HUMIC SUBSTANCES AND PHOSPHORUS FRACTIONS IN AREAS WITH CROP-LIVESTOCK INTEGRATION, PASTURE AND NATURAL CERRADO VEGETATION IN GOIÁS, BRAZIL

[SUSTANCIAS HUMICAS Y FRACCIONES DE FÓSFORO EN ÁREAS CON INTEGRACIÓN CULTIVO-GANADERÍA, PASTURA Y VEGETACIÓN NATURAL DE "CERRADO" EN GOIÁS, BRAZIL]

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SUMMARY

Crop-livestock integration (CLI) coupled with a no-till planting system (NTS) has proven to be an important alternative farming system, promoting efficient land use and soil conservation by maintaining soil organic matter (SOM). The present study quantified the humic fractions of SOM and soil P fractions and analyzed their relationship in CLI, pasture and natural Cerrado areas in Goiás, Brazil. The samples were obtained from a pasture area (covered with *Urochloa decumbens* grass for 15 years); a CLI area (planted in annual rotation with *Urochloa ruziziensis* for 13 years); and a native Cerrado area, sampled for comparison purposes. Total organic carbon (TOC) and carbon in the fulvic acid fraction (C-FAF), humic acid fraction (C-HAF) and humin (C-HUM) were evaluated at a depth of 0-5; 5-10; 10-20 and 20-40 cm; and inorganic (IP) and organic (OP) P fractions at a depth of 0-5 and 5-10 cm. The highest TOC values, humic fractions and OP were found in the Cerrado area. Similarities in relation to the humic fractions and TOC were found between CLI and pasture areas in all the layers between 0 and 40cm. The area currently managed with CLI, but originally covered by Cerrado, had already developed chemical stability (C-FAF, C-HAF, C-HUM and TOC) that was similar to that found in the Cerrado area at a depth of 20-40 cm and with higher C-FAF and C-HUM accumulation compared to the pasture area. Compared to pasture and Cerrado, the CLI system favored the increase in labile, moderately labile and moderately resistant P, both for total P (TP) and IP. IP fractions were found in areas treated with high doses of phosphate fertilizer, whereas OP fractions corresponded to those under low or null anthropogenic influence. Organic P fractions were directly related to the humic SOM fractions.

Keywords: organic carbon; humin; humic and fulvic acids; organic and inorganic phosphorus; crop rotation.

RESUMEN

La integración cultivo-ganaderia (CLI) con sistemas sin labranza (NTS) han probado ser una alternativa importante de sistema de producción que promueve el uso eficiente de la tierra y conservación del suelo al mantener materia orgánica (SOM). El presente trabajo cuantificó las fracciones húmicas de SOM y P del suelo y su relación con CLI, pastura y vegetación natural del cerrado en Goiás, Brazil. Las muestras fueron obtenidas de un área de pastura (cubierta de Pasto *Urochloa decumbens* por 15 años), un área de CLI (rotación annual con *U. ruziziensis* por 13 años) y un área de Cerrado native que fue muestreada para próposito de comparación. El carbono orgánico total (TOC) y carbón en la fracción de ácido fulvico (C-FAF), ácido húmico (C-HAF) y humin (C-HUM) fueron evaluados a una profundidad de 0-5; 5-10; 10-20 y 20-40 cm; y las fracciones de P inorgánico (IP) y orgánico (OP) a una profundidad de 0-5 y 5-10 cm. El valor más alto de TOC, fracciones húmicas y OP fueron encontradas en el área de Cerrado. Se encontró similitudes entre CLI y áreas de pastura en todas las capas entre 0 y 40 cm. El área actualmente manejada con CLI pero originalmente cubierta por Cerrado ha alcanzado estabilidad química con valores (C-FAF, C-HAF, C-HUM y TOC) similiares a los encontrados en el Cerrado a 20-40 cm y con una mayor acumulación de C-FAF y C-HUM accumulation comparada con el área de pastura. Comparada con el área de pastura y Cerrado, el sistema CLI favorece el incremento de P lábil, moderadamente lábil y moderadamente resistente para TP e IP. Se encontró fracciones de IP en áreas tratadas con altas dosis de fertilización con fosfato, mientras que la fracción OP correspondió a zonas con baja o nula influencia antropogénica. Las fracciones de P fueron directamente relacionas con las fracciones de SOM.

Palabras clave. Carbón orgánico; ácidos húmico y fúlvico; fósforo orgánico e inorgánico; rotación de cultivo.

INTRODUCTION

The Cerrado is the second largest biome in Brazil, occupying nearly 204.7 million hectares, corresponding to approximately 24 % of the country's area (IBGE, 2004; Sano et al., 2007). It is located in the central region of Brazil and exhibits the second largest biodiversity in the world (Mittermeier et al., 2005). The Cerrado is currently an important farming area, and in the states of Bahia, Mato Grosso and Goiás it is predominantly occupied with crops such as soybean, corn, bean, cotton and sugarcane (Sano et al., 2008; Siqueira Neto et al., 2010; Loss et al., 2011; Pacheco et al., 2012).

Approximately 97% of Goiás belongs to the Cerrado biome (IBGE, 2004), and 55% of its territory is used for agricultural and urban purposes (Sano et al., 2008). With respect to the areas under land use, 27.7% are planted with commercial crops, 71 % with pasture and the remainder are occupied by forest crops and urban areas. Of the 66 million hectares (Mha) used for pasture cropping in the Cerrado (Sano et al., 2006), more than 50 Mha are estimated to undergo degradation because of excessive livestock grazing (Klink et al., 2008).

In the environment described, crop-livestock integration (CLI) has gained attention as an alternative agricultural system, and coupled with a no-till planting system (NTS), increases the sustainability of systems for grain and meat (especially beef) production (Balbinot et al., 2009; Carvalho et al., 2010; Loss et al., 2012a). The CLI system associates the growth of annual crops and herbage species, especially brachiaria grass, over cropland with partial or complete soil correction (Balbinot et al., 2009; Salton et al., 2011; Pacheco et al., 2012; Loss et al., 2012a,b).

Grasses of the genus *Urochloa* (brachiaria) are the main herbage grown as pasture crop in the Midwest of Brazil because they adapt well to soil and climatic conditions, exhibit high phytomass production, are relatively easy to remove and do not serve as host for the main crop pathogens (Kluthcouski et al., 2003).

The CLI-NTS association deserves attention in the context of demands for food production and environmental preservation (Kluthcouski et al., 2003; Landers, 2007; Balbinot et al., 2009), especially in areas that are vulnerable to degradation because it allows the maintenance and/or improvement of physical, chemical and biological properties of soil (Maughan et al., 2009; Loss et al., 2011; Muniz et al., 2011; Tirloni et al., 2012). Earlier studies (Fontana et al., 2006; Franzluebbers and Stuedemann, 2008; Marchão et al., 2009; Carvalho et al., 2010; Fernadez et al., 2011; Loss et al., 2012a,b) discussed the NTS-CLI association in crop rotation systems. Nevertheless, many aspects have yet to be elucidated, particularly concerning the dynamics of humic SOM fractions and phosphorus fractions in CLI systems.

Carbon dynamics in the humic fractions has been used in SOM evaluation to explain pedogenesis (Fontana et al., 2011), improvement in physical soil properties (Loss et al., 2010), decrease in phosphorus fixation (Fontana et al., 2008) and changes in land use (Nadi et al., 2012; Vergnoux et al., 2011; Benites et al., 2010; Loss et al., 2013).

The dynamics of phosphorus (P) fractions, in turn, is much more complex and depends on a number of intrinsic soil factors such as texture (Viegas et al., 2010; Tokura et al., 2011), management system (Garcia et al., 2007; Pavinato et al., 2009; Pereira et al., 2010), chemical and organic fertilization (Gatiboni et al., 2007; Tirloni et al., 2009; Pavinato et al., 2010; Cereta et al., 2010; Guardini et al., 2012) and environmental (biotic and abiotic) factors (Fernandez et al., 2008; Resende et al., 2011).

Agricultural systems such as CLI, which seeks the maintenance of plant cover with minor soil turnover, can modify the dynamics of humic SOM fractions (Loss et al., 2013) and P fractions (Matos et al., 2006; Gatiboni et al., 2007; Guardini et al., 2012). In this respect, the present study tests the hypothesis that the CLI system increases or maintains the humic SOM and soil P fractions in relation to well managed pasture under heavy grazing and natural Cerrado areas. To that end, we quantified the humic SOM and soil P fractions in areas under CLI, pasture and Cerrado in Goiás and correlated these variables.

MATERIALS AND METHODS

Study Area Location and History

The study was carried out in Montividiu, Goiás, on the *Vargem Grande* farm, which belongs to the *Agropecuária Peeters* Company (*Rio Verde* Macroregion). Soil samples were collected in 3 areas: crop rotation under NTS+CLI for 13 years (17º 19' 35.5" S and 51º 29' 29.7" W, 961 m altitude); a pasture area cropped with *Urochloa decumbens* Stapf for 15 years (17º 22' 04.5" S and 51º 29' 52.7" W; 946 m altitude); and a natural, intact Cerrado area (17º 22' 12.2" S and 51º 29' 49.8" W; 942 m altitude) used as reference.

The Rio Verde region of Montividiu has annual rainfall of approximately 1700 mm, average mean temperature of 22.5 ºC and very distinct rainy and dry seasons (EMBRAPA/CNPM, 2011). The lowest rainfall rates are recorded from May to September, and the highest from December to March. Soil in the study area is Oxisol (Soil Survey Staff, 2006) with clayey texture (*Latossolo Vermelho Distrófico*; Embrapa, 2006), and its attributes in the 0-20 cm layer are shown in Table 1.

The cropland, first occupied by native Cerrado vegetation (Cerradão), had been used for farming for 26 years (since the 1984/85 crop) until it was planted with brachiaria grass (*Urochloa decumbens* Stapf) as herbage for beef cattle for 10 years (1984/85 to 1993/94). After this period, it was planted with commercial crops, in a rotation system, associated to CLI for 16 years (1994/95 to 2009/10), with conventional soil management (CTS) in the first 3 years (1994/95 to 1996/97) and NTS-CLI with crop rotation in the last 13 years (1997/98 to 2009/10) (Figure 1).

The CLI area, managed with crop rotation, was planted with soybean in the summer (October to February) and corn as an off-season crop (February to June). *Urochloa ruziziensis* (Germain et Evrard), was sowed with the off-season crop to increase straw production and served as herbage for beef cattle grazing in the dry season (June to September), thereby composing a CLI system (Figure 1).

After the 2007/2008 crop, other cultures were introduced into the rotation system. Cotton was cropped from November 2007 to August 2008. In 2008/2009, soybean was cropped, and off-season corn planted with *Urochloa ruziziensis* to enhance straw production and allow beef cattle grazing in the dry season (CLI season). In 2009/2010, beans were grown from September to December, and cotton from December 2009 to August 2010. Soil samples were taken during the cotton crop, in April 2010. It is important to note that off-season corn crops were associated to brachiaria grass between the rows, and both crops were sowed simultaneously.

The pasture area was exclusively planted with *Urochloa decumbens* Stapf., established for 15 years (since 1995). It had been covered by native vegetation (Cerradão) until 1990/91, when it was used for rice and soybean cropping under CTS for 5 years (1990/91 to 1994/95 crop) (Figure 1). During this period, the area received the last applications of mineral fertilizer and limestone. After pasture establishment, fertilizers and soil amendments were no longer applied. In the grazing period, stocking density was approximately 1.4 animal units (AU) ha^{-1}, always avoiding over-stocking.

Table 1. Chemical characterization of soil[1] sampled at 0-20 cm in CLI, pasture and Cerrado areas in Montividiu, Goiás.

Area	pH H_2O (1:2.5)	Ca	Mg	K	H+Al	Al	P_{Avl}
		---------- $cmol_c$ kg^{-1} ----------					mg kg^{-1}
Pasture	4.87	2.41	3.68	0.08	8.23	0.00	3.00
CLI	5.24	2.10	4.73	0.11	7.92	0.00	7.00
Cerrado	4.07	1.39	2.41	0.09	12.71	0.46	1.33

[1]According to Embrapa (1997)'s method. CLI: crop-livestock integration. Sodium (Na) levels were 0 (zero) in all the areas and depths; Ca: exchangeable calcium; Mg: exchangeable magnesium; K: exchangeable potassium; H+Al: exchangeable hydrogen + aluminum; Al: exchangeable aluminum; P_{Avl}: available phosphorus.

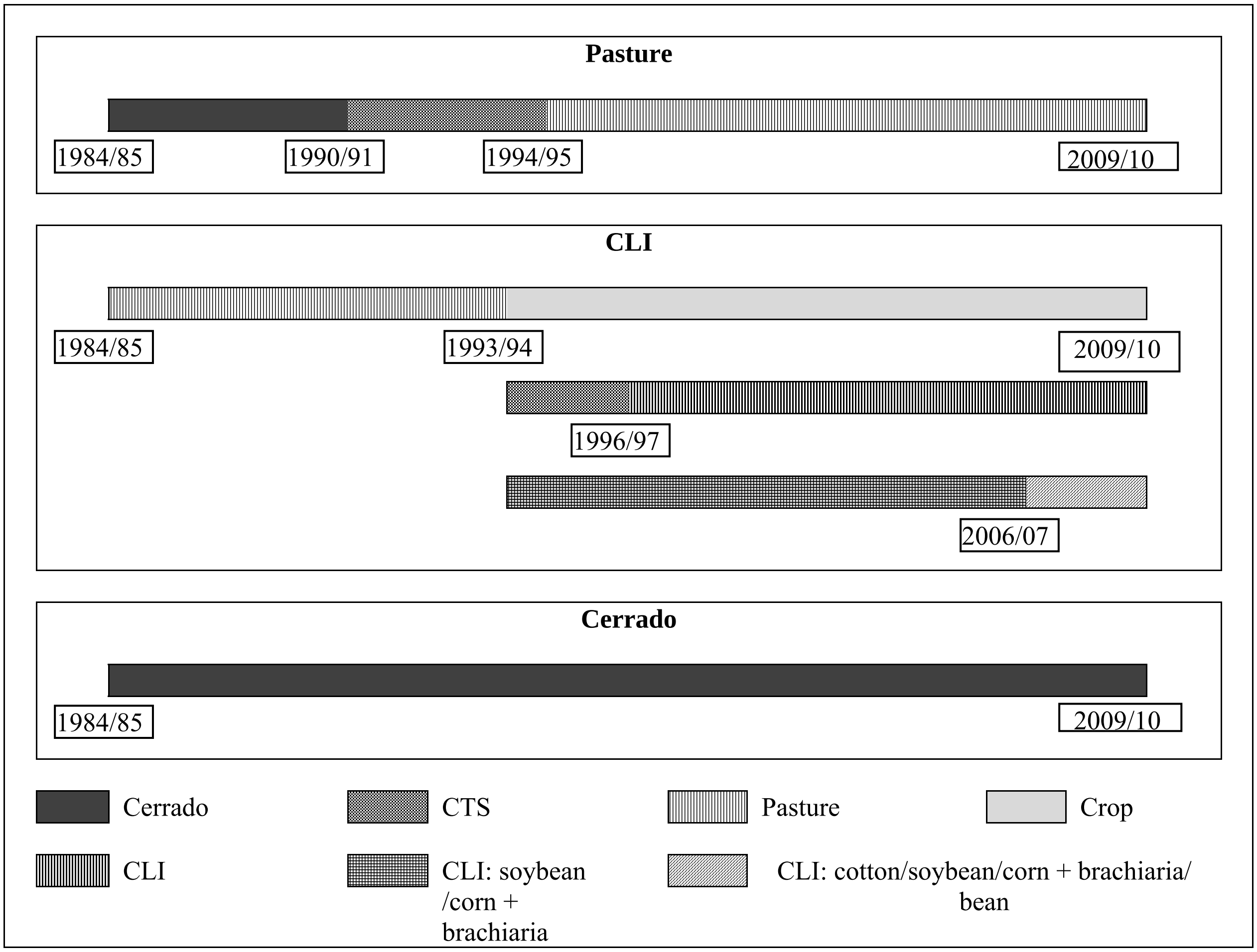

Figure 1. History of land use in the different areas evaluated in Montividiu, GO. CLI: crop-livestock integration; CTS: conventional soil management.

The Cerrado (Cerradão) area was sampled to compare it with pasture and CLI areas, serving as a reference to discuss the values recorded in the anthropogenic areas. Cerradão is composed of a wood layer, with the main stratum containing 8 to 15m trees and a crown cover of 50 to 90%. The shrubby layer is usually well defined, measuring between 2 and 5m high. Although the wood vegetation represents the main Cerradão stratum, less shaded areas are covered by herbaceous plants (Ribeiro and Walter, 1998).

In the CLI area, the same fertilization protocol was repeated over the years, except for the dosage, which was specific to each crop, as follows:

- Soybean: 360 kg ha^{-1} 2:20:18 + 20 g ha^{-1} Mo + 6 g ha^{-1} Co (at planting);
- Corn + brachiaria: 320 kg ha^{-1} 08:20:20 + 0.6 % Zn (at planting) + 60 kg ha^{-1} N nearly 40 days after corn emergence;
- Bean: 400 kg ha^{-1} 05:20:10 (at planting) + 40 kg ha^{-1} N nearly 28 days after emergence;
- Cotton: 550 kg ha^{-1} 10:30:10 (at planting) + 200 kg ha^{-1} 20:00:20 nearly 40 days after emergence.

The last limestone application was performed in 2007, with 3.0 Mg ha^{-1} dolomitic limestone, at 82 % total neutralization power (TNP), to increase base saturation to 60 %.

By the last crop, the average productivity observed in the CLI area was 3,840 kg ha^{-1} for soybean, 5,922 kg ha^{-1} for off-season corn intercropped with brachiaria grass, 2,520 kg ha^{-1} for bean and 4,680 Kg ha^{-1} for cotton.

After cotton harvesting, cattle grazed in the area from July to September, making use of corn residues and brachiaria grass for nearly 70 days. Stocking density at this period was nearly 3.0 AU ha^{-1} (1 AU = 450 kg animal). The cattle tested were a beef breed (Nelore) (300 to 350 kg live weight), which corresponded to 4 to 5 animals/ha (1,350 kg ha^{-1}). Only clumps of brachiaria remained in the area after cattle were removed. During the first rainfall events, in the first two weeks of September, the brachiaria crop received NPK (20:00:20) top dressing at 200 kg ha^{-1}. Following resprouting, when the area was fully covered, the grass was thinned and the new rotation crop planted (Figure 1).

Sample collection and analysis

The areas under the different soil use systems (pasture, CLI and Cerrado) featured similar topography (flat land), soil (clayey texture) and were exposed to the same climatic conditions, differing only in terms of land use. Soil and plant residues were sampled in April 2010. Were opened five trenches in all areas. Across the planting rows of 600 m^2-plots in the areas under CLI to collect soil samples. In the pasture area, cattle grazing sites were avoided, and in the Cerrado we sampled soil from the central area of the fragment. Soil samples were collected at depths of 0–5 cm; 5–10 cm; 10–20 cm and 20-40 cm, in triplicate for each layer, producing a composite sample with five repetitions in each layer. Litter in the Cerrado and crop residues in pasture and CLI areas were collected using a 0.50 x 0.50 m (0.25 m^2) metal frame, with 5 repetitions.

Total organic carbon (TOC) was determined by dry combustion at 900 ºC with a C autoanalyzer (CHN-600 Carlo Erba EA-1110, Italy) at the Laboratory of Isotopic Ecology, CENA (Center for Nuclear Energy in Agriculture), in Piracicaba, São Paulo state. The humic substances were fractioned into fulvic acid fraction (FAF), humic acid fraction (HAF) and humin (HUM) using the differential solubility technique, 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 and Bremner (1988).

Total organic and inorganic P fractions were determined as proposed by Bowman (1989). The labile fractions were determined by extraction with 0.5 mol L^{-1} sodium bicarbonate at 8.5 pH, as described by Bowman and Cole (1978a) and adapted by Duda (2000).

Statistical Analysis

The study had a completely randomized design evaluating 3 areas (pasture, CLI and Cerrado). Data were subjected to Lilliefors' test to evaluate distribution normality and Cochran and Barttlet's test to test variance homogeneity. Data were then analyzed using the ANOVA F-test, and statistically different means at 0.05 error probability were contrasted by Tukey's test. Analyses were performed using the SAEG statistical package (2007). In addition, Pearson's correlation was performed to test the dependence between humic SOM and P fractions, using the t-test at a significance level of 0.05.

RESULTS AND DISCUSSION

Total organic carbon and humic SOM fractions

TOC profile at depths of 0-5 and 5-10 cm was similar among the areas evaluated. TOC was higher in Cerrado than in pasture and CLI areas, and the last two did not differ from each other (Table 2). The TOC values found are close to those reported by Fonseca et al. (2007) in top layers of soil planted with brachiaria in a no-till system or covered by native vegetation. These authors observed that the Cerrado area and the area planted with beans/corn+brachiaria/beans in a rotation system exhibited TOC levels of 62.9 and 33.6 g kg^{-1} at a depth of 0-2.5 cm and 37.7 and 24.7 g kg^{-1} at 15-17.5 cm, respectively.

Except for the 10-20 cm layer, TOC was stable in the CLI system, since it was similar to that found in pasture areas, which are considered to have highly stable carbon dynamics if well managed (Corraza et al., 1999; Fontana et al., 2006; Salton et al., 2008). One noteworthy aspect is that the pasture area studied had been formed for 15 years and managed with an adequate grazing system in order to avoid excessive pasture use.

The highest TOC levels were recorded in the top (0-5 and 5-10 cm) and subsurface (10-20 cm) layers of the Cerrado area (Table 2), likely because of microclimate stability under tree canopy, where the constant deposition of organic matter, mainly leaves, promotes better conditions for establishing and maintaining microbial soil population. According to Beutler (2012), dry phytomass is 5.55 Mg ha^{-1} in the Cerrado, 4.25 Mg ha^{-1} in the CLI area and 2.56 Mg ha^{-1} in the pasture area. Because of the richness of ecological niches and heterogeneity of carbon sources, soil with high organic matter content (obtained from phytomass input) tends to maintain higher stability in the microbial population over the year (Grayston et al., 2001).

Table 2. Total organic carbon and carbon in the humic fractions of soil in areas under different management systems in Cerrado vegetation, Goiás.

Area	TOC	C-HUM	C-FAF	C-HAF
	g kg^{-1}			
	0-5 cm			
Pasture	36.43 b	25.81 b	4.57 b	3.51 b
CLI	29.61 b	21.40 c	4.23 b	3.81 b
Cerrado	65.40 a	54.34 a	6.34 a	5.24 a
SEM	1.54	0.66	0.15	0.05
P-value	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	13.61	6.91	11.25	4.97
	5-10 cm			
Pasture	24.20 b	16.71 b	4.06 b	3.37 a
CLI	24.27 b	15.78 b	3.65 b	3.15 a
Cerrado	33.61 a	33.89 a	5.13 a	4.15 a
SEM	0.65	0.45	0.10	0.16
P-value	< 0.001	< 0.001	< 0.001	0.063
CV (%)	9.17	7.62	9.34	17.66
	10-20 cm			
Pasture	18.34 c	13.17 b	3.45 b	1.58 c
CLI	23.49 b	12.89 b	3.56 b	2.58 b
Cerrado	30.15 a	23.27 a	4.29 a	3.17 a
SEM	0.76	0.37	0.09	0.09
P-value	< 0.001	< 0.001	< 0.001	< 0.001
CV (%)	12.21	7.83	9.45	14.22
	20-40 cm			
Pasture	16.45 a	7.88 b	2.57 b	2.33 a
CLI	17.46 a	9.88 a	3.37 a	1.90 a
Cerrado	16.48 a	10.46 a	3.93 a	2.61 a
SEM	0.27	0.21	0.10	0.13
P-value	0.26	< 0.001	< 0.001	0.111
CV (%)	6.29	6.98	11.76	21.49

Means followed by different letters within a column differ statistically (Tukey test, $P<0.05$). ^{ns}: non significant (F-test, $P>0.05$). C-FAF: carbon in the fulvic acid fraction; C-HAF: carbon in the humic acid fraction; C-HUM: carbon in humin; TOC: total organic carbon; CV: coefficient of variation; CLI: crop-livestock integration; SEM: Standard error of the mean.

At a depth of 10-20 cm, TOC content in the CLI area (23.49 g kg^{-1}) was higher than in the pasture area (18.34 g kg^{-1}), indicating that CLI enhances TOC levels in addition to increasing phytomass production (Beutler, 2012). This result demonstrates the beneficial effects of the CLI system at deeper soil layers, particularly at the 20-40 cm layer, where TOC levels were similar in the different areas. This pattern indicates that the CLI and pasture areas are well managed and exhibit TOC levels similar to those of the original Cerrado area. Grasses such as brachiaria, found in bot pasture and CLI areas, have potential for storing most of the subsurface carbon content (Salton et al., 2011) because of the great capacity of their roots in accumulating carbon in soil (Lal, 2002). These results are similar to those reported by Loss et al. (2012a), also in Goiás. They evaluated, at a depth of 20-40 cm, similar TOC levels among NTS areas containing brachiaria and livestock husbandry (CLI), a NTS without pasture and a natural Cerrado area.

In general, the highest carbon content in the humic fractions, especially C-HUM, was found in the Cerrado area, at all the layers. Some exceptions were C-FAH at 5-10 and 20-40 cm layers, which were similar among the areas. In relation to C-FAF and C-HUM, no differences were found between Cerrado and CLI at the depth of 20-40 cm. The higher carbon content in the humic fractions of Cerrado soil results from the larger amount of dry phytomass (Beutler, 2012), which increases TOC levels (Table 2). This increase is particularly observed in C-HUM, which, according to Fontana et al. (2006) and Loss et al. (2010), consists of 70% TOC in mineral soils.

C-HUM in the top layer (0-5 cm) was higher in the pasture area than in CLI, similar between these areas at 5-10 and 10-20 cm and lower in the pasture area in the 20-40 cm layer (Table 2). These differences may be caused by the high C/N ratio and plant residues in pasture top soil (0-5 cm) (Beutler, 2012). Pasture areas under good management practices show potential for accumulating carbon in the labile and recalcitrant fractions at higher levels than in native vegetation (Roscoe et al., 2006).

C-HUM and C-FAF levels in the 20-40 cm layer and C-FAH at 10-20 cm were higher in CLI than in the pasture areas (Table 2), which can result from the diversity of plant species in the former area (brachiaria grass and legumes such as corn, beans and cotton). Different plant species associated to fertilizer applications results in higher plant residue input and soil exploitation in the CLI area (Beutler, 2012), culminating in higher carbon levels in the humic fractions.

The low C/N ratio in plant residues in the CLI area (Beutler, 2012) allowed more rapid decomposition in relation to pasture and Cerrado areas, producing lower C-HUM levels (0-5 and 5-10 cm). However, for CLI and pasture, the similarity between C-FAF and C-FAH (at 0-5 and 5-10 cm) can result from differences in C/N ratio associated to the amount of dry phytomass in these areas. Therefore, the high C/N rate in the pasture area is equivalent to the high phytomass content in the CLI area, resulting in similar C-FAF and C-FAH content and TOC values in top soil (Table 2).

Organic Phosphorus (OP) Partitioning

Labile OP. The two soil layers in the CLI area exhibited the highest levels of sodium bicarbonate ($NaHCO_3$)-extractable P, including total (TP-bic) and inorganic (IP-bic) fractions, and at a depth of 0-5 cm they did not differ from the Cerrado (Table 3). In the pasture area, TP-bic and IP-bic values were similar to those found in the Cerrado at 5-10 cm. The bicarbonate-extractable P is considered to be a labile fraction (Bowman and Cole, 1978b). Therefore, the increase in TP-bic and IP-bic levels in CLI is likely caused by P cycling, which is more intensive in this area, associated to the use of phosphate fertilizer. Gatiboni et al. (2007) observed that an increase in the dose of phosphate fertilizer enhances TP-bic and IP-bic fractions, thereby reducing organic labile P (OP-bic).

The values of bicarbonate-extractable organic P (OP-bic) were higher in Cerrado and pasture areas at 0-5 cm and in Cerrado and CLI areas at 5-10 cm. The proportion of OP-bic, an important source of labile P for plants without fertilization, is higher than that of IP-bic, as observed in Cerrado and pasture areas. Therefore, in these stable systems, SOM mineralization is slower, increasing OP-bic content. In CLI areas, which undergo high anthropogenic disturbance, SOM mineralization is more intense, making organic P fractions available to plants.

Gatiboni et al. (2007) evaluated the pattern of the different P fractions in increasing doses of phosphate fertilization in a no-till planting system in *Latossolo Vermelho* (Oxisol). At low P doses, they found that OP-bic participation in P supply to plants was higher than that of the IP-bic fraction.

Moderately labile OP. The acid (H_2SO_4)-extractable P fractions, shown in Table 4, are considered moderately labile (Bowman and Cole, 1978b). In the two layers evaluated, the acid-extractable P (TP-H) level was higher in the CLI area, and at 0-5 cm it was similar between CLI and the pasture area. The high TP-H content in the CLI area results from consecutive application of top fertilization, lack of soil turnover and low erosion rate. According to Rheinheimer et al. (2000), phosphorus adsorption occurs primarily at more demanding (less labile) sites, and the remaining phosphorus is redistributed into lower energy fractions with greater possibility of becoming available to plants.

Table 3. Sodium bicarbonate-extractable (bic) labile P: total phosphorus (TP), inorganic phosphorus (IP) and organic phosphorus (OP) fraction.

P fraction (mg kg^{-1})	Depth (cm)	Area			SEM	P-value	CV (%)
		Pasture	CLI	Cerrado			
TP-bic	0-5	16 b	18 ab	19 a	0.38	0.018	8.16
	5-10	12 c	30 a	17 b	0.65	< 0.001	12.88
IP-bic	0-5	4 c	10 a	7 b	0.30	< 0.001	17.46
	5-10	3 b	19 a	5 b	0.47	< 0.001	20.29
OP-bic	0-5	12 a	9 b	13 a	0.39	0.002	13.19
	5-10	9 b	12 a	12 a	0.30	< 0.001	10.61

Means followed by different letters in a row differ statistically (Tukey test, P<0.05). CLI: crop-livestock integration; CV: coefficient of variation; SEM: Standard error of the mean.

Table 4. Acid-extractable (H) moderately labile P: total phosphorus (TP), inorganic phosphorus (IP) and organic phosphorus (OP) fractions.

P fraction (mg kg^{-1})	Depth. (cm)	Area			SEM	P-value	CV (%)
		Pasture	CLI	Cerrado			
TP-H	0-5	171 a	204 a	102 b	5.51	< 0.001	13.41
	5-10	129 b	223 a	84 c	1.63	< 0.001	4.36
IP-H	0-5	143 b	193 a	85 c	5.25	< 0.001	14.48
	5-10	108 b	215 a	71 c	1.54	< 0.001	4.53
OP-H	0-5	28 a	11 c	17 b	0.61	< 0.001	12.63
	5-10	20 a	7 c	13 b	0.53	< 0.001	15.11

Means followed by different letters in a row differ statistically (Tukey test, $P<0.05$). CLI: crop-livestock integration; CV: coefficient of variation; SEM: Standard error of the mean.

The lowest TP-H values in the Cerrado area, in turn, are likely caused by the nonexistence of P application. In soils highly weathered or free of fertilization, phosphorus availability is highly dependent on intermediary labile inorganic and organic forms (Novais and Smyth, 1999).

According to local information, the last phosphate fertilizer application in the pasture area occurred more than 15 years before the present study. However, TP-H values in the pasture area were similar to those found in the CLI area at 0-5 cm, showing a significant influence of the remaining phosphorus. The higher OP-H levels in the two layers of the pasture area suggest that the different P forms have been redistributed over the years (Table 4).

The pattern of acid-extractable inorganic P fraction (IP-H) was similar to that of TP-H fraction, which has higher participation in TP-H composition than OP-H. All the areas differed in relation to IP-H values, and the highest values were observed in the CLI area followed by pasture and Cerrado. The organic fraction of acid-extractable P (OP-H) was different among the areas. The highest values were found in pasture and the lowest in the CLI area, in both 0-5 and 5-10 cm layers.

Moderately resistant P. Table 5 shows the values of the alkali (NaOH)-extractable P fractions, which, according to Bowman and Cole (1978b), correspond to the moderately resistant fractions. The highest TP-OH and IP-OH values were found in the CLI area, and for TP-OH they did not differ from the Cerrado at 0-5 cm. The content of occluded P in CLI accounts for this result, given that the long period of P fertilization may have favored the temporary stabilization of electrical charges on the iron and aluminum oxide surface.

In both layers evaluated, the values of alkali-extractable organic P (OP-OH) were higher in the Cerrado than in the other areas. This fraction is highly correlated to SOM carbon fractions (Table 7), and given that the highest carbon levels were observed in the Cerrado area, OP-OH possibly exhibits a high association with the most stable carbon fractions, especially C-HUM (Table 2). The most resistant SOM fractions, which are more important in the mid- and long-term, are fundamental for the P cycle in non-anthropogenic environments.

Table 5. Alkali-extractable (OH) moderately resistant P: total phosphorus (TP), inorganic phosphorus (IP) and organic phosphorus (OP) fractions.

P fraction (mg kg^{-1})	Depth. (cm)	Area			SEM	P-value	CV (%)
		Pasture	CLI	Cerrado			
TP-OH	0-5	52 b	66 a	64 a	1.32	0.002	8.45
	5-10	45 b	68 a	50 b	1.66	< 0.001	11.82
IP-OH	0-5	30 b	48 a	36 b	1.14	< 0.001	11.58
	5-10	28 b	51 a	26 b	1.48	< 0.001	16.41
OP-OH	0-5	22 b	19 b	27 a	0.68	< 0.001	11.60
	5-10	17 b	17 b	24 a	0.84	0.008	16.78

Means followed by different letters in a row differ statistically (Tukey test, $P<0.05$). CLI: crop-livestock integration; CV: coefficient of variation; SEM: Standard error of the mean.

Total OP. Table 6 summarizes the results of organic phosphorus partitioning in soil. TP and TIP exhibited a similar pattern in the last two layers evaluated and were higher in the CLI area, followed by pasture and Cerrado.

TOP profile was also similar between the two layers evaluated, with the highest levels recorded in pasture and Cerrado areas. The lower TOP levels in CLI arise from phosphate fertilization practices, which decrease organic P availability. Beck and Sanches (1994) observed that organic P contribution is 9% in soils with phosphate fertilization and 34% in systems without fertilization. Gatiboni et al. (2005) report that the contribution of organic P to plant nutrition increased from 6 % in fertilized soil to 43% in soil without mineral fertilizer addition.

Residual phosphorus (ResP) was higher in the CLI area, in both layers evaluated. In the 0-5 cm layer, however, it was similar between pasture and Cerrado areas, whereas at 5-10 cm, ResP was higher in the pasture than in the Cerrado area. ResP levels are higher in the CLI area because the degree of P fixation, caused by iron and aluminum oxides that establish specific bonds to produce binucleate compounds or by phosphate penetration into crystal failures (Novais & Smyth, 1999), is also greater at this site. Reinforcing this theory, P recovery rate (RR) was lower in the CLI, at a depth of 0-5 cm. This means that this area concentrates elevated levels of high binding energy, especially in the form of occluded P.

Phosphorus recovery rates (RR) ranged from 54 to 68 %. Other studies report RR variation between 48 and 109 % (Guerra et al., 1996), 50 and 82 % (Cunha et al., 2007b) and 40 and 169 % (Zaia et al., 2008). The RR differences observed at 0-5 cm are likely related to the high quality of organic matter in the top layer and the decomposition rate of plant residues, since RR was higher in the areas with higher C/N ratio (pasture=84, Cerrado=35 and CLI=31, according to Beutler (2012)). At a depth of 5-10 cm, RR was similar among the areas because this layer is less susceptible to the influence of plant residues than the top layer, especially in systems without anthropogenic interference.

In the two layers assessed, OP proportion was higher in the Cerrado. The lowest values were found in the CLI area. In general, OP values ranged from 6.68 to 19.25 %. Adopting the same procedure used in the present study for P determination, Zaia (2005) found a P variation (in relation to total P) of 22.6 to 39.6% in forest Oxisol and Cunha et al. (2007b) found a 14.6 to 24.1% variation in Cambisol planted with pasture grass. The values relative to native and pasture areas reported by these authors are similar to those recorded in the present study.

In general, TOP is associated to areas with lower content of available P (Mehlich-1). This reinforces the fact that organic P is an important source of this nutrient in environments with low natural fertility and with no or very low mechanical disturbance by anthropogenic activities.

Table 6. Summary of soil organic phosphorus partitioning in different management systems in the Cerrado of Goiás.

Attributes	**Areas**			SEM	P-value	CV (%)
	Pasture	CLI	Cerrado			
			0-5 cm			
TP (mg kg^{-1})	351 b	530 a	300 c	5.83	< 0.001	5.74
TIP (mg kg^{-1})	177 b	251 a	128 c	6.21	< 0.001	13.00
TOP (mg kg^{-1})	62 a	38 b	58 a	0.77	< 0.001	5.64
ResP (mg kg^{-1})	111 b	241 a	115 b	2.23	< 0.001	5.54
RR (%)	68.01 a	54.49 c	61.68 b	0.74	< 0.001	4.65
OP (%)	17.91 a	7.19 b	19.25 a	0.31	< 0.001	8.01
			5-10 cm			
TP (mg kg^{-1})	312 b	542 a	260 c	3.10	< 0.001	3.24
TIP (mg kg^{-1})	139 b	279 a	102 c	1.82	< 0.001	4.06
TOP (mg kg^{-1})	46 a	36 b	49 a	1.24	0.003	10.97
ResP (mg kg^{-1})	127 b	221 a	110 c	2.04	< 0.001	5.19
RR (%)	59.41 a	58.33 a	57.79 a	0.51	0.44	3.38
OP (%)	14.76 b	6.68 c	18.69 a	0.37	< 0.001	10.70

Means followed by different letters in a row differ statistically (Tukey test, $P<0.05$). ^{ns}: non significant (F test, $P>0.05$). CLI: crop-livestock integration; CV: coefficient of variation; **TP:** total phosphorus (TP-bic + TP-H + TP-OH + ResP); **TIP:** total inorganic phosphorus (IP-bic + IP-H + IP-OH); **TOP:** total organic phosphorus (OP-bic + OP-H + OP-OH); **ResP:** residual phosphorus (residual P after 3 extraction stages: bic, H and OH); **RR:** recovery rate; **OP:** organic phosphorus content in relation to total P (per cent value); SEM: Standard error of the mean.

Correlation between SOM fractions and OP, TIP, TP and Pavl

All the SOM fractions (TOC and HUM, FAF and FAH) were correlated between themselves, with coefficients above 0.80. Since these fractions are interdependent, when soil is impacted in a system, all the fractions may undergo a similar effect. However, it is essential to know that some of these fractions are more or less susceptible to these interferences, according to their sensitivity to changes in soil management. C-HUM levels (Table 2) are directly related to TOC levels (Table 2), with a high positive correlation between them (Table 7).

OP-bic was positively correlated to TOC, FAF and HUM, but did not exhibit an association with FAH, which shows intermediary chemical stability between C-HUM and C-FAF. This means that OP-bic was mainly correlated to the fractions of highest (C-HUM) and lowest (C-FAF) chemical stability. OP-bic is considered to be a labile P fraction in soil. Therefore, the C-FAF fraction, which is more labile (of higher mobility), likely activates OP-bic availability to soil. On the other hand, C-HUM, which is the most recalcitrant (resistant) fraction of SOM, probably plays a regulating role, storing OP-bic and keeping its availability in the mid- and long-term.

OP-H was not correlated to any of the SOM fractions. The OP-H fraction is likely associated to organic forms that were not considered in the present study, such as microbial phosphorus. In the pasture area, where the rate of CO_2 emission from pasture grass respiration is high (Beutler, 2012), OP-H levels were also higher. According to Bowman and Cole (1978b), the OP-H fraction represents the moderately labile OP fraction and is associated to non-humic substances and to fulvic acids. However, the results obtained in the present study for fulvic acids contradict Bowman and Cole (1978b).

OP-H may have interacted with low-molecular-weight organic acids (citric, malic, oxalic, tartaric and other). Because these organic acids compete for P adsorption sites, they force P, in the organic form, to be released to the solution by chelation of Fe and Al oxy-hydroxides, thereby increasing P solubility in soil (Guppy et al., 2005; Andrade et al., 2003; Tirloni et al., 2009). Therefore, the high production of plant residues in the CLI system (Beutler, 2012) likely releases a high content of these of low-molecular-weight acids, favoring OP H^+ release more than in the other areas.

Table 7. Pearson's correlation coefficient between organic matter attributes and organic phosphorus in Cerrado soil under different management systems, in Goiás.

	TOC	C-HAF	C-FAF	C-HUM	OP-bic	OP-H	OP-OH	TOP	TIP	TP	Pavl
TOC	1.00										
C-HFA	**0.81**	1.00									
C-FAF	**0.83**	**0.83**	1.00								
C-HUM	**0.95**	**0.84**	**0.88**	1.00							
OP-bic	**0.47**	0.31	**0.44**	**0.46**	1.00						
OP-H	0.24	0.06	0.25	0.16	0.09	1.00					
OP-OH	**0.69**	**0.74**	**0.74**	**0.77**	**0.47**	0.24	1.00				
TOP	**0.58**	**0.45**	**0.61**	**0.56**	**0.49**	**0.82**	**0.72**	1.00			
TIP	**-0.40**	**-0.45**	**-0.56**	**-0.54**	-0.25	**-0.42**	**-0.54**	**-0.59**	1.00		
TP	**-0.40**	**-0.39**	**-0.55**	**-0.52**	-0.28	**-0.52**	**-0.51**	**-0.65**	**0.98**	1.00	
Pavl	**-0.47**	**-0.44**	**-0.58**	**-0.57**	-0.36	**-0.59**	**-0.62**	**-0.76**	**0.91**	**0.92**	1.00

Bold values are statistically significant (t-test, $P<0.05$). **TOC**: total organic carbon; **C-HAF**: carbon in the humic acid fraction; **C-FAF**: carbon in the fulvic acid fraction; **C-HUM**: carbon in humin; **OP-bic**: bicarbonate ($NaHCO_3$)-extractable organic P; **OP-H:** sulfuric acid (H_2SO_4)-extractable organic P; **OP-OH**: sodium hydroxide (NaOH)-extractable organic P; **TOP**: total organic P; **TIP**: total inorganic P; **TP:** total P; **Pavl:** available P (Mehlich-1).

OP-OH was positively correlated to all SOM attributes, with the lowest correlation observed for TOC (0.69). OP-OH was the fraction exhibiting the highest correlation with the humic SOM fractions, indicating the close relationship between OP-OH and SOM attributes. According to Olsen and Sommers (1982), this fraction is associated to humic acids or is adsorbed on the surface of Fe and Al compounds. Since OP-OH is considered a moderately resistant organic P fraction, humin likely exhibits a close relationship with organic P availability to plants, as confirmed by its high correlation with the humic fractions (r=0.77).

In general, TOP was correlated to all SOM attributes, suggesting that organic matter dynamics is directly related to phosphorus dynamics in soil. A positive correlation between TOC and TOP was earlier reported by Cunha et al. (2007b) in a study carried out in the state of Rio de Janeiro. With regards to SOM fractions, the highest correlation was found between TOP and C-FAF (0.61, Table 7). These results indicate the significant C-FAF potential to compete for P adsorption sites, keeping P in soil solution, as reported by Roselem (2008).

The accessibility of microorganisms and plants to organic P forms may be higher if associated to C-FAF than with C-FAH, since the latter is more resistant to mineralization (Stevenson, 1994; Guppy et al., 2005). According to Guppy et al. (2005), C-FAF is more effective than C-FAH in reducing P adsorption. This is confirmed by the positive correlation between C-FAF and TOP (r=0.61), which was higher than that obtained between C-FAH and TOP (r=0.45), and also by the lack of correlation between C-FAH and OP-bic (r=0.44) and C-FAF and OP-bic (Table 7).

TIP, TP and Pavl were negatively correlated to all SOM attributes, supporting the theory that low levels of the carbon fractions promote high availability of organic P to plants. However, this is beneficial in the short-term and lasts until organic matter is available to decompose; in the mid- and long-term, inorganic P forms are possibly reduced. This reinforces the importance of maintaining management systems with adequate SOM levels so that P dynamics becomes more efficient in agricultural systems.

The organic P fractions (OP-bic, OP-H, OP-OH, and TOP) showed positive correlations except between OP-H and OP-bic and between OP-H and OP-OH, owing to the different P sources. OP-H is obtained from a microbial source, whereas OP-bic and OP-OH originate from humic sources. Except for OP-H, the other fractions might derive from humic substances, which represent the most active source of organic P in soil.

CONCLUSIONS

The CLI area produced TOC values similar and/or higher than those of the pasture area in all the soil layers evaluated from 0 to 40 cm.
The area converted from natural Cerrado to CLI has developed chemical stability (C-FAF, C-HAF, C-HUM and TOC); it is similar to the Cerrado area in the 20-40 cm layer, with higher accumulation of C-FAF and C-HUM than the pasture area.
Compared to pasture and Cerrado areas, the CLI system favors the formation of very labile, moderately labile and moderately resistant P, for both TP and IP fractions.
Inorganic P fractions are associated to areas that received high doses of phosphate fertilization, whereas organic fractions prevail in soil under low or null anthropogenic influence. Organic P fractions are directly correlated to humic SOM fractions.

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