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Effect of sugarcane residue management (mulching vs. burning) on organic matter in a clayey Oxisol from southern Brazil

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Abstract

Changes in residue management may help sustain land productivity, and may have noticeable consequences in the global carbon budget when large areas are involved. The effects of sugarcane residue management on topsoil carbon were assessed in a clayey Oxisol of Brazil, largest world's producer of sugarcane. The carbon concentration of the whole soil and particle-size fractions were determined in a long-duration sugarcane plantation (50 years), with either a pre-harvest residue burning (BUR) or a 6-year green trash management (MUL, residue mulching). Soil carbon concentrations were greater in MUL than in BUR. The difference was significant at a 0-5 cm depth (25.2 vs. 21.0 g C kg^{-1}) but not at 5-10 cm (22.3 vs. 20.5 g C kg^{-1}); nevertheless it was significant at 0-10 cm (23.7 vs. 20.7 g C kg^{-1}). This difference resulted in carbon sequestration in MUL, which amounted to 0.65 Mg C ha^{-1} yr^{-1} at 0-10 cm depth and corresponded to 14% of aboveground residue carbon returned to the soil. Differences in soil carbon between MUL and BUR mainly affected the fraction < 2 µm. It was hypothesized that the preferential enrichment in fine fractions resulted in a long-term carbon storage.

Keywords

Soil organic carbon; Particle-size fractionation; Sugarcane; Residue mulching; Brazil

1. Introduction

Soil management practices such as no-tillage or residue mulching have been reported to promote the storage of carbon from atmospheric origin, and to constitute potential carbon sinks (Balesdent et al., 2000; IPCC, 2001; Six et al., 2002). Their assess remains of major importance nowadays (i) for mitigating the increased atmospheric concentrations in greenhouse gases (especially carbon dioxide), and (ii) for addressing the problem of agroecosystem transformation and sustained land productivity. However, the potential of these practices to sequester soil organic carbon (SOC) has to be confirmed for a range of crops and locations.

With this object, we studied the effect of sugarcane residue management on SOC characteristics in a clayey Oxisol of southern Brazil. Indeed, Brazil is the largest producer of sugarcane in the world and consequently, changes in the management of sugarcane residues in this country may have noticeable outcomes on the global carbon budget. Sugarcane leaves represent a considerable biomass which is either burned or mulched depending on the harvesting procedure. Traditional harvesting involves pre-harvest leaf burning to facilitate the hand-cutting of cane, and results in an important emission of greenhouse gases. In contrast, mechanized harvesting does not involve burning: residues are mulched on the soil surface, allowing a possible increase in SOC concentration. Now, changes in management not only influence SOC quantity but may also affect its quality (Feller and Beare, 1997). In this manner, particle-size fractionation can be valuably used in studies about SOC dynamics and the effect of soil management on SOC pools. Indeed, this method has been reported to separate SOC pools that have different decomposition rates, fine fractions being more stable than the coarser ones (Cerri et al., 1985; Balesdent et al., 1987).

The objective of the present study was to compare the effects of sugarcane residue burning and mulching on total SOC and size-fraction SOC, in a clayey Oxisol of southern Brazil.

2. Materials and methods

2.1. Site

The study was carried out in a sugarcane plantation near Pradópolis, in São Paulo State (21°22'S, 48°03'W). The climate is tropical to subtropical, and mean annual rainfall and temperature are 1560 mm and 22.9°C, respectively. The soil is a typic Hapludox (Soil Survey Staff, 1999), and is developed on basalt. It is clayey, its clay fraction being dominated by kaolinite, and iron and aluminium oxihydroxides mainly. The site had been under continuous sugarcane cultivation (*Saccharum officinarum*) for 50 years. Until 1995, pre-harvest burning of leaves occurred two to seven days before the manual harvest. In 1995, the site was divided into 12 randomized plots (31 × 70 m each), and sugarcane was planted after disc plowing, subsoiling and disc harrowing. From 1995 to 2001, six plots were cropped with mechanized harvest involving residue mulching (treatment MUL) but no pre-harvest burning, whereas the six other plots were cropped with pre-harvest residue burning, as previously (treatment BUR).

For both treatments, N, P_2O_5 and K_2O inputs were 25, 125 and 125 kg ha^{-1} at planting (every six years), and 85, 50 and 100 kg ha^{-1} after harvest (every year), respectively. Fertilizers were incorporated into the soil for BUR, and spread onto the surface for MUL. The soil was not tilled between 1995 and 2001. Crop yields were 115, 106, 103, 96, and 85 Mg ha^{-1} for BUR, and 104, 114, 99, 82, and 78 Mg ha^{-1} for MUL. The aboveground biomass (a 10-12 cm layer) returned to the soil in MUL amounted to 15.7, 12.8, 11.3, 14.5, and 15.2 Mg DM ha^{-1}.

2.2. Soil sampling and analyses

Soil samples were collected in August 2001, just before the harvest, at two depths: 0-5 and 5-10 cm. Deeper soil layers were not sampled as sampling carried out in 1998 did not indicate significant differences in SOC and nitrogen concentrations between MUL and BUR below the 10 cm depth (De Luca, 2002). In each plot and at each depth, one soil sample was constituted from six individual samples, three located on the central row and three on the central inter-row. Samples were air-dried and sieved (2 mm). Subsamples were finely ground (< 0.2 mm) for carbon and nitrogen analyses. Plots were not sampled in 1995, but it was assumed that soil properties did not change between 1995 and 2001 in BUR, due to a steady state resulting from similar cultivation for several decades.

The soil samples were fractionated following Gavinelli et al. (1995), with the objective of maximizing soil dispersion while minimizing the degradation of organic constituents. The fractionation procedure was carried out on 20 g of soil. It involved dispersion with sodium hexametaphosphate (HMP); shaking with agate balls; wet-sieving through 200- and 50-µm sieves; ultrasonication then re-sieving (50 µm) of the heavy subfraction 50-200 µm (extracted through density fractionation in water); ultrasonication of the fraction 0-50 µm then wet-sieving through a 20-µm sieve; sedimentation/decantation (five cycles at least) to obtain fractions 2-20 and 0-2 µm; centrifugation, then collection and 0.2-µm filtration of an aliquot of the supernatant for the determination of solubilized organic carbon. All the fractions were air-dried, weighed and finely ground. One fractionation was carried out for each plot (0-5 cm depth), i.e., in six replicates for each treatment. Carbon and nitrogen of the whole soils and the particle-size fractions were analyzed in triplicate using a Carlo Erba NA 2000 Elemental Analyzer. In the absence of carbonates, all carbon was assumed to be organic. Water-soluble organic carbon was determined using a Shimadzu TOC 5000 analyzer. Data are presented as mean values with their standard deviations. They were tested for statistical significance by Student’s unpaired *t*-test. No assumptions were made on normality and variance equality (Dagnélie, 1975).

3. Results

3.1. Total soil carbon and C/N ratio (Table 1)

Compared to BUR, total SOC concentration in MUL was 20% greater at the 0-5 cm depth (25.2 vs. 21.0 g C kg^{-1}; $p < 0.05$), 9% greater at the 5-10 cm depth (22.3 vs. 20.5 g C kg^{-1}; $p > 0.05$), and 15% greater at the 0-10 cm depth (23.7 vs. 20.7 g C kg^{-1}; $p < 0.05$). Total SOC concentration decreased from the surface layer (0-5 cm) to the 5-10 cm depth in MUL (25.2 vs. 22.3 g C kg^{-1}; $p < 0.05$) but not in BUR (21.0 vs. 20.5 g C kg^{-1}; $p > 0.05$). On average, the C/N ratios were ca. 13.5 and 13.0 in the 0-5 and 5-10 cm layers, respectively; they did not differ significantly between treatments or between depth layers.

3.2. Carbon and C/N ratio in the size fractions (Table 2)

The cumulative fraction yield after fractionation ranged from 100 to 102%, the excess being probably due to fixation of phosphates from HMP. Carbon recoveries ranged from 98 to 99% on average. Considering carbon concentrations (g C kg^{-1} fraction), fractions 50-200 µm tended to be depleted (12 g C kg^{-1}) and fractions 2-20 µm richer (27.6 and 23.4 g C kg^{-1} in MUL and BUR, respectively) than the other fractions (21-22 and 17-21 g C kg^{-1} in MUL and BUR, respectively). For a given fraction, carbon concentrations did not differ significantly between treatments except in the 0-2 µm fraction, with a concentration 24% higher in MUL than in BUR ($p < 0.05$). Considering carbon amounts (g C kg^{-1} soil), fractions < 20 µm included more carbon than fractions > 20 µm (> 6 vs. < 2 g C kg^{-1} soil). Each of the three fractions > 20 µm included less than 10% of total SOC, fractions 2-20 and 0-2 µm including 30 and 40% of total SOC, respectively, and the water-soluble fraction 10%. The main difference between treatments was found in the 0-2 µm fraction, which included 35% more carbon in MUL than in BUR (10.8 vs. 8 g C kg^{-1} soil; $p < 0.05$). The amount of water-soluble carbon was also significantly greater in MUL than in BUR, but the difference was small (2.6 vs. 2.0 g C kg^{-1} soil; $p < 0.05$). Thus, the greater SOC concentration in MUL compared to BUR resulted mainly from the greater amount of carbon in the 0-2 µm fraction. The C/N ratio decreased from coarse to fine fractions, but did not differ significantly between treatments: on average, it ranged from 19 to 32 in the fractions > 20 µm, and was 15 and 11 in the 2-20 and 0-2 µm fractions, respectively. This is consistent with data in the literature, which indicated that these fractions included poorly decomposed plant debris, humified plant and fungi debris, and amorphous organic matter associated with decomposed bacterial cells, respectively (Feller and Beare, 1997).

4. Discussion

4.1. Total soil carbon

Compared to the soil under residue burning (BUR), the soil under residue mulching (MUL) contained more SOC: its SOC concentration was 4.2 g C kg^{-1} higher (+20%) at 0-5 cm, and 3.0 g C kg^{-1} higher (+15%) at 0-10 cm. Soil bulk density was 1.3 g cm^{-3} at the 0-5 and 5-10 cm depths for both MUL and BUR; compared to BUR, bulk density in MUL was smaller under the rows, nevertheless it was greater under the inter-rows, probably due to mechanized harvesting (De Luca, 2002). Thus SOC stocks in MUL and BUR were 16.4 and 13.7 Mg C ha^{-1} in the 0-5 cm layer, and 30.8 and 26.9 Mg C ha^{-1} in the 0-10 cm layer, respectively. Assuming that the SOC stock was constant in BUR due to similar cropping system for 50 years (steady state), the difference between MUL and BUR corresponded to an increase in MUL. At the 0-5 and 0-10 cm depths, this increase within six years reached 2.7 and 3.9 Mg C ha^{-1} respectively, i.e., 0.45 and 0.65 Mg C ha^{-1} yr^{-1} on average. Thus SOC storage under sugarcane cultivation with residue mulching was comparable to that achieved under no-tillage (i.e., with residue mulching): reviews regarding SOC storage for annual crops under no-tillage have reported increases averaging to 0.2 and 0.5 Mg C ha^{-1} yr^{-1} in dry and wet tropical areas, respectively (IPCC, 2001), and to 0.35 Mg C ha^{-1} yr^{-1} in tropical and subtropical areas (Six et al., 2002). Considering that the annual aboveground biomass returned to the soil was 13.9 Mg DM ha^{-1} and assuming that it included 40% carbon, it can be concluded that 27.8 Mg C ha^{-1} have been mulched in six years (five harvests). Compared to BUR, SOC at 0-10 cm increased by 3.9 Mg C ha^{-1} in MUL, which represented 14% of the aboveground biomass carbon returned as mulch. This was consistent with rates estimated under annual cropping systems involving residue mulching in tropical areas: SOC increases at 0-10 cm represented 11% of aboveground residue carbon for a sandy loam Ultisol (Barthès et al., 2004), 7 to 11% of aboveground residue carbon for a sandy clay loam Ultisol (Bayer et al., 2001), and 7 to 25% of total residue carbon for a clayey Oxisol (Sà et al., 2001).

4.2. Carbon in the size fractions

For the clayey Oxisol under study, SOC storage under residue mulching affected mainly the fraction < 2 µm: at the 0-5 cm depth, 67% of the difference in total SOC between MUL and BUR (4.2 g C kg^{-1}) was in the 0-2 µm fraction (2.8 g C kg^{-1}), which included 40% of total SOC. The water-soluble and 2-20 µm fractions, which included 10 and 30% of total SOC, represented 14 and 12% of the difference in total SOC between MUL and BUR, respectively.

Preferential SOC storage in fine fractions under cropping systems involving residue mulching has been reported by several authors: in a clayey Vertisol under long-term sugarcane cultivation with residue mulching, Graham et al. (2002) measured a 12 g C kg^{-1} SOC increase at a 0-5 cm depth, of which 0.5 g C kg^{-1} only affected the light fraction (density < 1.7) mainly constituted of coarse organic particles; in sandy Entisols under mulch in Senegal, Feller et al. (1987) observed carbon enrichment mainly in the fraction < 50 µm; in a sandy clay loam Ultisol under no-till systems, Bayer et al. (2001) also observed that SOC enrichment affected overall the fraction < 53 µm. In contrast, SOC enrichment resulting from residue burying has been reported to affect (i) all the fractions in clayey soils (Kapkiyai et al., 1999), but (ii) mainly the coarse fractions in sandy soils (Feller et al., 1983; Barrios et al., 1996). This suggests that the effect of residue return on the size-distribution of SOC depended on the location of the residues: mulching would increase the carbon concentration of the fine fractions mainly, whatever the texture, whereas burying would enrich all the fractions in clayey soils but coarse fractions mainly in sandy soils. Tillage, and plowing especially, results in the rapid incorporation of coarse plant debris into the soil, which does not occur when residues are left on the soil surface. However, mulching promotes the activity of soil macrofauna (Klavidko, 2001), as confirmed by Feller (2001) for the plots under study: the macrofauna diversity, density and biomass were greater in MUL than in BUR. As far as earthworms are concerned, density and biomass were also much greater in MUL than in BUR. It might thus be assumed that mulching stimulated the activity of macrofauna, earthworms especially, which contributed to residue burying and decomposition, and determined the enrichment of the fine fractions in carbon. Moreover, earthworms secrete mucus that is rich in water-soluble carbon (Brown et al., 2000), and could contribute to the greater amount of water-soluble carbon in MUL than in BUR. Literature data indicated that the mean residence time of carbon associated with fine soil fractions was rather long, and could amount to ca. 40 years for the Oxisol under study (Cerri et al., 1985), whereas it was less than 5 years for carbon associated with coarse fractions (Feller and Beare, 1997). This suggests that the carbon enrichment of the fine soil fraction under sugarcane residue mulching will result in long-term carbon storage, as it affected a pool with a slow turnover. Moreover, according to Hassink (1997), the capacity of a soil to protect carbon depends on the amount of SOC associated with particles < 20 µm. The maximum amount of SOC associated with this fraction could be estimated by the following equation:

$$\text{associated C (g C kg}^{-1}\text{ soil)} = 4.09 + 0.37 \times \%\ \text{particles} < 20\ \mu\text{m}.$$

Following this relationship, SOC bound to fine fractions could reach up to 32 g C kg^{-1} soil at a 0-5 cm depth in the Oxisol under study, indicating that its protective capacity was not saturated in MUL (SOC associated with particles < 20 µm was 18 g C kg^{-1} soil).

5. Conclusion

Sugarcane cultivation with residue mulching returns great amounts of carbon to the soil, which are otherwise lost when residues are burned. The comparison between residue management systems showed that residue mulching resulted in carbon accumulation in the clayey Oxisol under study: after six years, total SOC had increased by 15% at the 0-10 cm depth, which represented 0.65 Mg C ha^{-1} yr^{-1}, and 14% of mulched carbon. For the period under study, carbon enrichment mainly affected the 0-2 µm fraction, and to a lesser extent, the water-soluble fraction, whereas coarse fractions were not enriched. The mean residence time of carbon associated with the fine fractions being rather long, it might be assumed that the preferential storage in fine fractions resulted in a long-term carbon storage. Macrofauna and earthworms particularly, the biomass of which was greater under mulch, could have an important role in the carbon enrichment of the 0-2 µm fraction. Additional research is needed to assess directly the effect of earthworms on soil carbon pools. The present study was carried out within a productive cycle of sugarcane, which is generally six-year long: consequently, further research is also needed to assess the effects of replantation on SOC dynamics.

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Table 1. Total soil carbon (g C kg^{-1} soil) and nitrogen (g N kg^{-1} soil) and C/N ratios under sugarcane residue burning (BUR) or mulching (MUL) at the 0-5, 5-10 and 0-10 cm depths (means and standard deviations over six replicates).

Depth	Carbon (g C kg^{-1} soil)		Nitrogen (g N kg^{-1} soil)		C/N ratio	
	BUR	MUL	BUR	MUL	BUR	MUL
0-5 cm	21.0 ± 1.7 Aa	25.2 ± 2.4 Ba	1.6 ± 0.2 Aa	1.9 ± 0.2 Ba	13.5 ± 1.5 Aa	13.5 ± 0.6 Aa
5-10 cm	20.5 ± 2.3 Aa	22.3 ± 1.2 Ab	1.6 ± 0.2 Aa	1.7 ± 0.1 Aa	13.0 ± 1.5 Aa	13.1 ± 0.4 Aa
0-10 cm	20.7 ± 1.9 A	23.7 ± 1.7 B	1.6 ± 0.2 A	1.8 ± 0.2 A	13.2 ± 1.5 A	13.3 ± 0.5 A

For a given depth layer, capital letters mark significant differences between treatments ($p < 0.05$).
For a given treatment, lower-case letters mark significant differences between depth layers ($p < 0.05$).

Table 2. Carbon distribution in particle-size fractions in BUR (residue burning) and MUL (residue mulching) at the 0-5 cm depth (means and standard deviations over six replicates).

Treatment	Fraction	Weight	Carbon		C/N ratio
		(g kg^{-1} soil)	(g C kg^{-1} fraction)	(g C kg^{-1} soil)	
BUR	200-2000 µm	28.5 ± 4.4	21.4 ± 4.1	0.6 ± 0.2 Aa	29.0 ± 5.1 Aa
	50-200 µm	156.5 ± 21.2	12.0 ± 2.2	1.9 ± 0.6 Abc	21.7 ± 2.8 Ab
	20-50 µm	87.1 ± 6.3	16.6 ± 1.3	1.5 ± 0.2 Ab	19.6 ± 2.4 Ab
	2-20 µm	286.1 ± 21.7	23.4 ± 2.9	6.7 ± 1.3 Ad	14.6 ± 0.7 Ac
	0-2 µm	454.2 ± 43.1	17.7 ± 2.1	8.0 ± 0.6 Ad	11.1 ± 1.3 Ad
	Water-soluble	nd	nd	2.0 ± 0.2 Ac	nd
	Sum	1012.3 ± 3.5	nd	20.8 ± 2.0 A	nd
	NF soil	1000.0	21.0 ± 1.7	21.0 ± 1.7 A	13.5 ± 1.5 A
	Sum / NF soil (%)	101.2	nd	98.9 ± 3.3	nd
MUL	200-2000 µm	29.3 ± 4.9	22.1 ± 9.6	0.7 ± 0.3 Aa	31.9 ± 8.0 Aa
	50-200 µm	140.3 ± 12.7	12.1 ± 1.6	1.7 ± 0.1 Ab	21.9 ± 1.5 Ab
	20-50 µm	81.2 ± 6.8	20.8 ± 3.5	1.7 ± 0.3 Ab	19.3 ± 1.8 Ac
	2-20 µm	258.1 ± 32.2	27.6 ± 1.9	7.2 ± 1.3 Ad	14.9 ± 0.7 Ad
	0-2 µm	495.7 ± 28.7	21.9 ± 2.0	10.8 ± 0.6 Be	11.0 ± 0.2 Ae
	Water-soluble	nd	nd	2.6 ± 0.3 Bc	nd
	Sum	1004.5 ± 2.5	nd	24.6 ± 2.0 B	nd
	NF soil	1000.0	25.2 ± 2.4	25.2 ± 2.4 B	13.5 ± 0.6 A
	Sum / NF soil (%)	100.5	nd	97.9 ± 2.3	nd

NF soil: non fractionated soil (< 2 mm).
nd: nt determined.
For a given fraction, capital letters mark significant differences between treatments ($p < 0.05$).
For a given treatment, lower-case letters mark significant differences between fractions ($p < 0.05$).