CTL allows the effects of this activity to be mitigated, with lower PR. Maintaining bark in the area is one of the reasons for this.Studies on soils, including soils in the eucalyptus crop, adopt PR values ranging from 2.0 to 3.0 MPa as limiting plant development (Betioli Júnior et al., 2012; Jesus et al., 2015; Reichert et al., 2018). Thus, values considered limiting to the root development of eucalyptus were not observed.

As observed by Sena et al. (2017) in a study on sandy soil growing eucalyptus in the east of Mato Grosso do Sul, a soil can be considered degraded when it combines the following properties: low total porosity, low macroporosity, high density, low TOC, low CS and high PR, just as observed in the HMS in which the cover material coming from the harvest was removed. In light of the above, sandy soils and their physical properties manifest the need to adopt systems that favor soil structuring, such as those that increase organic matter content (Jesus et al., 2015; Marques et al., 2016; Sena et al., 2017). Nevertheless, mid-to-long-term evaluations are necessary, given the dynamic changes in soil physical quality imposed by the harvest management systems, edaphic and climatic conditions, and management operations in the next crop (such as nitrogen fertilization).

CONCLUSION

Keeping the residual phytomass on the soil surface can positively impact total organic carbon, with lower reduction in total organic carbon under the cut-to-length harvest management system. However, carbon stock is greater at the layer of 0.20-0.60; as the soil has a sandy texture, carbon moves through the soil profile, which has lower soil mechanical penetration resistance at the surface (0.00-0.10 m), once more under the cut-to-length system.

In the cut-to-length harvest management system, maintaining residual crop phytomass on the soil surface provides better soil physical conditions, with greater macroporosity (0.00-0.05 m), aggregates with more carbon, and lower soil mechanical penetration resistance compared to systems that maintain only part of the harvest residual phytomass or no harvest residual phytomass on the surface.

ACKNOWLEDGEMENTS

We thank CAPES and FAPESP for providing the Doctorate scholarship and the financial support, and Eldorado Brasil, a pulp company, for allowing study in their experimental areas and logistical support. São Paulo Research Foundation (FAPESP, grant number 2017/14049-2).

SUPPLEMENTARY MATERIAL

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-45-e0200190/1806-9657-rbcs-45-e0200190-suppl01.pdf

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