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Changes in soil organic carbon fractions in response to sugarcane planting in the central-south region of Brazil

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Sugarcane planting area in Brazil has considerably increased during recent years by occupying areas used for pasture and grain crops production. Land use change (LUC) processes related to sugarcane expansion can affect the soil organic carbon (SOC) stocks, and the quality of the soil organic matter. Preliminary studies have shown that the land-use transition into sugarcane leadto a decrease in the SOC, however no studies have accessed the impact of LUC on the SOC distribution within soil particle-size classes. The study investigated the modifications on total SOC, particulate organic carbon (POM) and mineral-associated C (MOC) in response to conversion from native vegetation (NV), pastures and annual cropland (AC) to sugarcane crop (SCN). Soil samples were collected at 34 field-sites to 20 cm depth and POM fraction separated through 53-mm sieve after soil dispersion. The study results indicated that LUC affects both the labile as well as the more stable SOM fraction, with a mean C content decreasing of 40 and 30% in POM and MOC respectively, following the transition from NV to SCN. The replacement of pastures caused C depletion by 33% at POM and 30% at MOC; meanwhile C accumulation at MOC (5%) was detected for the conversion from AC to SCN. The impact of LUC on POM for AC-SCN transition could not be totally clarified, however the result could be an indication that the POM response to LUC varies as function of previous management in AC.

Key words: Soil organic carbon, C fractionation, particulate organic matter, mineral-associated C, land use change.

INTRODUCTION

Sugarcane (*Saccharum officinarum* sp.) is a perennial grass originating from New Guinea that has been cropped in Brazil since the colonial period, reaching a harvested area of 9.7 Mha which accounts for 40% of worldwide production (FAOSTAT, 2011).

Since sugar from sugarcane is the main feedstock used to produce ethanol in Brazil, the planted area with this energetic crop has meaningfully grown in the last decade, and the trend is to continue expanding for the next years in order to achieve the national goals of production (Conab, 2013; Brasil, 2009; Cerri et al., 2010).

As the soil is an important natural reservoir of carbon

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(C), land use changes (LUC) during the transition to sugarcane production can lead to a decrease in soil carbon stocks (Lal and Kimble, 1997; Six et al., 2002). Land use and land changes are widely recognized as key drivers of global C dynamics (Schimel, 1995; Houghton et al., 1999). Soil organic matter (SOM) has a very complex and heterogeneous composition, and it is generally mixed or associated with the mineral soil constituents to form soil aggregates (Del Galdo et al., 2003).

A recent study performed in Brazil demonstrated that the greenhouse gases (GHG) emissions due to LUC for conversions from native vegetation and pastures to sugarcane could result in net transitional soil C debt with payback times ranging from 17 years in native vegetation, and 5 to 6 years in pastures. Conversely, when sugarcane replaced annual cropland, the soil C stocks increased by 17% in the 0 to 30 cm depth layer (Mello et al., 2014).

In addition to the C quantity, land use practices affect the soil C quality varying the distribution between particulate organic matter and SOM associated to the mineral fraction (Cambardella and Elliott, 1992; Christensen, 2001). Christensen (2001) proposes that the main effects of land use management can be observed by changes in the distribution of soil organic carbon (SOC) within particle-size classes.

Several studies have shown the influence of soil tillage system on the C pools, suggesting that particulate organic matter can be used as an early indicator of changes in C dynamics (Cambardella and Elliott, 1992; Six et al., 1999; Bayer et al., 2002; Freixo et al., 2002). However, few studies have been carried out to determine the impact of LUC on particle-size fractions, and no studies have been performed involving the land-use transition into sugarcane.

The correct evaluation of soil C changes and SOM dynamics is the one which functionally distinguishes among different SOM fractions. The development of management systems for sustained production requires a better understanding of the impact of land-use and LUC in the SOM pools.

In this context, this study aimed to investigate the modifications on total soil organic C and C content of the particle-size fractions, as results of LUC due to sugarcane planting in Central-South region of Brazil. The study used the physical fractionation method, based on the premise that SOM associated with particles of different size and therefore also of different mineralogical composition differ in structure and function (Christensen, 1992).

MATERIALS AND METHODS

Study area

The study area involved seven counties distributed throughout the Central-South region of Brazil, covering the states of Minas Gerais, São Paulo, Goiás and Paraná. Comparative soil samples were collected from sugarcane fields and native vegetation, pastures and annual crops areas as indicated by Mello et al. (2014). The selection of the study areas considered historical land use information and existence of reference areas (pasture, annual cropping or native vegetation) with similar geomorphic characteristics (topography, soil type etc.) as the sugarcane sites. Consequently, 34 study sites forming 17 comparison pairs were selected for soil sampling: 17 sugarcane fields, 13 pastures, 2 annual crops and 2 native vegetation areas.

Soil sampling and C determination

In each evaluated site, three pits were opened and soil samples were taken from the layers of 0 to 10 cm and 10 to 20 cm depth, totalizing 6 soil samples per site and 204 for the study area. Soil samples were sieved (2 mm), ground and sieved at 150 µm for carbon determination by dry combustion on a LECO® CN elemental analyzer (furnace at 1350°C in pure oxygen).

Soil C fractions were determined according to the method described by Cambardella and Elliott (1992), and adjusted by Feller and Beare (1997) and Christensen (1997). Briefly, 20 g of 2 mm sieved soil was mixed with 80 mL of hexametaphosphate solution (0.5%), refrigerated and subsequently sonicated for 15 min with a maximum power output of 500 W. The dispersed soil was sieved through a 53 mm sieve, and the sand-sized organic material (POM) retained on the sieve was thoroughly rinsed, transferred to aluminum pans, oven-dried (60°C), and weighed. The dried samples were ground, and the total carbon content in the fraction was determined by dry combustion on a LECO® CN elemental analyzer. Mineral-associated organic C (MOC) was estimated by difference between total C (TOC) and POM C.
Soil texture was determined as described by Mello et al. (2014).

Statistical analyses

The study was arranged in a completely randomized design comprising four land use systems - with three pseudo replications. Data was checked for normality using the Shapiro test and for homoscedasticity by Bartlett test. Analysis of variance with the F-test was performed, and differences detected were compared using the Tukey tests at a significance level set at $P < 0.05$.

The comparison of the relative portion of the fractions (POM and MOC) was performed using the Student t test. Changes in the TOC and the C content in each fraction were estimated considering the means between comparison pairs, hence descriptive analysis is presented for those results since only two comparison pairs were studied for native vegetation and annual crops situations.
All statistical analysis was performed using R Statistical Software (R Development Core Team (2011).

RESULTS

Total soil organic C and relative fractions of POM and MOC

The TOC content was quantified for all the land use systems-involving both layers: 0 to10 and 10 to 20 cm depth (Figure 1). The mean comparison test performed, which included all the sugarcane sites without considering the previous management, indicated TOC higher in

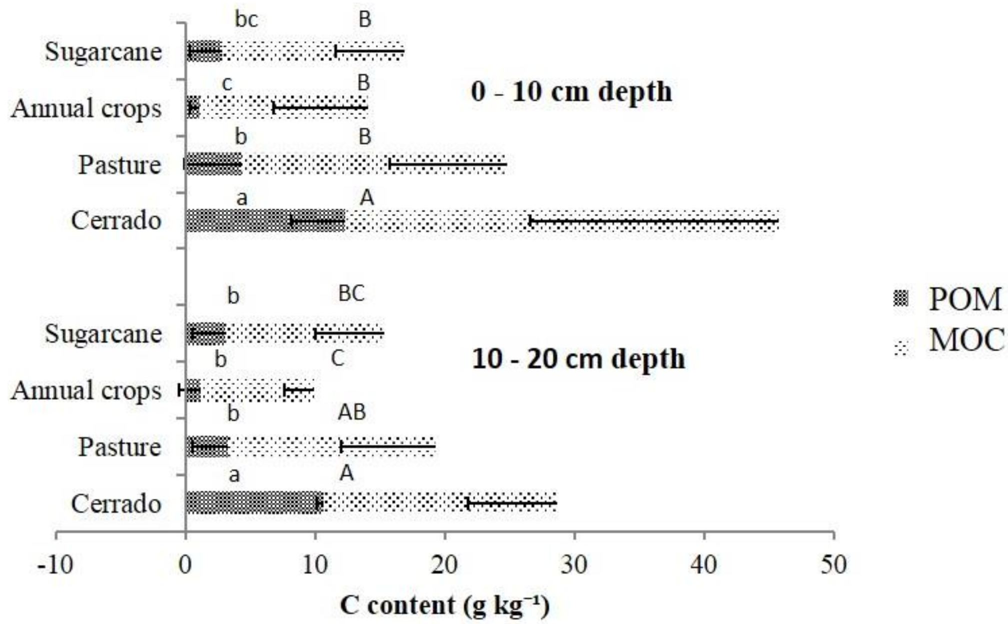

Figure 1. Total soil organic C (g kg-1) in each land use system for the 0 -10 cm and 10 – 20 cm depth. (* Means followed by the same capital letter within MOC and same lowercase letter within POM fraction in each layer are not significantly different according to Tukey's test at the 5% level).

native vegetation than in the other land use systems in both depths, with more contrasting differences in the top layer. The TOC in pastures was higher than quantified in sugarcane only in the 0 to 10 cm layer. No significant differences (P<0.05) were detected between sugarcane and annual cropping.

Carbon content in POM and MOC fractions was influenced by management at all sites and differences varied across depth. In the top layer (0 to 10 cm depth) the C in POM was more variable than in 10 to 20 cm layer, where no differences were estimated among the planted areas. Opposite pattern was found for the C content in the MOC fraction (Figure 1).

A trend of C declining with depth was observed in all land use systems. The TOC was 1.3 times lower in the deeper layer than in the top with changes more contrasting at MOC than in POM fraction. The mean relative amount (%) of POM and MOC as a portion of total soil C was estimated for the sugarcane sites and compared with the land use system used as reference (Figure 2A and 2B). According to the statistical analysis, the relative portion of both soil organic C fractions was not different between sugarcane, and the areas selected as reference of previous management for the two soil depth studied.

The proportion of POM in the condition accessed was affected by the soil clay and silt content. Relationships between POM relative fraction and silt plus clay content occurred in both layers, with higher coefficient of correlation in the 10 to 20 cm depth (R^2 = 0.59) than in the top layer (R^2 = 0.28).

Relative changes in soil C fractions

Carbon variation for each fraction due to the planting of sugarcane was quantified through the difference between the mean C content found in the sugarcane areas and their references. Subsequently the relative change in each C fraction was estimated (Table 1).

Greater C losses were found for the conversion from native vegetation to sugarcane crop. The LUC affected the labile organic carbon (POM) as well as the more stabilized C fraction (MOC). The impact of those processes was higher in the superficial layer than in the 10 to 20 cm layer.

In contrast, sugarcane planting over areas used for annual cropping production seems to increase the SOC, favoring the C accumulation in the mineral-associated fraction.

DISCUSSION

Soil organic carbon content reflects the long-term balance between additions and losses of organic carbon to the ecosystem. In this study, we compared the TOC content among the different land use systems accessed without considering the previous management of the sugarcane areas. Under this approach, higher C contents were found

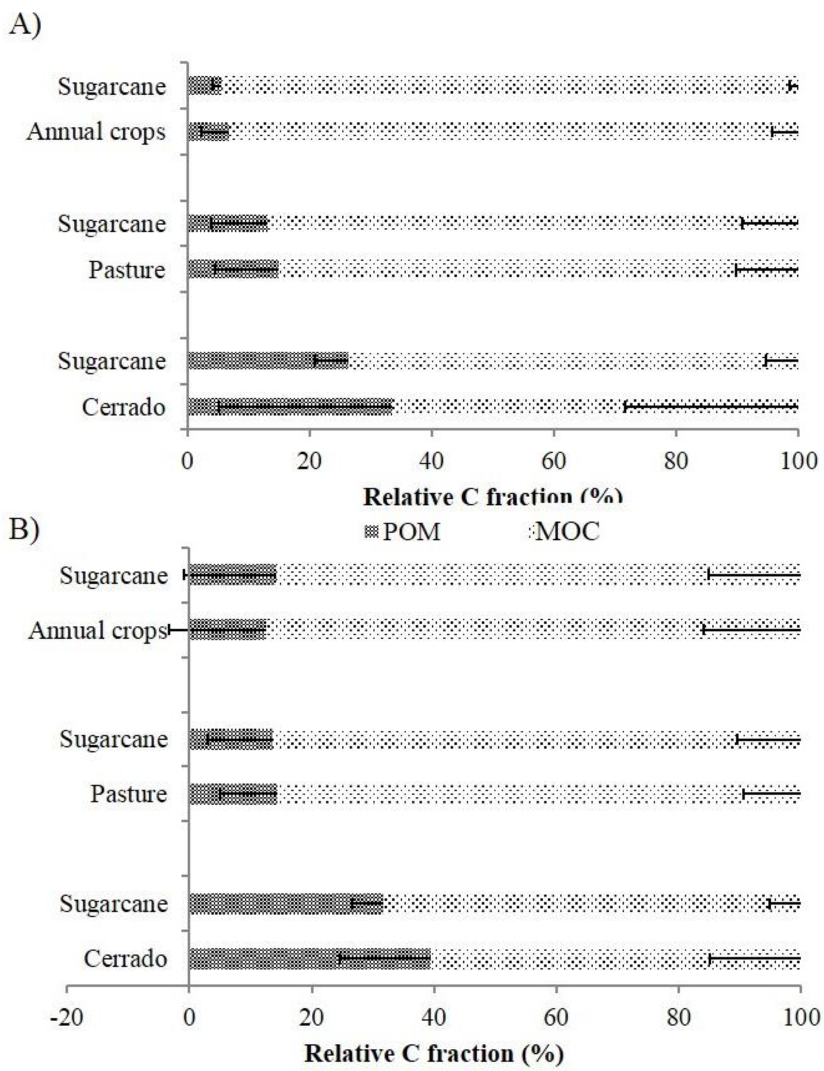

Figure 2. Relative portion (%) of particulate organic C (POM) and mineral-associated C fraction (MOC) for each conversion type involving sugarcane planting in 0 -10 cm depth (A) and 10 to 20 cm depth (B).

Table 1. Relative changes (%) in total C content (COT), particulate organic C (POM) and mineral associated C (MOC) due to the sugarcane planting in Central-South part of Brazil.

Reference	COT	POM	MOC
	0 - 10 cm depth		
Cerrado	-48.6	-50.82	-47.89
Pasture	-34.5	-37.11	-33.97
Annual crops	3.25	-23.13	5.53
Reference	**10 - 20 cm depth**		
Cerrado	-17.8	-29.15	-11.22
Pasture	-24	-20.18	-24.80
Annual crops	5.8	7.90	5.37

at native vegetation in both soil depth studied, in agreement with results reported in tropical soils. All studies that focused on the effects of land conversion from forest to cultivated land concluded that LUC induces a reduction of the available soil C and a decrease in its quality (Batlle-Aguilar et al., 2010). In tropical soils the soil C can be reduced by 50% in the first years of cultivation due to several processes, including microbial decomposition and erosion (Mielniczuk et al., 1999).

When compared with pastures, the study estimated that TOC under this land use system was 45 and 32% lower than native vegetation in 0 to 10 cm and 10 to 20 cm depth, respectively. Carvalho et al. (2010) studying different pastures areas in the Brazilian Cerrado region found C content varying as a function of the pastures management. Pasture lands can lead either to a positive or negative impact on the overall soil C. In this study, lower C content can be atributed to degradation process caused by the soil management. More than 70% of the total areas under cultivated pastures in Brazilian Cerrado region show some degree of degradation (Junior and Vilela, 2002; Batlle-Bayer et al., 2010) due to increasing stocking rates without maintenance fertilization, which results in a rapid decline of nutrients in the soil (Nair et al., 2011).

Even though no significant differences (P<0.05) were found in the C content of POM and MOC fractions among the planted areas, a trend of decreasing MOC (g kg^{-1}) from pasture to sugarcane areas (Figure 1) and in both fractions to annual crops sites was observed, pointing out the contrasting impact of the land use in SOC dynamic. Soil tillage has been indicated as a highly disturbing management practice (Silva-Olaya et al., 2013) which alters aggregate dynamics by enhancing the turnover time of SOM thus decreasing the formation of the more stabilized C fractions, such as POM C and mineral-associated C (Six et al., 1999).

Regarding the percentage of C presented for different fractions, the study found that POM fraction varied from 6 to 34% in the land use systems evidencing the differences in C inputs into the soil and the role of the historical use in the C dynamics, since the relative fractions in sugarcane crop followed the same pattern observed in the reference sites. Excepting for the annual crops areas, where less than 10% of POM was found, the values observed were within the range of values indicated by Feller and Beare (1997). C-turnover rates for the particulate organic matter associated with the sand-size fraction are higher, hence it is more depleted by annual cultivation than clay-bound organic matter (Chenu and Plante, 2006).

Despite the land use system affected the soil C content of all fractions; the sugarcane planting did not affect their proportional weight distribution when compared to the land use system reference (Figure 2A and 2B). The mean relative portion of POM and MOC does not vary significantly between sugarcane and its references in both layers, suggesting C losses in the labile fraction as well as in the stabilized pool, hypotheses corroborated later when estimated the relative change of each fraction as function of its reference (Table 1).

Mello et al. (2014) accessing the effects of LUC due to the sugarcane planting in South-Central part of Brazil on soil C stocks demonstrated soil C decrease following LUC from native vegetation and pastures, and increase where cropland is converted to sugarcane. In this study, using some of the areas sampled by Mello et al. (2014), the study estimated that the conversion from native vegetation to sugarcane crop affects both SOM pools. Particulate organic matter was the most sensitive fraction to LUC and declined by an average of 40% followed by the silt and clay sized fractions which had 30% less C in the surface soil horizon (0 to 20 cm depth) after the conversion. The same pattern was observed when sugarcane replaced pastures. Mean C losses of 33 and 30% in POM and MOC, respectively, were quantified for the same soil depth.

By analyzing each layer, the study found that the impact of LUC of SOC variation is greater in the top layer for both types of land use conversion, where wake relationship between POM and clay plus silt content was observed, evidencing that likely much of the POM found in this depth correspond to free particulate organic matter or unprotected SOM, which is relatively easily decomposable and are greatly depleted upon cultivation (Cambardella and Elliott, 1992; Six et al., 1999). At the 10 to 20 cm depth, the correlation between soil texture and relative fraction of POM suggests a protection of the labile C from decomposition in the inter-aggregates (occluded POM), which can influence the rate of C losses with soil perturbation. Even though SOC associated with mineral soil (MOC) is considered the more stable and recalcitrant fraction of SOM (Wiesenberg et al., 2010) these results imply that a significant proportion of the SOC at that pool is relatively labile, as suggested by Feller and Beaer (1997), and hence it is negatively affected by the LUC. Upon reviewing data obtained in literature Von Lützow et al. (2007) estimated that the generally higher allocation of SOC in smaller particles is not always congruent with a longer turnover time. In the sand fraction, ^{13}C turnover times ranged from 0.5 to 374 years, in the silt fraction from 115 to 676 years and in the clay fractions from 76 to190 years. The same trend was observed when used ^{14}C as indicator of mean residence time (MRT). Additionally, the authors found that the MRT and turnover time of fine clay is lower in than in the coarser clay fraction.

García-Oliva et al. (1994) reported that the C silt-associated fraction was subject to a lower loss rate than the clay-associated C fraction in a tropical deciduous forest after conversion to pasture. Similar results were found by Covaleda et al. (2011) comparing conserved and degraded forest soils. The clay-fraction is more enriched in new SOM because of microbial activity which decomposed faster than the silt-sized aggregate fraction (Gregorich et al., 1991). Since the study estimated the C associated with the mineral fraction as the difference between TOC and POM, the study believes that those differences between clay and silt association to SOM could explain the susceptibility of MOC to LUC in this study. Moreover, sugarcane crop maintains lower amounts of SOM when compared to pastures and native vegetation. Pre-harvest burning performed in this crop affects the potential mineralizable C of the SOM labile pool, soil microbial biomass and physical soil properties influencing the soil aggregation which is one of the main SOM stabilization mechanisms (Prieto-Fernández et al., 1998; Ceddia et al., 1999; Six et al., 2002; de Souza et al., 2005). Also, sugarcane fields pass through a cultivation cycle every five years which causes the emission of 3.5 Mg ha^{-1} C-CO_2 (Silva-Olaya et al., 2013); meanwhile either pastures or native vegetation remain for long periods without any soil perturbation.

In contrast to both conversions mentioned earlier, the LUC from annual cropland to sugarcane increased the TOC. According to Mello et al. (2014) the C stocks in sugarcane areas were 17% higher, leading to an accumulation of 36 Mg CO_2 ha^{-1} in the 0 to 30 cm of soil depth after 20 years of time span. In this study, using two of the comparison pairs reported by Mello et al. (2014) we estimated that 5% of that C increases occurred in the MOC fraction. Mean C depletion of 23% in POM fraction was observed at the 0 to 10 cm of soil depth and C accumulation at the deeper layer; however because of the high standard deviation of this parameter in both areas (sugarcane and annual crops) the POM dynamics cannot be conclusive. The two cropland areas had different management history and also different clay + silt content, variable that can influence the relative portion of the labile pool as indicated by the regressions performed for the 10 to 20 cm of soil depth. The combination of crop rotation and no-till at one of the reference sites resulted in higher C content at POM at the top layer which is depleted because of the conversion to sugarcane. In the 10 to 20 cm of soil depth the high clay + silt content of the same area seems to offer some degree of physical protection to labile fraction thus this is not strongly affected by the LUC. Conversely, management as well as soil attributes at the other reference site resulted in the opposite dynamic, thus C content in POM increased with the sugarcane planting in both layers. Even though the results of this pool cannot be conclusive, those could be an indication that the POM response to LUC varies as function of previous management in annual cropland, however a larger sample size of annual cropland to sugarcane conversion would be necessary to better evaluate soil C changes at the labile pool and to confirm that hypothesis. Sugarcane expansion at the Central-South region of Brazil is an important process that can affect the greenhouse gases (GHG) balance of this energy crop and consequently the overall sustainability of the biofuel production. In this sense, our results provide essential knowledge about the real SOC dynamic due to those LUC processes. With future expansion projected to involve mainly pastures and cropland areas it is important to develop management systems in sugarcane production that allow for the restoration of the stable C fraction (MOC) which has been considerably depleted because of the conversion from pastures, contributing to long-term soil C sequestration.

CONCLUSIONS

The proportion of particulate organic matter at 10 to 20 cm depth is affected by the clay plus silt content. Land-use conversion from native vegetation and pastures to sugarcane modifies the distribution of C within soil particle-size classes. Important C depletion in the stable fraction of SOM as well as in the labile fraction is caused by those kinds of transitions. In contrast, C accumulation in MOC is favored by the replacement of cropland areas by sugarcane.

Conflict of interests

The authors have not declared any conflict of interests.

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