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Organic Carbon and Physical Properties in Sandy Soil after Conversion from Degraded Pasture to *Eucalyptus* in the Brazilian *Cerrado*

Karla Nascimento Sena[(1)], Kátia Luciene Maltoni[(2)*], Glaucia Amorim Faria[(2)] and Ana Maria Rodrigues Cassiolato[(2)]

[(1)] Universidade Estadual Paulista, Faculdade de Engenharia, Programa de Pós-graduação em Agronomia, *Campus* de Ilha Solteira, Ilha Solteira, São Paulo, Brasil.
[(2)] Universidade Estadual Paulista, Faculdade de Engenharia, *Campus* de Ilha Solteira, Ilha Solteira, São Paulo, Brasil.

*** Corresponding author:**
E-mail: maltoni@agr.feis.unesp.br

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ABSTRACT: Soil is currently seen as the most relevant carbon sink and the most effective carbon stabilizer. In contrast, agriculture is the second largest C emitter, after burning of fossil fuels. This organic carbon (OC) introduced into the soil, mainly via organic matter (OM), is essential for several soil properties and plays an extremely important role in sandy soils. The objective of this study was to describe the changes in the amounts and pools of OC and the influence thereof on some physical soil properties in areas converted from pasture to *eucalyptus.* The following areas were analyzed*:* a degraded pasture (PAST), two areas of pasture-*eucalyptus* conversion after 2 and 15 years (EU02 and EU15, respectively) and a preserved *Cerrado* area (CER) in the east of the state of Mato Grosso do Sul. Soil samples were taken from the 0.00-0.05, 0.05-0.10, and 0.10-0.30 m layers. The OC was measured and analyzed, the carbon pool (CP) calculated, aggregate stability, bulk density (BD), and macro- and microporosity determined, and total porosity (TP) calculated to analyze the influence of land use on soil properties. The experimental design was completely randomized, and four clusters per area were established, with nine subsampling points, for a total of 36 subsamples per area, organized in 20 × 20 m grids, The soil under natural vegetation (preserved *Cerrado*) was used as a control. The change from CER to commercial cultivation accelerates the process of OC loss (reductions of 25-35 %) and reductions in soil physical quality. In the PAST area, OC was reduced by 30 % in the 0.00-0.05 m layer. Cumulative OC and CP were highest in the 0.00-0.05 m layer and decreased in the deeper layers in all land use treatments. Organic C in the 0.10-0.30 m layer was not influenced by land use, indicating the possibility of OC persistence in the soil for longer periods. Macroporosity and total porosity may be considered appropriate in CER and EU15, whereas the conditions for plant development in PAST and EU02 were restrictive. Land use systems reduced OC and the CP, indicating anthropogenic disturbance of the soil compared to CER. Fifteen years after planting *eucalyptus* in the pasture area, signs of recovery of some soil physical properties were observed, e.g., reduced BD and increased TP.

Keywords: aggregate stability, carbon pool, Oxisols, anthropogenic soils.

INTRODUCTION

Forest areas play an important role in the global carbon cycle, and areas planted to species of the *Eucalyptus* genus are the most extensive in Brazil (5.1 million ha), supplying a number of industries with raw material (Abraf, 2013), however, after three successive cycles of *Eucalyptus* in three Brazilian regions, in different soils and climates, reductions in the carbon pool were observed (Cook et al., 2016).

Once incorporated into the soil, C plays an important role in soil formation and properties. Moreover, the soil contains more C than the total C pools in the vegetation and atmosphere, i.e., soil is the largest C reservoir and is efficient as a stabilizer of this C (Oades, 1995; Schmidt et al., 2011; Guan et al., 2015), contributing to mitigate the greenhouse effect (Cerri et al., 2010; Souza et al., 2012).

When native vegetation is replaced by conventional agriculture, the soil undergoes drastic changes, which may affect its physical quality and cause a loss of organic matter (OM), among other effects (Vezzani and Mielniczuk, 2011). The impacts of land use on soil physical quality were quantified by the physical properties related to structural stability and evaluated by aggregate stability (Stefanoski et al., 2013). Soil aggregation is related to physical protection against biodegradation of the labile OM fractions (Balesdent et al., 2000), and their preservation is fundamental for soil structure and fertility and for the sustainability of agricultural systems (Paustian et al., 1998).

The implementation of soil conservation management systems has been cited as a necessary measure against the loss of organic matter (OM) (Vezzani and Mielniczuk, 2011). Practices related to this management system lead to a reduction in bulk density, increasing the OM content in the surface layer, improving aggregation, and increasing total porosity (TP) (Pagliarini et al., 2012; Stefanoski et al., 2013; Parihar et al., 2016). These effects are associated with plant residue inputs and the absence of excessive soil tillage by plowing, thus reducing the exposure of C protected in the aggregates against the attack of the microbial community, slowing down decomposition (Al-Kaisi and Yin, 2005).

Compared to conventional agriculture, *Eucalyptus* cultivation can be considered a conservation land-use system, since soil tillage is reduced, and low fertility soils are usually used for this purpose (Gama-Rodrigues et al., 2005). According to Higa et al. (2000), *Eucalyptus* cultivation requires deep soils, in which acidity and compaction can be corrected, ultimately leading to the introduction of this species in areas with deep and generally rather infertile soils.

Changing the land use from degraded pasture into planted *Eucalyptus* forests is expected to contribute to stabilization of organic carbon (OC) in the soil and thus to improvements in some physical properties. This study addressed changes in the quantities and pools of organic carbon and of some soil physical properties in areas transformed from pasture into planting of *Eucalyptus* for commercial purposes in a typic Hapludox with medium sandy texture in the eastern region of Mato Grosso do Sul, Brazil.

MATERIALS AND METHODS

A field study was carried out in August 2014 in areas selected for evaluations as follows: preserved *Cerrado* - CoER (S 20° 52’ 52’’ and W 51° 51’ 14’’), 2-year-old *Eucalyptus* - EU02 (S 20° 52’ 33’’ and W 51° 52’ 17’’), 15- year-old *Eucalyptus* - EU15 (S 20° 55’ 19’’ and W 51° 47’ 47’’) and Pasture - PAST (S 20° 52’ 36’’ and W 51° 53’ 29’’), in the municipality of Três Lagoas, Mato Grosso do Sul (MS), Brazil. These areas belong to FIBRIA, a large pulp and paper-producing company, except for PAST, a *Urochloa decumbens* pasture, located on a nearby private property where Nelore cattle are produced in an extensive system under continuous grazing at a stocking rate of 0.6 AU ha^{-1}. In this area, no restoration treatments had been applied in the previous 10 years and signs of degradation, such as bare soil, presence of weeds, and tall grasses, as for example *Paspalum notatum*, were evident (Domingos et al., 2008). The regional climate is Aw, with a mean annual rainfall and temperature of 1,240 mm and 24.2 °C, respectively.

The soils of these areas were classified as typic Hapludox, according to a survey of the company FIBRIA (Stolle, 2012), *Latossolos Vermelhos Distróficos típicos* (Santos et al., 2013), and were originally covered by *Cerrado sensu stricto* (savanna-like vegetation with trees). This vegetation was replaced by pasture in the 1960s, and in the last two decades, due to regional expansion of the pulp and paper industry, part of the pasture areas were converted into *Eucalyptus* plantations.

A completely randomized design was used for the field study, where each area was divided in four clusters, and nine subsamples were collected per cluster, resulting in 36 samples per area, organized in 20 × 20 m grids with a border length of 40 m. To evaluate the results, the soil under natural vegetation, i.e., CER, was used as a control.

For physical characterization of soil in the different areas, undisturbed soil samples were collected to determine aggregate stability in water, according to the method of Nimmo and Perkins (2002), associated with quantification of the sand fraction for each aggregate class by dispersing the aggregates in 1 mol L^{-1} NaOH, followed by shaking. These analyses were performed with four composite samples, consisting of nine subsamples from the 0.00-0.05 m layer, and of four composite samples, consisting of four subsamples from the 0.05-0.10 and 0.10-0.30 m layers.

Bulk density (BD) and macro-, micro- and total porosity were determined by the volumetric ring method and the porous plate apparatus (Donagema et al., 2011) by collecting four subsamples per cluster, for a total of 16 samples per area in the 0.00-0.05 m layer, and of one subsample per cluster, for a total of four subsamples in the 0.05-0.10 and 0.10-0.30 m layers.

In the study areas, particle size was characterized by the pipette method (Donagema et al., 2011) and fertility was analyzed (Raij et al., 2001). For these analyses, four subsamples per cluster were collected, resulting in a total of 16 in the 0.00-0.05 m layer, and one subsample per cluster, resulting in four subsamples in the 0.05-0.10 and 0.10-0.30 m layers.

The organic carbon pool (CP), representing cumulative carbon, was calculated for each soil layer by the expression CP = (OC × BD × th)/10 (Xie et al., 2007), where CP is the OC pool in a particular layer (Mg ha^{-1}); OC is the organic carbon content (g kg^{-1}); BD is the mean soil density of a layer (Mg m^{-3}), determined from undisturbed soil samples; and th is the thickness (m) of the soil layer. The CP was calculated for the layers 0.00-0.05, 0.05-0.10, and 0.10-0.30 m.

The aggregate morphology in the 0.0-0.05 m layer of each area was analyzed by scanning electron microscopy (White, 2008) with the EVO-LS15-ZEISS® equipment. Aggregates with diameters of 1.00-0.50 and 0.105-0.05 mm were selected, corresponding to the macro- and microaggregates, respectively.

The results were subjected to analysis of variance (homogeneity of variance and data normality) and the means among land uses were compared by the Dunnett test ($p<0.05$) with SAS 9.4 (2016) software.

RESULTS AND DISCUSSION

The soils of all the areas studied (Table 1) had sandy, medium-sized particles, acid pH, and a low sum of bases (Donagema et al., 2011; Santos et al., 2013).

In the area of this study, *Eucalyptus* was grown in degraded pasture areas, as in the case of the areas under evaluation, showing that in a 15-year-old *Eucalyptus* forest (EU15), where soil is less plowed and the OM input is higher than in the other land use systems, similar BD values as in the CER were observed in the 0.00-0.05 m layer, indicating possible recovery of this property (Tables 2 and 3).

Table 1. Physical and chemical characterization in four land uses (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST) and soil layers

Land use	Sand	Silt	Clay	P	OM	pH($CaCl_2$)	K^+	Ca^{2+}	Mg^{2+}	H+Al	Al^{3+}	SB	CEC
	g kg^{-1}			mg dm^{-3}	g dm^{-3}		mmol$_c$ dm^{-3}						
0.00-0.05 m													
CER	797	58	145	7.8	21	4	0.7	5.3	3.0	58	13	9	67
EU15	816	41	143	5.0	18	4	0.4	6.3	4.0	37	10	11	48
EU02	783	62	155	4.0	15	4	0.2	4.0	3.8	30	8	8	38
PAST	757	56	187	5.3	16	4	0.4	7.3	5.3	37	8	13	50
0.05-0.10 m													
CER	794	59	147	6.0	15	4	0.4	5.0	2.6	45	12	8	53
EU15	811	33	156	3.5	13	4	0.2	4.0	2.8	33	9	7	40
EU02	778	61	161	3.8	13	4	0.2	3.8	3.0	32	95	7	39
PAST	733	56	212	5.3	13	4	0.4	5.8	2.8	38	10	9	47
0.10-0.30 m													
CER	794	52	154	4.5	13	4	0.2	4.8	2.0	37	12	7	44
EU15	790	50	159	2.5	11	4	0.1	3.3	1.6	26	8	5	31
EU02	759	63	178	16.0	12	4	0.1	3.0	1.9	31	10	5	36
PAST	678	65	257	3.0	11	4	0.1	5.5	1.4	34	12	7	41

Sand, silt, and clay: pipette method; P, K^+, Ca^{2+}, and Mg^{2+}: extracted by ion exchange resin; H+Al: extracted by 0.5 mol L^{-1} calcium acetate at pH 7.0; Al^{3+}: extracted by 1 mol L^{-1} KCl; OM: organic matter. extracted by Walkley-Black method; pH: determined in a 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil:solution); SB: sum of bases; CEC: cation exchange capacity.

Table 2. Bulk density (BD), macro- and micropores, total porosity (TP), F values and coefficient of variation (CV) for land uses (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST)

Source of variation	BD	Macropores	Micropores	TP
	Mg m^{-3}	%		
F value				
Land use (LU)	64.99**	12.45**	10.07**	12.42**
Soil layers (L)	14.06**	9.12**	2.39^{ns}	0.79^{ns}
LU × L	8.78**	5.17**	0.72^{ns}	1.08*
CV (%)	7	55	20	19
Land use				
MSD Dunnett	0.04	2.26	2.73	3.45
CER	1.26	12.1	35.8	47.9
EU15	1.35***	12.7^{ns}	33.2^{ns}	45.9^{ns}
EU02	1.42***	7.1***	34.4^{ns}	41.5***
PAST	1.55***	8.8***	29.6***	38.4***
Soil layer				
0.00-0.05 m	1.36	11.4	32.6	44.0
0.05-0.10 m	1.43	9.6	32.9	42.5
0.10-0.30 m	1.43	7.9	35.0	42.9

Means followed, in the column, by *** differ statistically of the CER by the Dunnet test at $p<0.05$. ^{ns}: not significant; ** and *: significant at 1 and 5 %, respectively. MSD: Minimum Significant Difference.

The CER soil had a lower mean BD (1.26 Mg m^{-3}) than the soil under EU15 (1.35 Mg m^{-3}), EU02 (1.42 Mg m^{-3}), and PAST (1.55 Mg m^{-3}), indicating that these land use systems increased BD in all studied layers (Tables 2 and 3). These results reinforce the importance of soil management for conservation of the quality of physical properties since, taking CER as a reference, degradation processes were observed in the commercially used areas, which exhibited a similar response for OC (Tables 4 and 5).

Soil bulk density (BD) increased in the deeper layers, especially through reduction in the OC content, directly related to soil aggregation (Salton et al., 2008; Parihar et al., 2016). Density values from 1.40 to 1.80 Mg m^{-3} in sandy -textured soils and from 1.00 to 1.25 Mg m^{-3} in clayey soils were reported. For the development of *Quercus ilex* in sandy soils, BD values of 1.62 Mg m^{-3} were considered restrictive (Cubera et al., 2009). For medium-textured soils under pasture, Pariz et al. (2011) found BD values from 1.32

Table 3. Partitioning of the interaction between CER and each land use (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST) in each soil layer for macroporosity and bulk density

Source of variation	CER	EU15	EU02	PAST	MSD Dunnett	F value
			Bulk density (Mg m^{-3})			
Soil layer						
0.00-0.05 m	1.22	1.26 ^{ns}	1.39 ***	1.59 ***	0.07	79.50**
0.05-0.10 m	1.28	1.41 ***	1.46 ***	1.54 ***	0.06	15.35**
0.10-0.30 m	1.33	1.46 ***	1.45 ***	1.50 ***	0.05	6.68**
			Macroporosity (%)			
0.00-0.05 m	13.36	16.11 ^{ns}	7.82 ***	8.16 ***	3.58	18.36**
0.05-0.10 m	13.41	9.89 ^{ns}	6.44 ***	8.68 ^{ns}	4.94	4.21**
0.10-0.30 m	7.98	7.64 ^{ns}	5.96 ^{ns}	10.26 ^{ns}	2.82	1.50^{ns}

Means followed, in the line, by *** differ statistically of the CER by the Dunnet test at p<0.05. ^{ns}: not significant; ** and *: significant at 1 and 5 %, respectively. MSD: Minimum Significant Difference.

Table 4. F values and coefficient of variation (CV) for aggregate distribution (%). organic carbon (OC), and carbon pool (CP) in relation to land uses (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST) and soil layers

Source of variation	Diameter of aggregates						OC	CP
	>2.00	2.00-1.00	1.00-0.50	0.50-0.25	0.25-0.105	0.105-0.053		
	mm						g kg^{-1}	Mg ha^{-1}
F value								
Land use (LU)	8.74**	6.10**	6.18**	21.04**	6.07**	0.88^{ns}	51.14**	65.55**
Soil layer (L)	3.58*	3.95*	3.01 ^{ns}	7.19**	2.32^{ns}	1.07^{ns}	176.86**	1,726.42**
LU × L	1.69^{ns}	1.35^{ns}	1.72^{ns}	3.33*	1.00^{ns}	1.39^{ns}	12.20**	10.47**
CV (%)	11	112	177	81	84	195	5	5
Land use								
DMS Dunnet	10.00	2.16	4.33	2.13	1.50	1.02	0.43	5.70
CER	95.33	0.50	0.26	0.30	0.43	0.17	7.51	95.01
EU15	74.51***	3.70***	6.85***	6.52***	2.86***	0.79^{ns}	5.75***	65.46***
EU02	83.73^{ns}	0.83^{ns}	0.84^{ns}	1.33^{ns}	2.20***	0.45^{ns}	5.77***	76.18***
PAST	89.43^{ns}	2.48^{ns}	1.59^{ns}	2.00^{ns}	1.44^{ns}	0.64^{ns}	6.00***	85.09***
Layer								
0.00-0.05 m	91.38	0.78	0.65	1.05	1.13	0.21	7.71	52.96
0.05-0.10 m	88.15	1.98	2.21	2.74	1.83	0.62	6.03	43.49
0.10-0.30 m	82.26	2.89	4.31	3.83	2.25	0.71	5.02	144.87

Means followed, in the column, by *** differ statistically of the CER by the Dunnet test at p<0.05. ^{ns}: not significant; ** and *: significant at 1 and 5 %, respectively. MSD=Minimum Significant Difference.

Table 5. Partitioning of the interaction between CER and each land use (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST) in each soil layer for organic carbon pool (CP), and organic carbon (OC)

Land use	0.00-0.05 m	0.05-0.10 m	0.10-0.30 m	Averages	0.00-0.30 m
		CP (Mg ha^{-1})			
LSD Dunnett	5.45	7.69	17.54	5.70	21.60
CER	69.57	51.86	163.60	95.01	285.04
EU15	45.19***	34.99***	116.23***	65.46***	196.06***
EU02	41.88***	42.02***	144.65***	76.18***	228.57***
PAST	55.18***	45.09^{ns}	155.00^{ns}	85.09***	255.28***
F value	12.90**	4.53**	38.60**	65.55**	50.79**
		Organic carbon (g kg^{-1})			
LSD Dunnett	0.77	1.05	0.60	0.43	-
CER	10.01	6.92	5.60	7.50	-
EU15	7.41***	5.47***	4.37***	5.74***	-
EU02	6.44***	5.92***	4.95***	5.77***	-
PAST	6.99***	5.82***	5.17^{ns}	5.99***	-
F value	59.71**	9.234**	6.276**	51.14**	-

Means followed, in the column by ***differ statistically of the CER by the Dunnet test at $p<0.05$.^{ns}: not significant; ** and * significant at 1 and 5 % respectively. LSD: least significant difference.

to 1.89 Mg m^{-3} in the top 0.10 m of the soil and considered BD values of the order of 1.43 Mg m^{-3} critical. According to these assessments, the soil density values, particularly in the PAST and EU02 areas (Table 3) may be considered restrictives to plant development.

The BD values observed in the soil surface layer of the pasture area, can be attributed to animal trampling and the lack of conservation management in the area (Table 3). Similar results were reported by Martínez and Zinck (2004) for pasture, both for sandy and clay soil under pasture, where BD increased by 30 and 40 %, respectively. In a study with medium-textured soils, Pariz et al. (2011) also explained the BD increases observed by livestock trampling and added that this may be the cause for the heterogeneity observed in several physical properties of the topsoil.

As a result, the variables of soil resistance to water penetration and infiltration increase, which are variations that limit or impair plant development and production (TerAvest et al., 2015; Parihar et al., 2016).

Associated with the decrease in TP observed in EU02 and PAST, macroporosity was also reduced (Tables 2 and 3). In CER and EU15, macroporosity approached the minimum threshold allowing the liquid and gaseous exchange between the external environment and the soil of 0.10 m^3 m^{-3} or 10 %, which is considered critical for the growth of most crop roots (Rossetti and Centurion, 2015). For EU02 and PAST, however, the macropore values were considered restrictive. Soil tillage usually promotes a temporary increase in macroporosity, but this effect is eliminated, according to Silva et al. (2005), by natural soil reconsolidation or compaction, due to the absence of tillage over time, in contrast with the soil response observed in this study.

The condition of macro- and micropores was reflected in that of TP (Table 2), with higher TP in the CER and EU15 areas (Table 2) indicanting a recovery of porosity, density, and macroporosity in this area. However, higher BD and lower porosity in EU02 and PAST indicate the possibility of restrictions to plant development. Porosity tends to be lower in sandy (0.350-0.500 m^3 m^{-3}) than in loamy soils (0.400-0.600 m^3 m^{-3}) (Montanari et al., 2010). In this study, the TP in the areas evaluated ranged from 47.9 to 38.4 %, equivalent to 0.479 and 0.384 m^3 m^{-3}, within the expected range for sandy soil.

The distribution of water-stable aggregates (Table 4) indicated a predominance of macroaggregates (>0.250 mm) (Tisdall and Oades, 1982) and differed among the land use systems, although no differences among CER and land uses were observed for aggregates <0.105 mm. The percentage of aggregates >2 mm found in CER differed only from EU15. According to the literature (Silva et al., 2004; Siqueira Neto et al., 2009), in areas with less soil tillage, the stability of larger aggregates is greater, case of EU15 in this evaluation, where the stability of larger aggregates was lowest than CER, even after 15 years without tillage. The larger amount of water-stable aggregates (>2.00 mm) in a clayey Oxisol (360 g kg^{-1} of clay) under *Cerrado* was reported by Salton et al. (2008) in a study of different land use systems, which is in agreement with other studies including those of sandy soils (An et al., 2010; Anders et al., 2010; Fernández et al., 2010).

The soil sand content in EU15 was higher than in EU02 and PAST in all layers (Table 1), while the OC content was lower than in CER (Table 5), which explains the lower stability of the aggregates in this reforested area and reinforces the importance of organic matter associated with clays in the aggregate dynamics (Figure 1b), as mentioned by other authors (Santos et al., 2011; Verchot et al., 2011; Bast et al., 2014).

The macroaggregates with smallest diameter (1.0-0.50 and 0.50-0.25 mm) were better represented in the EU15 area (Table 4) than in the areas under other land uses, suggesting that larger aggregates (>2.0 mm) with lower stability were subdivided into smaller aggregates, as described by Six et al. (2000). The authors confirmed that the lower macroaggregate stability may indicate a loss of soil quality, which is directly related to a reduction in the OC content (Nichols and Toro, 2011; Bast et al., 2014; Parihar et al., 2016). This soil condition was confirmed by the presence of microaggregates <0.105 mm, which were not affected by land use, due to their higher stability. Similar results were reported by Pagliarini et al. (2012) for an Oxisol, where microaggregates were more stable than macroaggregates, the latter being more susceptible to changes due to land use.

The soil in the areas evaluated has sandy loam texture (Table 1), which may have led to the formation of less stable macroaggregates and stable microaggregates. The greater stability of microaggregates, however, was due to the presence of simple grains, the size of sand, increasing soil resistance and lack of response to land use (Figure 2) but indicating depositional covers, suggesting that these were part of the larger aggregates, and their greater stability is also related to the amount of sand, exceeding 80 % (Table 6).

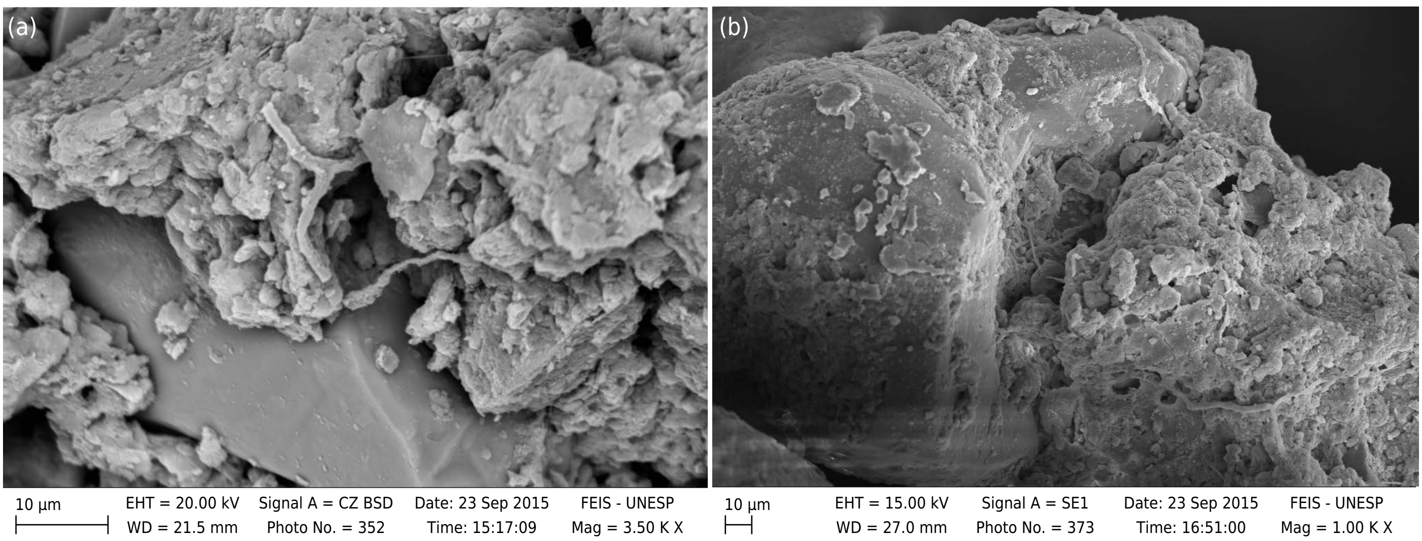

Figure 1. Images obtained by scanning electron microscopy (SEM) of the aggregates with a diameter from 0.50 to 1.00 mm in the 0.00-0.05 m layer under the land use systems (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15). (a) CER 0.50-1.00 mm; (b) EU15 0.50-1.00 mm.

The soil under the land use systems studied contains isolated sand grains with macroaggregate sizes, detected by scanning electron microscopy (SEM). The images showed that aggregate stability in PAST, similar to the CER, was defined by the presence of isolated sand grains with macroaggregate sizes (Figure 2). In relation to the layers, the

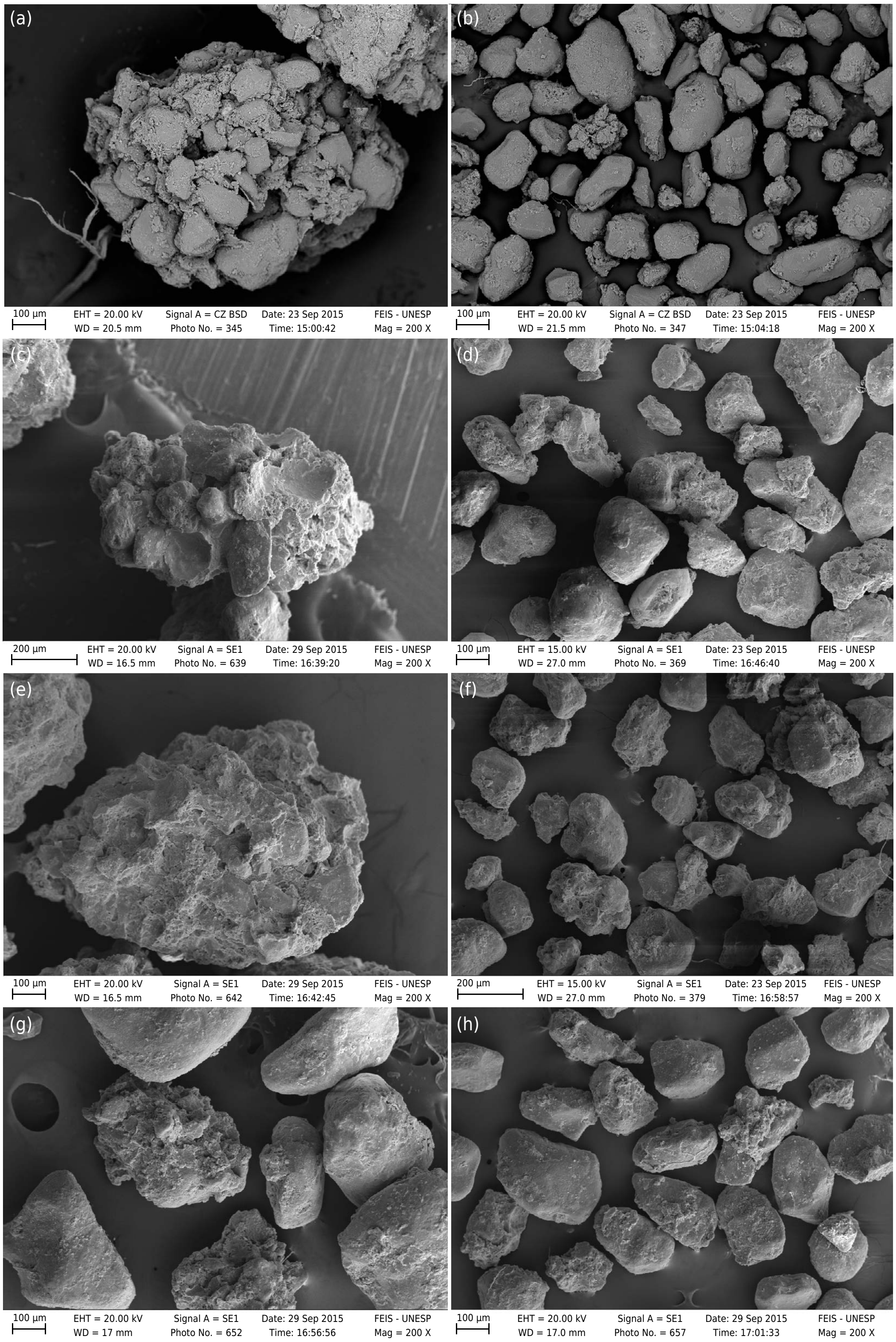

Figure 2. Scanning electron microscopy (SEM) images of the aggregates with a diameter from 0.50-1.00 and 0.05-0.10 mm in the 0.0-0.05 m layer under different land use systems [preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST). (a) CER: diameter 0.50-1.00 mm; (b) CER: diameter 0.05-0.10 mm; (c) EU15: diameter 0.50-1.00 mm; (d) EU15: diameter 0.05-0.10 mm; (e) EU02: diameter 0.50-1.00 mm; (f) EU02: diameter 0.05-0.10 mm; (g) PAST: diameter 0.50-1.00 mm; (h) PAST: diameter 0.05-0.10 mm].

Table 6. Values of sand (%) present in the aggregates. according to land use (preserved *Cerrado* - CER, 15-year-old *Eucalyptus* - EU15, 2 year-old *Eucalyptus* - EU02, and Pasture - PAST) for the different soil layers and sand grain diameters

Soil layer	Diameter of aggregates					
	>2.0 mm	2.0-1.0 mm	1.0-0.5 mm	0.5-0.25 mm	0.25-0.105 mm	0.105-0.053 mm
			CER[1]			
0.00-0.05 m	67.58	86.78	95.83	95.45	93.92	94.12
0.05-0.10 m	66.87	86.55	77.49	90.00	98.58	88.73
0.10-0.30 m	69.64	72.08	65.40	97.30	97.87	83.33
			EU15			
0.00-0.05 m	70.33	86.58	85.10	90.61	96.36	95.56
0.05-0.10 m	73.63	89.94	86.89	89.57	91.34	100.00
0.10-0.30 m	69.40	88.22	85.12	90.67	94.09	94.47
			EU02			
0.00-0.05 m	75.38	93.35	80.83	95.98	94.52	96.88
0.05-0.10 m	74.97	84.43	81.28	92.57	94.56	93.65
0.10-0.30 m	74.64	88.08	90.16	93.33	96.82	97.83
			PAST			
0.00-0.05 m	70.33	92.31	94.83	97.76	99.21	75.00
0.05-0.10 m	70.35	89.31	88.23	91.87	96.54	87.41
0.10-0.30 m	69.76	92.17	92.93	91.81	97.14	91.67

aggregates >2 mm were most stable in the 0.00-0.05 m layer, where the contact with crop residues and OC input was higher than in the deeper layers (Barreto et al., 2006; Mulumba and Lal, 2008; Barreto et al., 2009; Martins et al., 2009; Guan et al., 2015), in agreement with the higher OC contents of this layer (Table 2), reaffirming the importance of C for maintenance of aggregate stability (Salton et al., 2008).

The presence of macroaggregates is positively associated with the contents of soil OM (De Gryze et al., 2008; Salton et al., 2008; Anders et al., 2010), as observed for the CER aggregates (Figure 2a). They protect the soil against degradation and rainwater erosion, especially in tropical and subtropical areas (Bayer et al., 2006; Noellemeyer et al., 2008), and reduce the OM decomposition rate by physical protection (Ferreira et al., 2007; Salton et al., 2008; Costa Jr et al., 2012).

PAST and EU2 contain less OC than CER does (Table 4), and aggregates >2 mm are found at similar proportions between PAST, EU2 and CER areas, suggesting differentiated aggregate dynamics and C incorporation, which can be ascribed to the fasciculate, abundant, and fast-growing root system of the grasses, with residual effects in EU2 and actual in PAST. Grasses are capable of grouping soil particles physically and maintaining their aggregation since the presence of roots stimulates microbial activity, increasing the quantity of exudates acting as soil aggregation agents (Denef and Six, 2005; Salton et al., 2008).

Given the importance of OC, it is noteworthy that the highest OC levels in this study were observed in CER soil, followed by the other areas (EU15, EU02, and PAST) (Table 4). In the *Eucalyptus* stands, the potential for soil C incorporation is higher than in the agricultural areas, due to higher annual biomass deposition in the form of organic litter and dead roots (Silva et al., 2012). In these areas, however, the OC levels were lower than in the CER, indicating that not even 15 years of reforestation resulted in significant increases in OC in this sandy soil area. These results suggest that other actions, such as residue incorporation, integrated agrosilvopasture, and more effective conservation management must be applied to raise the OC content in the soil of these areas.

That the OC values in soil under conservation management systems tend to approach those of native areas has been reported elsewhere (Six et al., 2000; Madari et al., 2005), although in EU02 (minimum tillage) and EU15 (reforestation), this result was not yet reached. However, the lower OC contents in these areas indicated the negative impact on the soil upon conversion of natural vegetation into commercial cultivation systems, which may have reduced nutrient cycling in these areas. This effect may have been facilitated by the at least 700 g kg^{-1} of sand found in these soils (Table 1), paving the way for removal of silica and bases, as well as of organic colloids. In the Mediterranean region, the low pH and OC content of soils was attributed to their sandy and sandy loam texture (Parras-Alcántara et al., 2015). For *eucalyptus* areas, Cook et al. (2016) related the CP and soil C to clay content, and cited that an increase of 100 g kg^{-1} clay in the soil increases OC by 0.6-0.7 Mg ha^{-1}.

Soil OM content is acknowledged as an agent of formation and stabilization of soil aggregates (Six et al., 2004; Mulumba and Lal, 2008; Noellemeyer et al., 2008), and increasing it should be a priority, not only with a view to C sequestration, but also to increase the quality, fertility, nutrient cycling, and structure stability of soils (Li et al., 2007; Barreto et al., 2009). Under agricultural use, the organic fraction of soils is less stable than the mineral fractions; in other words, intensive land use with inadequate cultivation systems contributes to soil degradation (Cunha et al., 2012). This degradation is possibly induced by the land use system, reducing aggregate stability as a result of OC loss, which increases density and reduces porosity, as observed in this study.

The OC content and carbon pool (CP) were influenced by the soil layer (Tables 4 and 5). In general, the highest levels were observed in the surface layer of all treatments, with a tendency of decline in OC as well as the CP with increasing depth. This was confirmed by other authors (Costa Jr et al., 2012; Guareschi et al., 2012; Arruda et al., 2015; Guan et al., 2015; Cook et al., 2016), who reported that soil OC contents are higher near the surface, due to OM inputs from the vegetation.

The CER area had the highest CP in the 0.00-0.30 m layer and in all sub-layers evaluated (Table 5). The similarity in the CP between CER and PAST areas in the 0.05-0.10 and 0.10-0.30 m layers resulted from the input of plant residue by grass roots and animal waste (feces and urine) (Garcia et al., 2011). Although the CP values were lower in deeper layers, it should be noted that this carbon is more likely to remain in the soil for a longer time, simply due to the deeper location, where the soil is better preserved through being less influenced by human actions applied to the surface.

The treatments indicate a reduction in the CP in the deeper layers, which, compared to CER, is in the order of 35.04, 39.80, and 20.68 % in the 0.00-0.05 m layer for EU15, EU02, and PAST, respectively. For the 0.05-0.10 m layer, the reductions were lower, with 32.53, 18.97, and 13.05 %; and for the 0.10-0.30 m layer, with 28.96, 11.59, and 5.26 %, in the same order. A reduction in the CP of 23-34 % in areas where natural vegetation was replaced by commercial crop cultivation was also reported by Guan et al. (2015), corroborating our observations.

The CP values observed in the deepest layer (Table 5) corresponded to a layer with a thickness of 0.20 m, but to only 0.05 m in the upper layer, which was equivalent to the mean value of 40.90 Mg ha^{-1} in the CER; 29.06 Mg ha^{-1} in EU15; 36.16 Mg ha^{-1} in EU02; and 38.75 Mg ha^{-1} in the PAST area, actually indicating a CP reduction in the deeper layers. Analyzing the 0.00-0.30 m layer as a whole, the land uses differed of the CER, from the statistical point of view. The CER contain the highest C pool (285.04 Mg ha^{-1}), followed by the others. Highest values for the 0.00-0.30 m layer were reported by Sisti et al. (2004) and Fernandes and Fernandes et al. (2013) studying native *Cerrado* vegetation under anthropogenic influence (66.55 Mg ha^{-1}), undegraded long-term pasture (55.85 Mg ha^{-1}), and long-term degraded pasture (56.10 Mg ha^{-1}).

Research along this line reported that the conversion of *Cerrado* to cultivated areas and pastures leads to reductions in OC and soil C pools (Silva et al., 2004; Siqueira Neto et al., 2009; Kaschuk et al., 2010; Guan et al., 2015; Cook et al., 2016), as observed for the treatments studied. Based on the foregoing, soils with the properties of lower porosity, lower macroporosity, higher BD, lower OC, and lower CP than CER can be classified as anthropogenically disturbed, as is the case in the PAST, EU02, and EU15 areas.

CONCLUSIONS

The anthropogenic disturbance caused by land use systems influenced the soil physical properties.

Reduction in soil density and increase in porosity were observed fifteen years after planting *Eucalyptus* in a degraded pasture area.

Both macroporosity and total porosity can be considered restrictive for plant development in the pasture and 2-year-old *Eucalyptus* plantation.

The land use systems reduced soil organic carbon and the carbon pool, indicating occurrence of human disturbance in comparison with the soil under *Cerrado*.

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