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Oxidizable carbon and humic substances in rotation systems with brachiaria/livestock and pearl millet/no livestock in the Brazilian Cerrado

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Abstract

The crop-livestock integration system significantly increases the carbon content in chemical fractions of soil organic matter (SOM). This study aimed to evaluate chemical indicators of SOM attributes for sites under brachiaria/livestock and pearl millet/no livestock in Goias, Brazil. A third area covered with natural Cerrado vegetation (*Cerradão*) served as reference. Soil was randomly sampled at 0-5, 5-10, 10-20 and 20-40 cm. Total organic carbon stocks (TOC), oxidizable carbon fractions (OCF) (F1 > F2 > F3 > F4), carbon content in the humin (C – HUM), humic acid (C – HAF) and fulvic acid (C – FAF) fractions were evaluated. F1/F4, F1 + F2/F3 + F4, C – HAF/C – FAF and (C-HAF + C-FAF)/C – HUM indices were calculated, as well as stocks chemical SOM fractions. Brachiaria/livestock produced greater TOC stocks than pearl millet/no livestock (0-5, 5-10 and 10-20 cm). In terms of OCF, brachiaria/livestock generally exhibited higher levels in F1, F2, F4 and F1/F4 than pearl millet/no livestock. C – HUM (0-10 cm) and C – HAF (0-20 cm) stocks were larger in brachiaria/livestock than pearl millet/no livestock. Compared to the *Cerradão*, brachiaria/livestock locations displayed higher values for TOC (5-10 and 10-20 cm), C – HAF and C – HAF/C – FAF (5-10 cm) stocks. TOC, C – HAF stock and OCF show that land management with brachiaria/livestock was more efficient in increasing SOM than pearl millet/no livestock. Moreover, when compared with pearl millet/no livestock, brachiaria/livestock provided a more balanced distribution of very labile (F1) and recalcitrant (F4) carbon throughout soil layers, greater SOM humification. Brachiaria/livestock leads to higher values of F1 and F4 in depth when compared to pearl millet/livestock and provides a more homogeneous distribution of C-FAF and C-HAF in depth compared to *Cerradão*.

Additional key words: carbon stocks; crop-livestock integration system; humic and fulvic acids; labile and resistant fractions; no-tillage system.

Introduction

The Cerrado, after Amazon biome, is the second largest Brazilian biome, exhibiting complex dynamics that are strongly affected by seasonal fluctuation (wet-dry savannah) and anthropic activity (Bolliger *et al*., 2006; Sano *et al*., 2007). The Cerrado is characterized by a tropical savannah-like native vegetation of low trees, scrub brush and grasses. It covers approximately 204 million hectares (Mha) or 23% of Brazil's land area (Bustamante *et al*., 2006; Rodríguez Pacheco *et al*., 2012). About 62% of this area (127 Mha) is suitable for agriculture (Lilienfein & Wilcke, 2003). Cultivated pastures in the Cerrado region cover about 66 Mha (Sano

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Abbreviations used: ADGS (air-dried ground soil); AE (alkaline extract); CLI (crop-livestock integration); CTS (conventional tillage system); DAPE (days after plant emergence); F1-F4 (four oxidizable fractions); FAF (fulvic acid fraction); HAF (humic acid fraction); HUM (humin); LOM (light organic matter); NTS (no-tillage system); OCF (oxidizable carbon fractions); SOM (soil organic matter); TNP (total neutralizing power); TOC (total organic carbon).

et al., 2006). An estimated 50 Mha are subjected to a process of degradation by excessive grazing (Silva *et al*., 2004a; Klink *et al*., 2008).

In recent years, a growing number of studies have investigated carbon accumulation in Cerrado soils under different management systems, such as conventional management, no-tillage system (NTS) and pasture (Blanchart *et al*., 2007; Marchão *et al*., 2009; Carvalho *et al*., 2010; Loss *et al*., 2012a,b). However, these focused mainly on determining total organic carbon (TOC) stocks, which is insufficient to drive recommendations for better land use and management. Further research is needed to provide information on the profile of different TOC fractions including oxidizable organic carbon and carbon content in the humic fractions. The soil organic matter (SOM) fractions are more sensitive to reveal changes caused in the soil coming from the different systems for hand-ling compared to the TOC (Loss *et al*., 2009; Bouajila & Gallali, 2010; Briedis *et al*., 2012a,b; Pereira *et al*., 2012).

The NTS is an efficient management technique in reducing erosion and increasing the carbon and nutrient load in soil, especially when combined with annual crop rotation (Marchão *et al*., 2009; Sá *et al*., 2009; Boddey *et al*., 2010). Moreover, the association of crop and livestock in NTS can increase the chemical SOM fractions, enhancing carbon stocks (Loss *et al*., 2012a,b). The growth of forage grass interposed with annual crops and livestock production represents a management system commonly called crop-livestock integration (CLI). The CLI is a production system that succeeds, at the same area, pastures to animal production and vegetal crops, especially cereals (Balbinot *et al*., 2009; Marchão *et al*., 2009). CLI is considered an excellent alternative to recover areas degraded by modern agriculture (Carvalho *et al*., 2010; Souza *et al*., 2010; Loss *et al*., 2011a).

Some studies have shown that TOC estimation in cropped areas is not sensitive enough to detect short-term chemical changes in SOM caused by variations in land management (Majumder *et al*., 2008; Mirsky *et al*., 2008; Loss *et al*., 2009; Souza *et al*., 2010; Ciampitti *et al*., 2011; Zinn *et al*., 2011; Corsi *et al*., 2012; Loss *et al*., 2012b). Thus, complementary analyses such as chemical SOM partitioning (Oliveira-Júnior *et al*., 2008; Benites *et al*., 2010; Loss *et al*., 2010; Vergnoux *et al*., 2011; Nadi *et al*., 2012) and oxidizable carbon determination (Maia *et al*., 2007; Rangel *et al*., 2008; Loss *et al*., 2009; Kolar *et al*., 2009; Barreto *et al*., 2011; Loss *et al*., 2011b; Culman *et al*., 2012) are valuable tools not only in assessing soil changes due to land use, but also to quantify carbon levels in different soil fractions.

The main objective was to evaluate chemical SOM fractions in soil under different management systems in a Cerrado area in the state of Goiás state, Brazil. Against this backdrop, the present study tested the hypothesis that CLI (brachiaria/livestock) is superior to the NTS (pearl millet/no livestock) in promoting balanced carbon distribution among labile and recalcitrant SOM fractions and increasing soil carbon stocks.

Material and methods

The study was conducted at *Vargem Grande* farm, owned by *Agropecuária Peeters* and located in Montividiu, Goias (17° 21' S and 51° 28' W). Climate in the area exhibits a well-defined dry (May-September) and rainy season (October to April). Annual rainfall is 1,500 mm and the maximum and minimum temperatures are 30.1°C and 17.8°C, respectively. The soil in the systems evaluated was classified as Rhodic Hapludox (Soil Survey Staff, 2010) with clayey texture [Latossolo Vermelho Distrófico (Embrapa, 2006)]. Mineralogical composition was predominantly gibbsite, kaolinite and hematite. Chemical characterization and granulometric composition of the evaluated systems at 0-20 cm are shown in Table 1.

Land use history in the study area is illustrated in Fig. 1. In 1975, the natural *Cerradão* vegetation in the study area was replaced by brachiaria grass (*Urochloa decumbens*, syn. *Brachiaria*) for a period of 10 years. In 1985, management of the area began applying conventional tillage system (CTS) with ploughing (disc plow) and harrowing (disc harrow) to 40 cm of depth for growing grain crops (corn – *Zea mays* L., bean – *Phaseolus vulgaris* L., soybean – *Glycine max* L. and sunflower – *Helianthus annuus* L.). NTS with crop rotation (corn/bean/soybean/cotton) was introduced in 1991 and from 1999 onwards, part of the areas managed by the NTS began to use CLI. As such, both cropped areas evaluated were subject to NTS management for 17 years, one with rotation of the same crops from 1991 to 2008 and the other with CLI from 1999 to 2008.

The area managed exclusively by a NTS (17° 21.120' S; 51° 29.461' W, 859 m altitude) rotated sunflower/pearl millet/soybean/corn crops, and the CLI area (17° 21.854' S; 51° 28.599' W; 859 m altitude) contained brachiaria grass (*Urochloa ruziziensis*) intercropped with off-season corn crops to enhance straw

Table 1. Chemical characterization[1] and particle size of 0-20 cm of Oxisol under different soil management systems in Montividiu, Goiás, Brazil

Attributes evaluated	Soil management system		
	Pearl millet/ No livestock based system[2]	Brachiaria/ Livestock based system[3]	*Cerradão*
pH in H_2O	6.3	6.3	5.4
Ca ($cmol_c$ dm^{-3})	3.6	4.1	1.2
Mg ($cmol_c$ dm^{-3})	2.5	2.3	1.8
K (mg dm^{-3})	87.7	83.8	58.5
P (mg dm^{-3})	8.1	12.1	1.9
Al ($cmol_c$ dm^{-3})	0.11	0.10	0.70
Clay (g kg^{-1})	660	655	620
Silt (g kg^{-1})	126	115	130
Sand (g kg^{-1})	214	230	250

[1] As methodology recommended by Embrapa (1997). [2] Pearl millet/No livestock-based system: Sunflower/Pearl millet/Soybean/Corn. [3] Brachiaria/Livestock-based system: Corn/Brachiaria grass/Bean/Cotton/Soybean.

production during the dry season, producing a rotation system among corn/brachiaria grass/bean/cotton/soybean. Off-season crops consisted of a short-term culture grown after the annual crop and under less suitable climate conditions. The third area studied was the natural *Cerradão* (17°2 6.642' S; 51° 22.522' W, 951 m altitude), located adjacent to the cropped site and representing original soil conditions. *Cerradão* is composed of a wood layer with the main stratum of trees presenting height between 8 m and 15 m, and a crown cover of 50 to 90%. The shrubby is usually well defined with height between 2 m and 5 m. Although the wood vegetation represents the main stratum of this vegetation, a herbaceous cover occurs in less shaded areas (Ribeiro & Walter, 1998).

For this study, in terms of comparison and standardization of terminology, the NTS (sunflower/pearl millet/soybean/corn) will be designated as pearl millet/no livestock based system and the CLI (corn/brachiaria grass/bean/cotton/soybean) will be designated as brachiaria/livestock based system.

The brachiaria/livestock system was employed in the area cropped with corn/brachiaria grass/bean/cotton/soybean. Corn was sowed simultaneously with grass (grass was planted between corn rows). Cattle were allowed to graze in the area at a density of 2 animals unit ha^{-1} for a period of 90 days (July to September) after corn harvesting. Each animal unit corresponds to 1 animal of 450 kg live weight. The animals used were adults, Nellore breed, beef cattle, with live weight between 300 and 350 kg. This equates to approximately 3 animals ha^{-1}, *i.e.,* 900 kg ha^{-1}. Animals were then removed and only grass clumps remained in the field. Following the first rainfall events, the grass

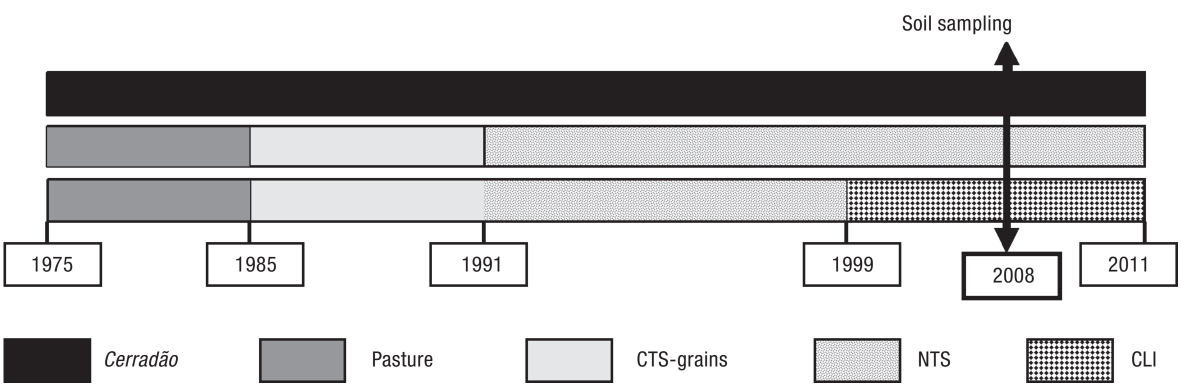

Figure 1. Land use history for the Vargem Grande farm in Montividiu, Goiás (Brazil). CTS: conventional tillage system; NTS: no-tillage system (Pearl millet/No livestock-based system: Sunflower/Pearl millet/Soybean/Corn); CLI: crop-livestock integration (Brachiaria/Livestock-based system: Corn/Brachiaria grass/Bean/Cotton/Soybean).

received 200 kg ha^{-1} NPK topdress (20:00:20) in the first two weeks of September. After sprouting, when grass covered the entire area, it was desiccated using glyphosate and the field was planted with bean.

The brachiaria/livestock system was limed in July 2005 with 3.60 Mg ha^{-1} of dolomitic limestone with total neutralizing power (TNP) of 70%, to enhance base saturation to 70%. The pearl millet/no livestock system was also limed at this period, with 3.90 Mg ha^{-1} of dolomitic limestone with TNP of 70% in order to enhance base saturation to 60%. Fertilization and cropping sequences from 2002 to 2008 for both areas are dis-

Table 2. Fertilization and cropping sequence in the two areas studied at Vargem Grande farm of Agropecuária Peeters, in Montividiu, Goiás, Brazil

Year	Month of planting	Crop	Fertilization	
			(N:P:K)	Topdress[1]
Brachiaria/Livestock-based system[2] (Corn/Brachiaria grass/Bean/Cotton/Soybean)				
2002	October	Soybean	580 kg ha^{-1} (02:20:18)	—
2003	February	Corn + Brachiaria grass	500 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea[3]
2003	October	Soybean	580 kg ha^{-1} (02:20:18)	—
2004	February	Corn + Brachiaria grass	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2004	October	Soybean	500 kg ha^{-1} (02:20:18)	—
2005	February	Corn + Brachiaria grass	490 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2005	September	Bean	400 kg ha^{-1} (05:20:10)	90 kg ha^{-1} urea
2005	December	Cotton	500 kg ha^{-1} (10:30:10)	250 kg ha^{-1} (20:00:20)
2006	October	Soybean	500 kg ha^{-1} (02:20:18)	—
2007	February	Corn + Brachiaria grass	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2007	October	Soybean	450 kg ha^{-1} (02:20:18)	—
2008	February	Corn + Brachiaria grass	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2008	September	Bean	400 kg ha^{-1} (05:20:10)	90 kg ha^{-1} urea
2008	December	Cotton	500 kg ha^{-1} (10:30:10)	250 kg ha^{-1} (20:00:20)
Pearl millet/No livestock-based system[4] (Sunflower/Pearl millet/Soybean/Corn)				
2002	August	Pearl millet	—	—
2002	October	Soybean	550 kg ha^{-1} (02:20:18)	—
2003	February	Corn	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2003	August	Pearl millet	—	—
2003	October	Soybean	550 kg ha^{-1} (02:20:18)	—
2004	February	Corn	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2004	August	Pearl millet	—	—
2004	October	Soybean	550 kg ha^{-1} (02:20:18)	—
2005	February	Corn	450 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2005	August	Pearl millet	—	—
2005	October	Soybean	550 kg ha^{-1} (02:20:18)	—
2006	February	Sunflower	300 kg ha^{-1} (02:20:20)	100 kg ha^{-1} urea
2006	August	Pearl millet	—	—
2006	October	Soybean	500 kg ha^{-1} (02:20:18)	—
2007	February	Corn	400 kg ha^{-1} (07:28:14)	100 kg ha^{-1} urea
2007	August	Pearl millet	—	—
2007	October	Soybean	500 kg ha^{-1} (02:20:18)	—
2008	February	Sunflower	300 kg ha^{-1} (02:20:20)	100 kg ha^{-1} urea
2008	August	Pearl millet	—	—
2008	October	Soybean	500 kg ha^{-1} (02:20:18)	—

[1] Timing topdress fertilization in corn (30 days after plant emergence-DAPE); in bean (25 DAPE); in cotton (35 DAPE); in sunflower (30 DAPE). [2] After harvesting off-season corn (corn + brachiaria grass), put up the cattle that remained in the area for three months. [3] Urea = 45% N. [4] From 2002 to 2008, pearl millet was annually sowed in the NTS area, always in August, to enhance straw yield for direct planting of soybeans. Before 2002, off-season and pearl millet crops were not planted and the area remained at rest from May to September. During this resting period, grass species such as colonião (*Panicum maximum*) and brachiaria grass (*Urochloa decumbens*) grew spontaneously.

Table 3. Average[1] productivity (kg ha^{-1}) of crops and coverage plants in different soil management systems in the Vargem Grande farm of Agropecuária Peeters, in Montividiu, Goiás, Brazil

	Soil management system		
	Brachiaria/ Livestock[2]	**Pearl millet/No livestock**[3]	***Cerradaõ***
Soybean	3,780	3,696	—
Corn	6,282	5,550	—
Cotton	4,470	—	—
Bean	2,580	—	—
Sunflower	—	2,340	—
Dry matter brachiaria	11,300	—	—
Dry matter pearl millet	—	7,800	—
Dry matter (Litter)			5,550

[1] Averages for the years 1999-2008. [2] Brachiaria/Livestock-based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [3] Pearl millet/No livestock-based system: Sunflower/Pearl millet/Soybean/Corn.

played in Table 2. The average productivity of crops and dry matter in systems evaluated during the period of 1999-2008 are shown in Table 3. The dry matter (litter) deposited in the *Cerradão* area at moment collection soil samples is also presented in Table 3.

For soil sampling in March 2008, the pearl millet/no livestock system was cropped with sunflower and the brachiaria/livestock system with corn + brachiaria grass. A 600 m^2 section was demarcated at each location and four trenches measuring 40 × 40 × 40 cm were opened crosswise to crop rows for soil sampling at depths of 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm. Three single samples were collected in each trench to form a composite sample, with a total of four replications in each land use system. After collection, the samples were identified, placed in plastic bags and transported to the laboratory, air-dried and sieved through a 2-mm-mesh sieve to obtain air-dried ground soil (ADGS). At the same depths, soil samples were collected to determine bulk density (Loss *et al*., 2012c). Values obtained were used to calculate the equivalent soil mass and analyze carbon stocks in SOM fractions.

Total organic carbon (TOC) was quantified (Yeomans & Bremner, 1988) and used to calculate the stocks (TOC 1995; Sisti *et al*., 2004). The reference soil mass used was the *Cerradao* soil (Loss *et al*., 2012a,c).

Carbon partitioning was performed by oxidation degrees according to Chan *et al.* (2001). This methodology is a modified Walkley & Black method, analyzing four oxidizable fractions (F1 – F4): very easily oxidizable fraction (F1), easily oxidizable fraction (F2), moderately oxidizable fraction (F3) and resistant fraction (F4). Ratios between F1/F4 and F1 + F2/F3 + F4 were also calculated for a better understanding of the dynamics of the oxidizable C fractions. These indices can better relate the differences between the systems evaluated (brachiaria/livestock, pearl millet/no livestock and *Cerradão*) compared with only individual fractions (F1, F2, F3 and F4); besides there is no information in the literature of such indices.

Humic substances of SOM were fractioned into fulvic acid fraction (FAF), humic acid fraction (HAF) and humin (HUM), using differential solubilization as proposed by the International Humic Substance Society (Swift, 1996) and adapted by Benites *et al*. (2003). Quantification of organic carbon in the fractions (C – HUM, C– FAF and C– HAF) was performed in accordance with Yeomans & Bremner (1988). The carbon content in the humic fraction was used to calculate the C – HAF/C – FAF ratio, alkaline extract –AE (AE = C – HAF + C-FAF) and humin (AE/C – HUM) as per Benites *et al.* (2003). Carbon stocks in each humic fraction were calculated using the equivalent soil mass method (Ellert & Bettany, 1995; Sisti *et al*., 2004). The reference soil mass used was the *Cerradão* soil (Loss *et al*., 2012a).

Data were checked for normality using the Lilliefors test and for homocedasticity by the Bartlett and Cochran test. They were then analyzed as a completely randomized design, with three soil management systems (pearl millet/no livestock, brachiaria/livestock and *Cerradão*) applied to the Cerrado areas, four trials in each. For variables oxidizable carbon fractions and humic fractions, soil depth was also considered as factor in the statistical model. The areas studied had the same topographic, soil and climate conditions, and therefore differed only in the type of management they received. Data underwent analysis of variance with the F test, and differences detected were compared using the LSD-Student test and a significance level set at 0.05.

Results and discussion

Total organic carbon stocks

TOC stocks in the top layer (0-5 cm) were greater in the *Cerradão* than in cropped areas (Table 4). This is likely associated to high organic matter deposition

Table 4. Total organic carbon stocks (Mg ha^{-1}) under different soil management systems in Montividiu, Goiás, Brazil

Depth (cm)	Soil management system			
	Pear millet/No livestock based system[1]	Brachiaria/Livestock based system[2]	*Cerradão*	CV[3] (%)
0-5	9.66^{B}	10.57^{B}	19.19^{A}	4.26
5-10	11.28^{B}	13.60^{A}	11.24^{B}	2.87
10-20	22.08^{B}	26.88^{A}	20.50^{C}	3.09
20-40	34.74^{A}	34.21^{A}	33.09^{A}	4.15
0-40	77.78^{B}	85.26^{A}	84.02^{A}	4.18

[1] Pearl millet/No livestock-based system: Sunflower/Pearl millet/Soybean/Corn. [2] Brachiaria/Livestock-based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [3] CV: coefficient of variation. Means followed by the same letter in a row do not differ among areas studied (LSD-student test; $p < 0.05$).

in *Cerradão* combined with the lack of anthropic activity. At depths of 5-10 cm and 10-20 cm the largest TOC stocks were found in the brachiaria/livestock system, and at 10-20 cm deep, the lowest TOC stocks were recorded in the *Cerradão*. TOC stocks were similar among sites at depths of 20-40 cm (Table 4). The largest TOC stocks in depth in cropped areas can derive from a consistent root development, *i.e.,* pearl millet and brachiaria grasses. Associated with dry mass production of these grasses, and also the crop residues from annual crops (Table 3) and fertilization used (Table 2) compared with only dry matter in *Cerradão* area (Table 3).

According Parihar *et al*. (2012), pearl millet (cycle photosynthetic C_4, so as brachiaria grass) is more efficient carbon accumulator and having efficient photosynthetic process due to its C_4 nature than plants C_3. Therefore, pearl millet and brachiaria grass (both C_4) are more efficient in accumulating carbon than *Cerradão* (cycle photosynthetic C_3), which resulted into largest TOC stocks at 10-20 cm deep. These results reinforce the efficiency of cropping without soil tillage (pearl millet/no livestock and brachiaria/livestock) in increasing TOC stocks for deeper soil layers. These findings corroborate Siqueira-Neto *et al*. (2009, 2010), who evaluated TOC stocks in Rhodic Hapludox under NTS in Rio Verde, Goias. These authors showed that carbon distribution at depth increased, as a tendency to replenish the original levels found in natural *Cerradão*.

The association of conservative cropping and grass species (pearl millet/no livestock and brachiaria/livestock) was efficient at increasing TOC stocks at the depth of 10-20 cm (Table 4). Conservative crops not only maintain, but also increase TOC stocks in relation to the reference soil (*Cerradão*) when managed properly and combined with coverage plants exhibiting a high straw yield (Table 3) that are well adapted to local conditions.

Larger TOC stocks in the brachiaria/livestock system were likely due to corn intercropping with brachiaria grass. In addition to providing crop residue mulch of slow degradation, the root system of grass species such as corn and brachiaria grass favors organic matter allocation. Brachiaria grass in particular has a well-developed root system that spreads throughout the soil.

In regard to the 0-40 cm layer, TOC stocks in brachiaria/livestock and *Cerradão* were greater than in the pearl millet/no livestock (Table 4), reinforcing brachiaria/livestock system efficiency in comparison to pearl millet/no livestock system for improving TOC stocks. TOC stocks in the brachiaria/livestock system-managed site were similar to those of original soil (*Cerradão*), indicating this system is promising for recovering soil carbon. In the *Cerradão*, as well as the lack of soil turning, continuous and varied deposition of organic substrate with different decomposition rates may enhance carbon in light organic matter (C-LOM) (Loss *et al*., 2012b). In turn, brachiaria/livestock system promotes the mixture of crop straws and brachiaria to animal excreta (Table 2), which are unevenly deposited on the soil and decomposes over time, not only increasing TOC levels, but also incorporating N, P and K into soil. According Loss *et al*. (2012c), this same experiment, the integration of crop, pasture with animals and fertilization in brachiaria/livestock system resulted in lower soil density values (0.89 Mg m^{-3} and 0.97 Mg m^{-3}, 0-5 cm and 5-10 cm) as compared in pearl millet/no livestock system (0.94 Mg m^{-3} and 0.96 Mg m^{-3}, respectively 0-5 cm and 5-10 cm). And also resulted in increased levels of N, P, K, Ca and Mg compared with pearl millet/no livestock system.

Elevated TOC stocks in the 0-40 cm layer is associated to nutrient stock (Ca, K, N and P) in brachiaria/livestock system (Loss *et al.*, 2012c), both higher than in pearl millet/no livestock system. Improved SOM levels (*i.e.,* TOC stocks) increases soil capacity for nutrient retention and accounts for up to 70% of cation exchange capacity in tropical soils (Silva *et al.*, 2004b). C-LOM may contribute to the high TOC stocks found at the brachiaria/livestock system (Loss *et al.*, 2012b). These authors found higher values of C-LOM in brachiaria/livestock system compared with pearl millet/no livestock system at depths of 5-10 cm.

TOC stocks found in layer 0.0-40.0 cm (85.26 Mg ha^{-1} and 77.78 Mg ha^{-1}, respectively, for brachiaria/livestock system and pearl millet/no livestock system) are similar than those found by Jantalia *et al*. (2007). The authors evaluated the dynamics of the TOC stocks in an Oxisol (Latossolo Vermelho) in Planaltina in Brazil's Federal District (also in a Cerrado and NTS environment), with the following crop rotations: corn, soybean, pearl millet (NTS1) and the same previous rotation, but associated with *Andropogon gayanus* grass (NTS2). TOC stock values found by Jantalia *et al*. (2007) were 84 Mg ha^{-1} for NTS1 and NTS2 at 0.0-40.0 cm depth. Marchão *et al*. (2009), evaluated TOC stocks in a Cerrado Brazilian in Federal District, in clayey Oxisol under 13-year effects of integrated crop-livestock management systems, found TOC stocks equal 52.21 Mg ha^{-1} in layer 0.0-30.0 cm.

According Briedis *et al*. (2012a), the practice of liming on NTS for a long time, promotes an increase in the levels TOC and the SOM fractions, such as total and labile polysaccharides, and carbon extracted in hot water. These authors also observed that the greatest proportionate increase TOC occurs in the labile SOM fraction (*i.e.,* fraction F1), which is largely related to crop residues (Table 3). Thus, liming, fertilization, crop rotation and grazing in brachiaria/livestock system for a long period (1999-2008), promotes greater return to the system via C cultures, which increases the fraction F1 (5-10 cm and 10-20 cm, Table 5) and therefore the TOC stocks (10-20 cm and 5-10 cm, Table 4).

Oxidizable fractions of soil total organic carbon

At 0-5 cm deep, the highest levels of oxidizable carbon in different TOC fractions were found in the *Cerradão*, with the exception of F2, which was similar between the *Cerradão* and brachiaria/livestock system (Table 5). Greater plant input in the *Cerradão*, which increases both TOC (Table 4) and oxidizable carbon levels, explains this result.

Compared to pearl millet/no livestock system, brachiaria/livestock system had higher carbon levels in the F1 fraction at depths of 5-10 cm and 10-20 cm, and in the F2 fraction at 0-5 cm, 10-20 cm and 20-40 cm. This is caused by brachiaria grass intercropping with

Table 5. Oxidizable organic carbon fractions[1] (F1 to F4, in g kg^{-1}) in soil under different management systems in Montividiu, Goiás, Brazil

Management system[2]	F1	F2	F3	F4
0-5 cm				
Pearl millet/No livestock	10.50^{Ba}	5.81^{Ba}	7.69^{Ba}	1.25^{Ca}
Brachiaria/Livestock	11.43^{Ba}	7.69^{Aa}	4.56^{Cb}	4.06^{Ba}
Cerradão	18.00^{Aa}	7.70^{Aa}	10.97^{Aa}	15.10^{Aa}
CV(%)[3]	6.17	8.87	8.10	9.84
5-10 cm				
Pearl millet/No livestock	8.25^{Bb}	6.88^{Aa}	5.50^{Bb}	1.25^{Ca}
Brachiaria/Livestock	11.25^{Aa}	7.25^{Aa}	6.25^{Aa}	2.63^{Bb}
Cerradão	8.50^{Bb}	3.00^{Bb}	4.88^{Cb}	3.75^{Ab}
CV(%)[3]	4.71	8.87	7.00	5.87
10-20 cm				
Pearl millet/No livestock	8.88^{Bb}	2.97^{Bb}	5.13^{Ab}	1.25^{Ca}
Brachiaria/Livestock	10.88^{Aa}	4.00^{Ab}	3.75^{Cb}	2.63^{Bb}
Cerradão	8.75^{Bb}	3.50^{Ab}	5.25^{Ab}	3.75^{Ab}
CV(%)[3]	8.28	9.89	10.61	6.31
20-40 cm				
Pearl millet/No livestock	6.90^{Ac}	2.45^{Bb}	2.48^{Bc}	1.05^{Ba}
Brachiaria/Livestock	6.93^{Ab}	3.95^{Ab}	2.50^{Bc}	2.05^{Ab}
Cerradão	6.22^{Ac}	2.45^{Bb}	5.48^{Ab}	2.03^{Ab}
CV(%)[3]	6.84	9.33	9.23	8.34
CV(%)[4]	9.12	7.26	10.02	15.10

[1] The oxidizable organic carbon fractions correspond to the part of organic C oxidized by $K_2Cr_2O_7$ in acid solution with: F1: < 3 mol L^{-1} H_2SO_4; F2: between 6 and 3 mol L^{-1} H_2SO_4; F3: between 9 and 6 mol L^{-1} H_2SO_4; and F4: between 12 and 9 mol L^{-1} H_2SO_4. [2] Pearl millet/No livestock-based system: Sunflower/Pearl millet/Soybean/Corn. Brachiaria/Livestock-based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [3] Coefficient of variation between management systems, considering each oxidizable carbon fraction and depth. [4] Coefficient of variation between depths, considering each oxidizable carbon fraction and management systems. Means followed by the same uppercase letter not differ among the management systems and same lowercase letter not differ among depths (LSD-student test; $p < 0.05$).

an off-season corn crop, which can increase plant residue content (Table 3) and enhance TOC (Table 4) and carbon levels in the most labile SOM fractions (F1 and F2) (Table 5). In areas where plant residues provide organic matter input, an elevated carbon content is found in F1 and F2 fractions, with higher levels in F1 (Chan *et al*., 2001; Maia *et al*., 2007; Majumder *et al*., 2008; Rangel *et al*., 2008; Loss *et al*., 2009, 2011b). Thus, crops planted in the brachiaria/livestock system have the advantage of receiving highly-liable organic matter (easily decomposable organic matter), which improves physical and chemical properties of soil (Blair *et al*., 1995; Kolar *et al*., 2009; Loss *et al*., 2011a,b; Briedis *et al*., 2012a,b; Tirloni *et al*., 2012). Owing to root development, commercial crops planted under this system exhibit better water and nutrient absorption.

Overall evaluation found the *Cerradão* displayed higher carbon levels in the F3 (at 0-5 cm and 20-40 cm) and F4 fractions (at 0-5 cm, 5-10 cm and 10-20 cm) (Table 5). This was likely provoked by the accumulation of organic compounds of high chemical stability and high molecular weight, generated by SOM decomposition and humification in natural environments (Stevenson, 1994) and was evidenced by raised C – HUM levels in the 0-5 cm and 5-10 cm layers (Table 6). Similar results were recorded by Rangel *et al*. (2008).

The brachiaria/livestock system displayed higher carbon levels than the pearl millet/no livestock system in the F3 fraction at a depth of 5-10 cm, and in the F4 fraction at the other depths evaluated (Table 5). F3 and F4 are resistant fractions that last longer in soil (Stevenson, 1994; Chan *et al*., 2001). Therefore, when comparing cropping systems, it seems that the use of brachiaria grass in brachiaria/livestock system contributes to the production of high molecular weight and chemically stable substances, such as C – HUM and C – HAF. Corroborating this finding, greater C – HUM stocks (0-5 cm and 5-10 cm) and C – HAF stocks (0-5 cm, 5-10 cm and 10-20 cm) were also recorded in the brachiaria/livestock system (Table 7).

Overall, results of oxidizable carbon fractions indicated the brachiaria/livestock system had the highest carbon values in the F1, F2 and F4 fractions in comparison with the pearl millet/no livestock system (Table 5). Thus, the brachiaria/livestock system provides better carbon distribution among soil layers, with fractions of higher liability (F1 and F2) co-occurring with more resistant fractions (F4). The F1/F4 ratio (Table 8) found in brachiaria/livestock system samples was in fact close to that of the *Cerradão* (reference), showing the brachiaria/livestock system provides a more balanced carbon distribution between F1 and F4 fractions than pearl millet/no livestock system.

Table 6. Carbon levels (g kg^{-1}) in the humic fractions[1] of SOM soil under different management systems in Montividiu, Goiás, Brazil

Management system[2]	C–HUM	C–FAF	C–HAF
0-5 cm			
Pearl millet/No livestock	13.49^{Ca}	4.83^{Ba}	3.81^{Ca}
Brachiaria/Livestock	18.17^{Ba}	5.08^{Ba}	5.50^{Ba}
Cerradão	28.22^{Aa}	6.47^{Aa}	8.99^{Aa}
CV(%)[3]	9.69	9.93	9.89
5-10 cm			
Pearl millet/No livestock	12.55^{Bb}	4.95^{Aa}	3.76^{Ca}
Brachiaria/Livestock	12.63^{Bb}	4.49^{Ba}	5.07^{Aa}
Cerradão	15.29^{Ab}	4.99^{Ab}	4.33^{Bb}
CV(%)[3]	8.35	9.12	8.16
10-20 cm			
Pearl millet/No livestock	11.65^{Ac}	4.30^{Ba}	3.32^{Aa}
Brachiaria/Livestock	11.29^{Ac}	4.44^{Ba}	3.55^{Ab}
Cerradão	12.13^{Ac}	5.07^{Ab}	3.68^{Ac}
CV(%)[3]	15.20	10.16	14.59
20-40 cm			
Pearl millet/No livestock	10.58^{Ad}	4.17^{Aa}	2.29^{Ab}
Brachiaria/Livestock	10.19^{Ad}	4.07^{Aa}	2.35^{Ac}
Cerradão	8.23^{Bd}	3.89^{Ac}	2.01^{Bd}
CV(%)[3]	9.16	16.16	12.41
CV(%)[4]	7.25	11.23	8.01

[1] The humic fractions are: C-HUM, carbon in the humin fraction; C-FAF, carbon in the fulvic acid fraction and C – HAF, carbon in the humic acid fraction. [2] Pearl millet/No livestock based system: Sunflower/Pearl millet/Soybean/Corn. Brachiaria/Livestock based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [3] Coefficient of variation between management systems, considering each humic fraction and depth. [4] Coefficient of variation between depths, considering each humic fraction and management systems. Means followed by the same uppercase letter not differ among the management systems and same lowercase letter not differ among depths (LSD-student test; $p < 0.05$).

Regarding the depth factor, we found the same pattern for pearl millet/no livestock system and *Cerradão* for F1 with highest carbon content in 0-5 cm, decreasing with depth with the lowest values at 20-40 cm. Standard opposite was observed for brachiaria/livestock system, being checked at that depth (0-5 cm, 5-10 cm and 10-20 cm) no differences were observed in the increase of depth. Only at the depth of 20-40 cm we found lower values of F1 (Table 5). This indicates that

Table 7. Carbon stocks (Mg ha^{-1}) in the humic fractions[1] of SOM soil under different management systems in Montividiu, Goiás, Brazil

Management system[2]	C–HUM	C–FAF	C–HAF
0-5 cm			
Pearl millet/No livestock	4.64^{C}	1.66^{B}	1.31^{C}
Brachiaria/Livestock	6.24^{B}	1.75^{B}	1.89^{B}
Cerradão	9.71^{A}	2.22^{A}	3.08^{A}
CV(%)[3]	8.29	7.92	8.49
5-10 cm			
Pearl millet/No livestock	5.68^{C}	2.19^{A}	1.68^{C}
Brachiaria/Livestock	6.19^{B}	2.05^{A}	2.30^{A}
Cerradão	6.80^{A}	2.22^{A}	1.93^{B}
CV(%)	9.96	17.51	10.38
10-20 cm			
Pearl millet/No livestock	10.95^{A}	4.12^{B}	3.16^{B}
Brachiaria/Livestock	10.64^{A}	4.12^{B}	3.54^{A}
Cerradão	11.21^{A}	4.70^{A}	3.54^{A}
CV(%)	8.67	10.26	10.61
20-40 cm			
Pearl millet/No livestock	19.81^{A}	7.68^{A}	4.60^{A}
Brachiaria/Livestock	18.80^{A}	6.32^{B}	3.47^{B}
Cerradão	15.07^{B}	7.11^{A}	3.68^{B}
CV(%)	8.72	12.02	12.74
0-40 cm			
Pearl millet/No livestock	41.08^{A}	15.65^{A}	10.75^{B}
Brachiaria/Livestock	41.87^{A}	14.24^{A}	11.20^{B}
Cerradão	42.79^{A}	16.25^{A}	12.23^{A}
CV(%)	8.72	15.02	13.75

[1] The humic fractions are: C–HUM, carbon in the humin fraction; C–FAF, carbon in the fulvic acid fraction and C–HAF, carbon in the humic acid fraction. [2] Pearl millet/No livestock based system: Sunflower/Pearl millet/Soybean/Corn. Brachiaria/Livestock based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [3] CV: coefficient of variation. Means followed by the same letter in a column not differ among the areas evaluated (LSD-student test; $p < 0.05$).

it is more efficient to add carbon very easily labile in depth in the brachiaria/livestock system by means of fertilizers and crop rotation (Table 2) and the dry mass brachiaria (Table 3) compared to pearl millet/no livestock and *Cerradão* systems. And this is directly reflected in the larger TOC stocks (5-10 cm and 10-20 cm, Table 4) and nutrients stocks (Ca, Mg, P and K) found in all depths in the area of brachiaria/livestock system compared to other systems (Loss *et al*., 2012c).

The results of this study corroborate those of Briedis *et al*. (2012b), who found a linear relationship between TOC and particulate organic carbon, showing that 21% of TOC was due to the more labile fraction. The results of Briedis *et al*. (2012b) and those found in these studies indicate that the continuous input of residues in brachiria/livestock system increase the carbon of F1 in surface and depth.

For fraction F2, there was a similar pattern among the cultivated areas with higher concentrations of carbon in 0-5 cm and 5-10 cm, with decrease in carbon in 10-20 cm and 20-40 cm. For *Cerradão* area, there was a reduction of more abrupt carbon values of F2 in relation to the cultivated areas, with higher levels observed only in the surface layer (0-5 cm). These results indicate that for F2, cultivated areas are more efficient in adding carbon at greater depths (0-10 cm) when compared to *Cerradão* (0-5 cm). And, it is associated with greater efficiency in crop rotations (Table 2) and the dry mass production (Table 3) cultivated areas compared to *Cerradão*.

For fraction F3, it was found the same pattern for pearl millet/no livestock and *Cerradão* (higher carbon content in 0-5 cm and lower by 20-40 cm). As for the brachiaria/livestock system, met largest carbon values in 5-10 cm that 0-5 cm and 10-20 cm, with the lowest values found in 20-40 cm. This higher carbon content of F3 may be due to the addition of very easily oxidizable carbon (F1) in depth, which favors the formation of larger carbon moderately labile (F3) in the 5-10 cm depth in the brachiaria/livestock system (besides the use of livestock, which also adds carbon via the addition of cattle faeces on the soil surface, improving the environment chemically, and therefore, altering the physical and biological attributes, which favors the uptake of carbon in depth) compared to the others.

For fraction F4, we found no differences for pearl millet/no livestock in depth, differing from other systems that had higher levels of carbon in the F4 in 0-5 cm, and decreased for the other depths. These results indicate that the pearl millet/no livestock system favors only the increment of very labile carbon (F1 and F2) and moderately labile (F3), while brachiaria/livestock system and *Cerradão*, both favoring the input of labile carbon (F1 and F2) as recalcitrant carbon (F3 and F4). This result, for the *Cerradão* area would be expected as it is a natural system without human interference, indicating that there is a natural balance of labile and recalcitrant. And among the agricultural systems, which is closest to this situation is the brachiaria/livestock system, which is evidenced by the standard F1/F4 index (Table 8), where the brachiaria/livestock

Table 8. Relationship between carbon in the humic substances[1] and in oxidizable fractions[2] (F1 to F4) of soil under different management systems in Montividiu, Goiás

Management system[3]	C–HAF/ C–FAF	AE[4]/ C–HUM	F1/F4	F1 + F2/ F3 + F4
0-5 cm				
Pearl millet/No livestock	0.79^{C}	0.64^{A}	8.40^{A}	1.82^{A}
Brachiaria/Livestock	1.08^{B}	0.58^{A}	2.82^{B}	2.22^{A}
Cerradão	1.39^{A}	0.55^{A}	1.19^{C}	0.99^{B}
CV(%)[5]	6.35	10.95	4.49	8.57
5-10 cm				
Pearl millet/No livestock	0.76^{B}	0.69^{A}	6.60^{A}	2.24^{A}
Brachiaria/Livestock	1.13^{A}	0.76^{A}	4.28^{B}	2.08^{A}
Cerradão	0.87^{B}	0.61^{A}	2.27^{C}	1.33^{B}
CV(%)	7.23	11.56	5.62	6.54
10-20 cm				
Pearl millet/No livestock	0.77^{A}	0.65^{A}	7.10^{A}	1.86^{AB}
Brachiaria/Livestock	0.80^{A}	0.71^{A}	4.14^{B}	2.33^{A}
Cerradão	0.73^{A}	0.72^{A}	2.33^{C}	1.36^{B}
CV(%)	6.50	6.23	5.55	8.62
20-40 cm				
Pearl millet/No livestock	0.55^{A}	0.61^{A}	6.57^{A}	2.65^{A}
Brachiaria/Livestock	0.58^{A}	0.61^{A}	3.38^{B}	2.39^{A}
Cerradão	0.52^{A}	0.72^{A}	3.06^{B}	1.15^{B}
CV(%)	6.96	8.21	8.12	9.12

[1] The humic fractions are: C-HUM, carbon in the humin fraction; C-FAF, carbon in the fulvic acid fraction and C-HAF, carbon in the humic acid fraction. [2] The oxidizable organic carbon fractions correspond to the part of organic C oxidized by $K_2Cr_2O_7$ in acid solution with: F1: < 3 mol L^{-1} H_2SO_4; F2: between 6 and 3 mol L^{-1} H_2SO_4; F3: between 9 and 6 mol L^{-1} H_2SO_4; and F4: between 12 and 9 mol L^{-1} H_2SO_4. [3] Pearl millet/No livestock based system: Sunflower/Pearl millet/Soybean/Corn. Brachiaria/Livestock based system: Corn/Brachiaria grass/Bean/Cotton/Soybean. [4] AE: alkaline extract. [5] CV: coefficient of variation. Means followed by the same letter in a column do not differ among the areas evaluated (LSD-student test; $p < 0.05$).

system values were closer to *Cerradão* compared to pearl millet/no livestock, at all depths.

Carbon levels and carbon stocks in the humic soil organic matter fractions

The largest carbon concentration in humic substances at depths of 0-5 cm was observed in the *Cerradão* area (Table 6), as with TOC stocks (Table 4). The formation of humic substances in natural environments is related to microbial activity (Machado & Gerzabeck, 1993) and humification over time is therefore a final product of microbiological processes.

With regard to cropped areas at 0-5 cm, the brachiaria/livestock system had the highest C-HUM and C-HAF levels. C-HAF levels were also greater at 5-10 cm in the brachiaria/livestock system (Table 6). These results may be due to the use of brachiaria grass, which produces plant residues with a high C/N ratio. Moreover, slower decomposition of brachiaria/livestock residues raises C-HAF production. Similar results were reported by Rossi *et al*. (2011).

Variations in humic substance composition in no-tillage soils are caused by microbial activity (Machado & Gerzabeck, 1993). Lack of soil turnover favors humification, the formation of molecules of high molar mass and, therefore, natural condensing and prevalence of C – HAF in soil (Slepetiene & Slepetys, 2005).

The dynamics of SOM humic fractions can be explained as a function of Ca content since this element forms Ca-humate, which plays an important stabilization role (Oades, 1988; Correa *et al*., 2003). Applying a brachiaria/livestock system raises Ca levels and stocks (6.12, 5.61, 2.75 and 1.55 $cmol_c$ dm^{-3}, respectively for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm in brachiaria/livestock; 4.46, 3.68, 1.01 and 0.96 $cmol_c$ dm^{-3}, respectively for 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm in pearl millet/no livestock (Loss *et al*., 2012c)), increasing the content of more stable humic complexes (Fernandes *et al*., 1999). In fact, C – HAF (0-5 cm and 5-10 cm) and C – HUM (0-5 cm) levels were higher under brachiaria/livestock than pearl millet/no livestock (Table 6).

The highest C – FAF levels were found in pearl millet/no livestock at 5-10 cm. Compared to C – HAF, C – FAF has lower molecular weight and higher mobility in soil, favored by greater plant residue intake and, as a result, a higher humification tendency. In the pearl millet/no livestock, besides absence of livestock, lower dry matter production (Table 3) and lower Ca levels and stocks (Loss *et al*., 2012c) may compromise C – HAF formation, promoting a relative rise in C – FAF. Similar results were found by Rossi *et al*. (2011).

In relation to C – HUM levels, these were higher under brachiaria/livestock than pearl millet/no livestock at 0-5 cm, but not at other depths (Table 6). Since the humin fraction corresponds to nearly 70% of TOC, this may be a result of higher TOC stocks in brachiaria/livestock at 0-5 cm. In other soil layers, although brachiaria/livestock exhibited greater TOC than pearl millet/no livestock (Table 4), C – HUM levels were similar between these areas, suggesting that the conservative cropping provided by both systems promotes soil humification, particularly at 20-40 cm. Furthermore, cropped areas have larger C – HUM and C – HAF levels compared to the *Cerradão* (Table 6).

As observed for TOC stocks, similarity in humic fractions between cropped areas shows that the crop rotation used in both systems induces similar increases in carbon as in humic substances in subsurface soil layers. Root systems of brachiaria/livestock and pearl millet/no livestock may account for this result.

Regarding the depth factor, for C – HUM, all systems evaluated showed the same pattern, with values of C – HUM decreased with increasing depth. Indicating that regardless of the evaluated system, the addition of plant residues from crop rotation (Table 2) and the dry mass of cover crops in cultivated areas and litter in *Cerradão* (Table 3), favoring greater interaction with the mineral fraction and organic fraction in the surface layer. Thus, leads to higher concentrations of C – HUM, which has a greater chemical stability and less variation in depth, as other studies have reported (Stevenson, 1994; Fontana *et al*., 2006; Benites *et al*., 2010; Loss *et al*., 2010; Rossi *et al*., 2011; Pereira *et al*., 2012).

For C-FAF, it was found that among the cultivated areas were not observed variations in carbon content of this fraction with respect to depth factors. This differ from the *Cerradão* area, which had higher levels of C – FAF in 0-5 cm, with a decrease in the levels of depth, with the lowest values at 20-40 cm. In cultivated areas, the lack of differences in depth may result from the migration of organic acids of low molecular weight (*i.e.,* citric, malic, oxalic and tartaric acid; as Franchini *et al*., 2003), which favor the migration of C – FAF in depth, due to its greater mobility (Stevenson, 1994), resulting in a homogenization of the levels of C – FAF between the cultivated areas. In the *Cerradão* area, the contribution of more lignified plant material (litter), derived mainly from leaves and twigs of trees, probably through its decomposition, should release smaller amounts of organic acids of low molecular weight. This larger pattern in surface is due to the accumulation of plant material, with a decrease in depth, as seen in Table 6.

Similar pattern to that seen for the C – FAF was observed for C – FAH between the evaluated systems. In the *Cerradão* area, there were differences between all depths, with higher values observed at 0-5 cm and smaller values in 20-40 cm. As for the cultivated areas, there were only differences in depth (10-20 cm and 20-40 cm). This pattern demonstrates that the levels of C – FAH are highly dependent on the addition of plant residues, indicating that cultivated areas, exploitation of soil associated with the roots homogenize the contents of C-FAH on 0-5 cm and 5-10 cm, differing from *Cerradão* area where the vegetable supply is associated with the soil surface (0-5 cm) with drop sharp in depth, as shown in Table 6. These results are similar to studies by Rossi *et al*. (2011) and Pereira *et al*. (2012), both working in the *Cerrado* soils and crop rotation, including millet, sorghum and brachiaria.

The highest differences for C – HUM stocks were found in the *Cerradão* at depths of 0-5 cm and 5-10 cm, but at 20-40 cm this site had lower differences for C – HUM stocks than the cropped systems. No differences among the areas were detected in the 0-40 cm layer (Table 7). The *Cerradão* displayed the highest TOC stocks at 0-5 cm (Table 4), C – HUM levels at 0-5 cm and 5-10 cm (Table 6) and carbon levels in the F4 fraction (Table 5). This result for C – HUM stocks is expected given that the humin fraction (nearly 70% of soil TOC) is associated with the most stable and recalcitrant SOM forms, such as the F4 fraction.

Compared to pearl millet/no livestock, the brachiaria/livestock had the largest C – HUM stocks at 0-5 cm and 5-10 cm and C – HAF at 0-5 cm, 5-10 cm and 10-20 cm (Table 7). This is due to high stocks of TOC (Table 4) and Ca (Loss *et al*., 2012c) produced by corn intercropping with brachiaria/livestock, which favors the incorporation of plant residues with a high C/N ratio. The slow decomposition rate of residues in the brachiaria/livestock is more effective than pearl millet/no livestock in promoting the formation and stabilization of carbon as humin and humic acid.

The greatest C – FAF stocks were observed in the *Cerradão* at depths of 0-5 cm and 10-20 cm and at 20-40 cm, these stocks were higher in the *Cerradão* and pearl millet/no livestock than brachiaria/livestock (Table 7). Among humic substances, FAF is the fraction of highest mobility in soil (Stevenson, 1994) and can therefore be carried to the deepest soil layers.

At 20-40 cm, C – FAF and C – HAF stocks were larger under pearl millet/no livestock than brachiaria/livestock, likely because of pearl millet planted as coverage in August under pearl millet/no livestock to prepare for soybean planting in October. Because pearl millet has a well-developed root system reaching more than 2.0 m deep, it can extract nutrients at depth, recycling substances that are not absorbed by annual crops with shorter roots (Foy, 1997). In addition, according this author, carbon is incorporated into deep soil layers as the root system of pearl millet is decomposed, thereby increasing the humic fraction at depth in a higher proportion than in the brachiaria/livestock.

Despite the differences described, stocks of carbon as humic substances in the 0-40 cm layer were similar between cropped areas (Table 7). Thus, both grasses (brachiaria and pearl millet) used to increase straw production under no-till, direct planting, are equally efficient at forming carbon stocks and humic substances up to depths of 40 cm. Moreover, these grasses can recover the original stocks of soil C – HUM in areas cropped for over 17 years. In the 0-40 cm layer, C – HUM levels in these areas are the same of those in the natural *Cerradão* area.

Relationship between carbon in humic substances and oxidizable carbon fraction

Analysis of ratios between humic substances (Table 8) shows that HAF/FAF was higher in the *Cerradão* at 0-5 cm, but was similar to the pearl millet/no livestock at 5-10 cm. When comparing cropped locations, the brachiaria/livestock demonstrated a larger C – HAF/C – FAF ratio at depths of 0-5 cm and 5-10 cm. At 5-10 cm, it was also higher under brachiaria/livestock than in the *Cerradão*.

The high C – HAF/C – FAF ratio indicates C – HAF prevalence over C – FAF, especially in the brachiaria/livestock, caused by a greater input of plant residue due to corn intercropping with brachiaria grass (Table 3). This increases humification and C – HAF stabilization owing to transformation of the plant residues deposited in the soil in the brachiaria/livestock. In the surface (0-5 cm) layer, this pattern is also observed in the *Cerradão* since high TOC (Table 4) are produced by the substantial litter input provided by the natural coverage.

Higher proportions of C – HAF compared to C – FAF are indicative of soil preservation by conservative management (Canellas *et al*., 2003). In this sense, the brachiaria/livestock was more efficient in maintaining C – HAF levels when compared to pearl millet/no livestock, as corroborated in the present study by higher C – HAF levels in the brachiaria/livestock (Table 7). Similar results were found by Fontana *et al*. (2006).

At depths of 10-20 cm and 20-40 cm, management systems had similar HAF/FAF ratios, likely because C – HAF and C – FAF levels at these layers are close (Table 8). With regard to the AE/HUM ratio, no differences were observed among treatments at any soil depth. This pattern indicates a balance in distribution of humic fractions between the cropped areas and the *Cerradão*.

F1 and F4 correspond to the more labile and more recalcitrant (persistent) SOM fractions, respectively. F2 and F3 are intermediary, with F2 closer to F1 and F3 closer to F4. Low F1/F4 values that are close to 1.0 therefore indicate better distribution of C levels in the most labile and recalcitrant soil fractions. In this context, *Cerradão* soil had the best carbon distribution (lower F1/F4 ratio) up to 10-20 cm. In cropped areas, the brachiaria/livestock showed smaller F1/F4 values compared to pearl millet/no livestock (Table 8) at all the depths evaluated. This pattern indicates that the brachiaria/livestock provides a better distribution of labile and recalcitrant carbon forms compared to pearl millet/no livestock. The brachiaria/livestock has greater F1 than F4 content, promoting a higher F1/F4 ratio, as illustrated in Table 8.

In relation to the F1 + F2/F3 + F4 ratio, the best oxidizable carbon distribution was recorded in the *Cerradão* at all depths analyzed, reaching values close to 1.0 (Table 8). This indicates that areas preserved from anthropic interference achieve more balanced distribution of oxidizable carbon fractions. The F1 + F2/F3 + F4 ratio was greater in cropped areas than the *Cerradão* and did not differ between pearl millet/no livestock and brachiaria/livestock. In cropped sites, carbon content was higher in F1 + F2 than F3 + F4 fractions (Table 5). As such, these areas have a greater input of high liability materials (plant residues). Moreover, higher carbon levels in the most labile soil fractions are a result of the type of management (pearl millet/no livestock and brachiaria/livestock) combined with crop rotation. Both management systems provide constant plant input into soil which (Table 3), in conjunction with chemical fertilization (Table 2), accounts for the higher nutrient stocks in these areas (Loss *et al*., 2012c) than in the *Cerradão*. Similar results were recorded by Barreto *et al*. (2011).

The F1/F4 and HAF/FAF ratios enabled identification of differences in the chemical quality of SOM according to areas evaluated. Brachiaria/livestock promoted the most balanced distribution of the labile (F1) and recalcitrant (F4) carbon forms throughout soil layers especially compared to pearl millet/no livestock.

As conclusions, the brachiaria/livestock based system, associated with crop and fertilization, increased TOC stocks, as well as stocks C – HUM and C – HAF (0-5 cm and 5-10 cm) when compared to the pearl millet/no livestock based system. The use of brachiaria in the livestock system and pearl millet in the no livestock system, both serving as coverage to increase straw production for direct planting, was equally efficient in relation to carbon stock in humic substances up to depths of 40 cm. In addition, after 17 years of land management, these plants replenished C – HUM to original soil stocks at a layer of 0-40 cm.

The brachiaria/livestock based system provided more balanced distribution of labile (F1) and recalcitrant carbon (F4) in soil layers and higher SOM humification than pearl millet/no livestock based system. Within the fractions evaluated, C – HAF stocks and oxidizable carbon were the most reliable to differentiate soil dry matter quality. The brachiaria/livestock system leads to higher values of F1 and F4 in depth when compared to pearl millet/livestock system and provides a more homogeneous distribution of fractions C-FAF and C – HAF in depth compared to *Cerradão*.

The brachiaria/livestock system increases TOC stocks, C – HUM and C – HFA stocks, oxidizable carbon and also leads to higher grain yield (Table 3). Thus, it can be concluded that brachiaria/livestock system is a solution to the climatic conditions of the Cerrado (wet-dry savannah), producing straw enough for a no-tillage system efficient and sustainable.

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