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Storage and forms of organic carbon in a no-tillage under cover crops system on clayey Oxisol in dryland rice production (Cerrados, Brazil)

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Abstract

The management and enhancement of soil organic carbon (SOC) is very important for agriculture (fertility) as well as for the environment (carbon (C) sequestration). Consequently, changes in soil management may alter SOC content. No-tillage (NT) practices are potential ways to increase SOC. We studied the SOC from agricultural soils in the Cerrados in Central Brazil. We compared two different tillage systems: conservation agriculture with no-tillage under cover crops (NT) and disc tillage (DT) for 5 years in a context of rainfed rice production. The soil is a dark red Oxisol with high clay content (about 40%). The objectives of the study were: (i) to evaluate the short-term (5 years) impact of tillage systems on SOC stocks in an Oxisol and (ii) to better understand the dynamics of SOC in different fractions of this soil. We first studied the initial situation in 1998, and compared it to the 2003 situation. NT with cover crop (*Crotalaria*) was found to increase the storage of C in the topsoil layer (0–10 cm) compared to DT. The difference observed for the 0–10 cm layer under NT in comparison with DT represented C enrichment under no-tillage amounting to 0.35 Mg C ha^{-1} $year^{-1}$ and corresponding to less than 10% of cover crops residues returned to the soil. A particle-size fractionation of soil organic matter (SOM) showed that differences in total SOC between NT and DT mainly affected the 0–2 μm fraction and, to a smaller extent the 2–20 μm fraction.

This specific enrichment of SOC in the silt and clay fraction was attributed to (i) the storage of a water soluble C in the field and (ii) the effect of soil biota and especially fauna activity. 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. This study suggests a positive short-term effect of a no-tillage system on C sequestration in an Oxisol.

Keywords: Oxisol; No-tillage; Carbon sequestration; Particle-size fractionation of SOM; Cerrados; Brazil

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1. Introduction

No-tillage systems (NT) correspond to farming systems in which sowing is done in a narrow trench, without tillage and weeds are often controlled with herbicide. They are supposed to maintain a permanent or semi-permanent organic soil cover, the function of which is to protect the soil physically from sun, rain and wind and to feed soil biota. The NT systems use direct seeding into a mulch. NT systems can be divided broadly into two types: one with the mulch deriving from the crop residues, the second in which the cultivated plant is associated with another cover plant. In this case, mulch derives from both crop and cover plant residues.

Approximately 63 millions ha are currently under NT systems over the world, with USA having the largest area at about 21.1 million ha (Dersch and Böhm, 2001). The 18 millions ha covered by NT make Brazil the second largest adopter in the world (Bernoux et al., 2006).

In Brazil, NT was developed in response to soil erosion and continuous declines in land productivity under "conventional" systems based on soil tillage (CT). Several experiments conducted throughout humid tropical areas have demonstrated effectively the erosion-control efficiency of no-till farming (Lal, 1995). The main environmental reasons for the development of NT systems was to (i) protect the soil surface from sealing and crusting by rainfall, (ii) achieve and maintain an open internal soil structure and (iii) develop the means for safe disposal of any surface runoff that would nevertheless still occur. Consequently, the NT technical strategy was based on two essential farm practices: (i) not tilling the soil; (ii) simultaneously maintaining soil cover.

NT systems were first developed in the south of Brazil then extended at the beginning of the 1980s to the Cerrado region (Central area of Brazil covered by Savannah vegetation) and quickly gained in popularity in that region. Actually, it was shown to be beneficial agronomically and economically, as well as at the livelihood level (working time, etc.). Thus, they are considered as suitable farming systems, despite some necessary adaptations (Reyes, 2002).

Worldwide, greenhouse gas mitigation in soils (SOC storage and decrease in CH_4 and N_2O emissions) has become an active research area and there is increasing concern regarding human influence on the carbon cycle and restoration of degraded soils. It is generally acknowledged that conversion of native vegetation to agriculture has resulted in a massive net transfer of carbon from the soil to the atmosphere, hence contributing to the greenhouse effect.

Any modification of the land use and of the management, even for the agricultural systems at a steady state, can induce variations of the SOC stocks, converting the soil to either a sink or a source of atmospheric CO_2, with direct influence on the greenhouse effect (Lugo Ariel and Brown, 1992; Lal, 2004). For instance, in tropical areas, ploughing has a significant impact by decreasing in SOC stocks in the topsoil layer (Lal, 1976; Resck, 1998; Bayer et al., 2000a; Sá et al., 2001). That negative effect of ploughing can be due a lower aggregate stability, disruption of macroaggregates and more available oxygen, resulting in a major exposure of SOC to microbial mineralization (Tisdall and Oades, 1982).

In standard NT, organic fertilizers are generally used to complement organic amendments, and herbicides are applied to control weeds, especially during the transition phase from conventional to NT practices. The possibility to control, for a long period and in a tropical environment, a system where crops and cover plants are successively installed, and its economic interest have been recognized. We hypothesize that these systems can also enhance carbon sequestration in the soils. However, this is a complex issue, as the organic matter accumulation contributes to the supply of mineral elements and also to the enrichment of the SOM stock. Some authors showed that under NT systems, the stable SOC pool was significantly greater than under tillage systems. In Brazil, various studies (Testa et al., 1992; Castro Filho et al., 1998; Riezebos and Loerts, 1998; Bayer and Bertol, 1999; Corazza et al., 1999; De Maria et al., 1999; Bayer et al., 2000b, 2002; Amado et al., 2001; Machado and Silva, 2001; Freixo et al., 2002; Venzke Filho et al., 2002; Perrin, 2003; Scopel et al., 2003; Siqueira Neto, 2003; Zotarelli et al., 2003; Sisti et al., 2004) gave rates of SOC storage varying from 0 up to 1.7 Mg C ha^{-1} for the 0–40 cm soil, with the highest rates in the Cerrado region.

Another question is the form and dynamics of the stored SOC (Six et al., 2001). One approach for these studies, besides the study of the dynamics of the total SOC is to consider different SOM pools differing by their dynamics. One of the methodologies generally involved to study these dynamics is the physical fractionation of SOM (Christensen, 2001; Feller, 1995; Feller et al., 2001). It is known that the SOC turnover decreases from the plant residues fractions (sand-size) to the organo-silt and organo-clay fractions (Feller and Beare, 1997).

The objective of this paper was to evaluate for the Cerrados area of central Brazil and for a rainfed rice (*Oryza sativa*) crop system the effects of NT systems on the SOC stocks and the particle-size distribution of SOM.

2. Material and methods

2.1. Site description

The experiment was carried out in Goiânia, Goiás state, Brazil. The natural vegetation is a tree savannah forest (Cerrados). The local climate is tropical with a humid season from October to March and a dry season from April to September. The mean annual temperature is 22.5 °C and mean annual precipitation is 1500 mm.

The soil is a clayey Oxisol according to the USA classification, a ''latosolo vermelho escuro distrofico'' according to the Brazilian classification and a Ferralsol according to the ISSS Working Group R.B. (1998). This soil also shows a low level of cation exchange capacity, dominated by exchangeable Ca. Therefore, pH-H_2O is close to neutral (6.0–6.5).

2.2. Experimental design

The experimental layout was established in 1998 by L. Séguy and S. Bouzinac (CIRAD) and consisted of three different tillage systems. The experiment is located on a 400 m × 150 m field, situated 25 km from North-Goiânia, in a field of the Centro Nacional de Pesquisa sobre Arroz e Feijão (CNPAF) center. Six strips (10 m width) were installed in the 1980s to compare three different tillage systems: no-tillage (NT), conventional tillage (DP) and disc tillage (DT). These terraces were cultivated within a Centre International de Recherche Agronomique pour le Développement (CIRAD) and Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA) project. For this study only DT and NT treatments were studied. The non-studied treatment DP was a conventional tillage treatment, consisting of deep ploughing to a depth of 40 cm with burial of crop residues.

2.3. Treatments

Each plot was 8 m width; 50 m length. Rice and soya were cultivated in alternate years. The two treatments studied were:

DT: Disc tillage with an offset disk harrow to 15 cm depth. Crop residues were left on the soil surface.

NT: No-tillage treatment, with cover crops: *Brachiaria* (grass) and *Crotalaria* (leguminous plant) cultivated in alternate years. *Brachiaria ruziziensis* was planted in April after the rice plots were harvested. *Brachiaria* is the most common forage crop used in Brazil. It is a grass resistant to drought with high potential of root development. *Crotalaria spectabilis* was planted in April after the soya was harvested. *Crotalaria* is a leguminous plant that develops a large root system even during the dry season. Crop residues were left on the soil surface, in addition to the cover crops. Pre-emergent herbicides were used to protect the crop. NT treatments were treated before planting with Paraquat and glyphosate as needed for weed control.

Mineral fertilization was similar for the three treatments and was representative for the average practices in the region. The nitrogen fertilization was applied to the rice crop in form of ammonium sulfate (100 kg ha^{-1}) immediately after seeding and urea (100 kg ha^{-1}) 2 and 6 weeks after seeding and represented a total of 111 kg N ha^{-1} for the 2-year rotation. The P and K fertilization (Supertriple and KCl forms) corresponded to 120 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1}, respectively. There were 36 plots corresponding to 12 replicates for each treatment. The present study only considered the rice plots, with a mulch made of *Crotalaria* residues for NT plots.

2.4. Plots selected for this study

To study SOC dynamics and greenhouse gas fluxes (to be published later) four cultivated plots were selected in 2003 from the whole experimental design. The selection was based on the SOC carbon contents of the 0–10 and 10–30 cm layers at the beginning of the experiment (1998). For the whole experimental design, the initial (1998) SOC contents for the 0–10 cm layer ranged from 12.0 to 20.0 g C kg^{-1} soil (Lagaye, 1999) and the different plots were classified into three groups: 12.0–14.9; 15.0–17.9 and 18.0–19.9 g C kg^{-1} soil and more. C contents for the 10–30 cm layer were the same for both systems. On this basis, we selected four plots in the SOC class 15.0–17.9: two plots under NT treatment (NT11, NT15) and two plots under DT treatment (DT21 and DT24).

2.5. Soil sampling

The 1998 soil sampling was done immediately after installing the whole experiment with three replications per plot. The 2003 soil sampling for the four selected plots consisted in six replications per plot.

2.6. Particle-size fractionation of organic matter (PSOM fractionation)

From the six soil replicates, a composite soil sample was prepared for the PSOM fractionation by dry sieving at 2 mm. Fractionation of the 0–2 mm soil sample was conducted according to the method of Gavinelli et al. (1995) involving successive wet sievings of the soil under water and sedimentation steps, with the objective of maximizing soil dispersion while minimizing the degradation of organic constituents. The following fractions were separated: coarse sands and plant residues size 200–2000 μm (F200–2000); fine sands and plant residues size 50–200 μm (F50–200); silts size 2–50 μm (F2–20; F20–50) and clays size 0–2 μm (F0–2); water soluble fraction (WS). The fractionation procedure involved dispersion with sodium hexametaphosphate (HMP); shaking 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 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 (0–10 cm depth), i.e., 12 replications for each treatment.

2.7. Mechanical analysis

The protocol is similar to the previous PSOM fractionation, but includes a preliminary destruction of organic matter: 10 g of soil were mixed with 20 ml of hydrogen peroxide (H_2O_2, 30 vol.) during 24 h at room temperature. After adding a further 5 ml of H_2O_2 and bringing the volume in the beaker up to 200 ml with purified water, the suspension was heated at 80 °C during 6 h and gently boiled during 20 min.

2.8. C and N analysis

C and N contents of soils and particle-size fractions were determined using the Dumas dry combustion method (CHN Carlo Erba NA 2000 Thermo Finnigan apparatus). Each presented value is the mean of three laboratory replicates. As the soil did not contain calcium carbonate, total soil C is estimated to be equal to SOC. Water-soluble organic carbon was measured 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. Soil organic carbon contents and stocks

The SOC contents of the 0–10 cm and the 10–30 cm layers were calculated in Table 1. Bulk densities of the 0–10 cm layer measured in 2003, were poorly affected by tillage system mainly due to the short-term effect of this experimental design (only four cropping cycles), and were not significantly different for DT (1.25 g cm^{-3}) and for NT (1.27 g cm^{-3}). Moreover, neither SOC content nor bulk density were different in depth for these two treatments below 10 cm (data not shown). Thus, corrections for bulk density were not needed to estimate C stocks (Roscoe and Buurman, 2003). SOC stocks for NT in 1998 and 2003 were calculated with a mean bulk density of 1.30 in 1998 (Lagaye, 1999) and 1.27 in 2003 and SOC stocks for DT in 1998 and 2003 were calculated with a mean bulk density of 1.23 in 1998 (Lagaye, 1999) and 1.25 for 2003 (Table 1). The mean increase (average values for NT11 and NT15) of SOC stock by the NT system in comparison with the DT system was estimated to 1.4 Mg C ha^{-1} for four cropping cycles or 0.35 Mg C ha^{-1} year^{-1}.

For DT treatments there were no significant differences in SOC content for each year between the

Table 1
Soil C stocks (Mg ha^{-1}) in 1998 and 2003 for NT and DT and mean annual C enrichment (Mg ha^{-1} year^{-1})

Treatment	C content[a] (g kg^{-1} soil)		Bulk density (g cm^{-3})		C stock (Mg ha^{-1})		ΔC (2003–1998)[b] (Mg C ha^{-1})	ΔC (NT–DT)[c] (Mg C ha^{-1} year^{-1})
	1998	2003	1998	2003	1998	2003	2003–1998	2003–1998
NT	16.50 (0.14)	17.55 (2.05)	1.30	1.27	21.45	22.29	0.84	0.35
DT	16.65 (0.64)	15.95 (1.06)	1.23	1.25	20.48	19.94	−0.54	–

[a] Mean and standard error (between brackets) for 12 replicates (6 per plot).

[b] The difference in the mean C evolution between 1998 and 2003 for each treatment was significant (*t*-test at 5% probability).

[c] The mean annual enrichment in C was calculated between 1998 and 2003 considering four cropping cycles.

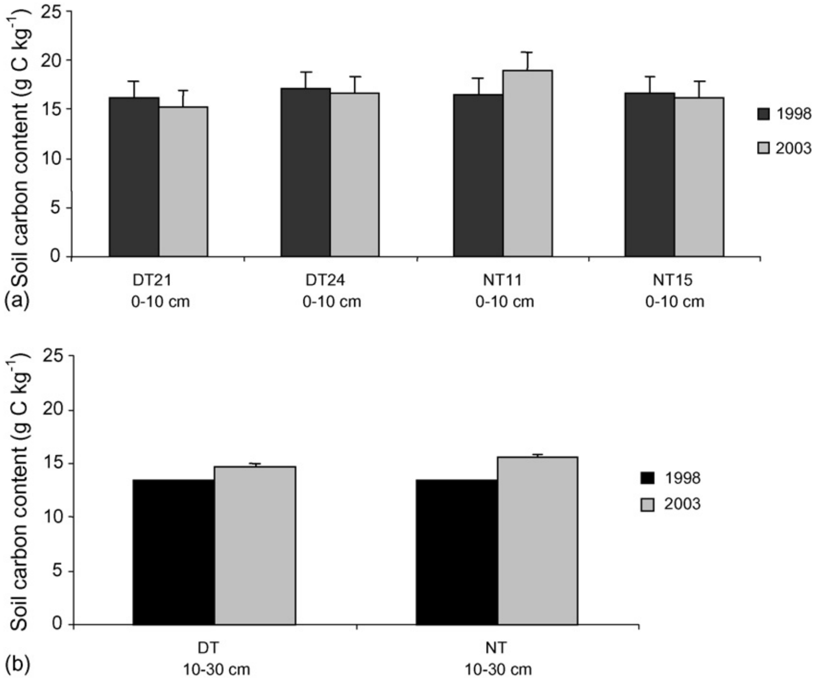

Fig. 1. SOC contents for the 0–10 cm (a) and 10–30 cm (b) soil layers for the selected plots in 1998 and 2003.

two plots and between the 2 years (1998 and 2003) with very similar mean values (16.2 and 15.2 g C kg^{-1} soil for DT21 and 17.1 and 16.7 g C kg^{-1} soil for DT24) for the 0–10 cm (Fig. 1a). For NT treatment, there was an increase in SOC content for NT11 (16.4–19 g C kg^{-1} soil) between the 2 years, but not for NT15 (16.6–16.1 g C kg^{-1} soil) for the 0–10 cm layer. For NT11 the difference was significant only at the 8% level (Fig. 1a).

According to Fig. 2(b), the increases of SOC in the top layer were not compensated for by decreases in SOC in deeper layers (10–30 cm), for a general increase in carbon content in the deeper layer was noticed for both treatments (13.5 g C kg^{-1} soil to 14.65 for DT and 13.5 g C kg^{-1} soil to 15.5 g C kg^{-1} soil for NT).

From 1998 to 2003, C contents in the 10–30 cm increased for both treatments: 13.5–14.65 g C kg^{-1} soil and 13.5–15.5 g C kg^{-1} soil for DT and NT, respectively.

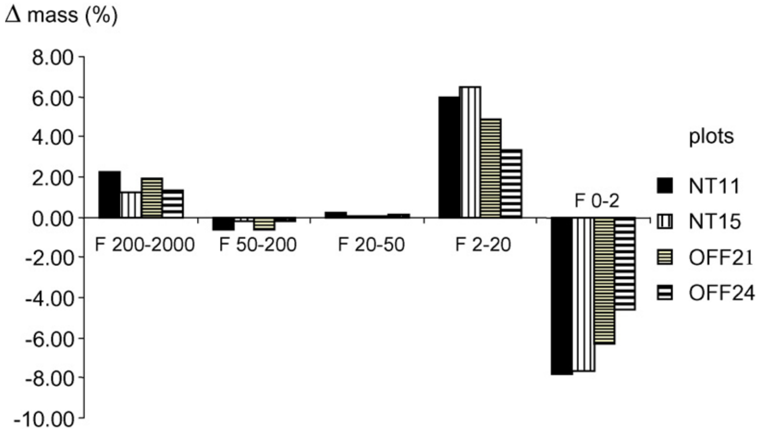

Fig. 2. Differences in the mass (mass%) of the different fractions obtained by PSOM fractionation or mechanical analysis (values expressed in % of the mass obtained by PSOM fractionation).

Table 2
Characteristics of the particle size organic matter fractions for the 0–10 cm soil layer of the four selected plots (mean and standard error (between brackets) for six replicates)

Plot	Treatment	Fraction	%Mass	Carbon			C/N ratio
				C g kg^{-1} fraction	C g kg^{-1} soil	C% C NFS	
NT11	NT	F200–2000	14.52 (0.04)	4.27 (1.40)	0.62 (0.20)	3.26 (1.06)	37.64 (15.88)
		F50–200	23.89 (0.26)	4.18 (0.36)	1.00 (0.08)	5.25 (0.40)	26.07 (1.33)
		F20–50	4.71 (0.22)	22.31 (1.11)	1.05 (0.02)	5.52 (0.12)	21.48 (0.98)
		F2–20	21.33 (0.25)	30.06 (0.29)	6.41 (0.03)	33.69 (0.16)	19.50 (1.78)
		F0–2	36.42 (0.34)	21.75 (0.03)	7.92 (0.07)	41.63 (0.39)	16.93 (1.54)
		WS	nd	9.55 (0.24)	2.88 (0.07)	14.66 (0.36)	nd
		sum	100.88 (0.02)	20.05 (0.26)	19.88 (0.26)	104.00 (1.35)	–
		NFS(*)	100.00 (0.00)	19.03 (0.00)	19.03 (0.00)	100.00 (0.00)	15.22 (0.00)
NT15	NT	F200–2000	14.29 (0.80)	2.04 (0.35)	0.29 (0.05)	1.81 (0.31)	35.26 (12.94)
		F50–200	24.61 (0.53)	3.44 (0.05)	0.85 (0.02)	5.27 (0.15)	27.25 (0.40)
		F20–50	4.35 (0.05)	16.42 (1.45)	0.71 (0.06)	4.44 (0.35)	23.19 (0.27)
		F2–20	19.53 (0.08)	27.89 (0.50)	5.45 (0.07)	33.87 (0.47)	24.38 (0.38)
		F0–2	38.24 (0.26)	20.69 (0.17)	7.91 (0.12)	49.21 (0.73)	20.51 (0.22)
		WS	nd	12.71 (0.57)	1.27 (0.06)	8.00 (0.38)	nd
		sum	101.30 (0.08)	16.65 (0.17)	16.48 (0.17)	102.60 (0.40)	–
		NFS(*)	100.00 (0.00)	16.08 (0.00)	16.08 (0.00)	100.00 (0.00)	15.24 (0.00)
OFF21	OFF	F200–2000	15.26 (0.33)	2.49 (0.53)	0.38 (0.07)	2.48 (0.48)	35.77 (9.21)
		F50–200	23.64 (0.43)	3.41 (0.03)	0.81 (0.02)	5.28 (0.12)	29.05 (0.49)
		F20–50	4.16 (0.18)	17.47 (0.15)	0.73 (0.03)	4.76 (0.22)	19.62 (0.03)
		F2–20	17.23 (0.22)	28.28 (0.60)	4.87 (0.11)	31.90 (0.69)	17.12 (0.86)
		F0–2	40.72 (0.22)	18.86 (0.51)	7.68 (0.25)	50.29 (1.61)	13.38 (0.47)
		WS	nd	4.80 (0.20)	1.44 (0.06)	9.40 (0.40)	nd
		sum	101.01 (0.16)	16.07 (0.4)	15.91 (0.40)	104.10 (2.64)	–
		NFS(*)	100.00 (0.00)	15.27 (0.00)	15.27 (0.00)	100.00 (0.00)	16.36 (0.00)
OFF24	OFF	F200–2000	14.51 (0.48)	2.11 (0.05)	0.31 (0.02)	1.83 (0.10)	26.54 (1.71)
		F50–200	22.98 (0.44)	3.46 (0.13)	0.79 (0.04)	4.74 (0.26)	29.51 (0.83)
		F20–50	4.01 (0.02)	15.67 (0.78)	0.63 (0.03)	3.75 (0.17)	19.82 (0.46)
		F2–20	19.37 (0.75)	27.89 (0.38)	5.40 (0.20)	32.23 (1.21)	16.91 (0.12)
		F0–2	40.03 (0.75)	19.52 (0.08)	7.81 (0.17)	46.61 (1.01)	15.07 (0.47)
		WS	nd	4.86 (0.13)	1.47 (0.04)	8.55 (0.23)	nd
		sum	100.90 (0.04)	16.55 (0.08)	16.41 (0.08)	97.71 (0.50)	–
		NFS(*)	100.00 (0.00)	16.76 (0.00)	16.76 (0.00)	100.00 (0.00)	16.39 (0.00)

NFS(*): non fractionated soil; nd: non determined.

3.2. Particle size fractionation of organic matter (PSOM fractionation)

As the 0–10 cm layer is mainly affected by the difference in SOM, PSOM fractionation was done on the 2003 soil samples (0–10 cm layer) for the four selected plots. Detailed results are presented in Table 2.

Total fraction mass, SOC and N balances vary from 100.88 to 101.03%; 97.7 to 104.1% and from 81.5 to 100.1%, respectively. Lower values for N (data not shown) were due to the non-measurement of the soluble N content in the water fraction. These results allow us to conclude that the PSOM fractionation was correctly achieved regarding the mass and C balances.

The evaluation of the dispersion level obtained by PSOM fractionation is an important criteria for the interpretation of the results of the fractionation method (Feller et al., 1991; Christensen, 1992). Therefore, we compared the mass distribution of the PSOM fractionation to the mechanical analysis including the H_2O_2 treatment for oxidation of SOM. The comparison was done on a mineral basis (without OM). Fig. 2 shows that aggregate disruption and dispersion of fine particles down to 20 μm were achieved but that the 2–20 μm fraction of the PSOM fractionation contains a part of the organo-clay fraction 0–2 μm. As a consequence the 0–2 μm fraction of the PSOM is impoverished in clay.

Concerning the mass and C variabilities due to the PSOM fractionation estimated from three replicates of each sample, the largest coefficients of variation were observed for the 200–2000 μm fraction (Table 3).

Table 3
Range of coefficient of variation (CV%) associated with the particle size organic matter fractionation of the C content and the C:N ratio for the 0–10 cm

Particle-size Œfraction	Coefficient of variation CV (%)		
	C (g kg^{-1} fraction)	C (g kg^{-1} soil)	C:N ratio
F200–2000	3–33	5–33	6–42
F50–200	1–9	2–8	1–5
F20–50	1–9	2–8	1–5
F2–20	0–3	0–4	1–9
F0–2	0–3	1–3	1–9
WS	2–4	2–5	–

WS: water-soluble organic carbon determined from the supernatant after 0–2 μm filtration (Gavinelli et al., 1995).

The main part of the SOC is represented by the 0–20 μm fraction both for DT (78%) and for NT (79%). The water soluble fraction is not negligible and represents from 8 to 15% of the total SOC (Table 2). The mean C:N ratios of the non-fractionated soil (NFS) were 15.2 for NT and 16.4 for DT. The C:N ratio is always higher for the 200–2000 μm fractions: 36.5 ± 14.1 for NT and 31.2 ± 5.5 for DT. It decreases from the coarse sand (26–38) to the clay fraction (13–20).

The effect of NT on the distribution of SOC (g C kg^{-1} soil) in the different fractions is shown in Fig. 3 for both 0–10 and 10–30 cm layers.

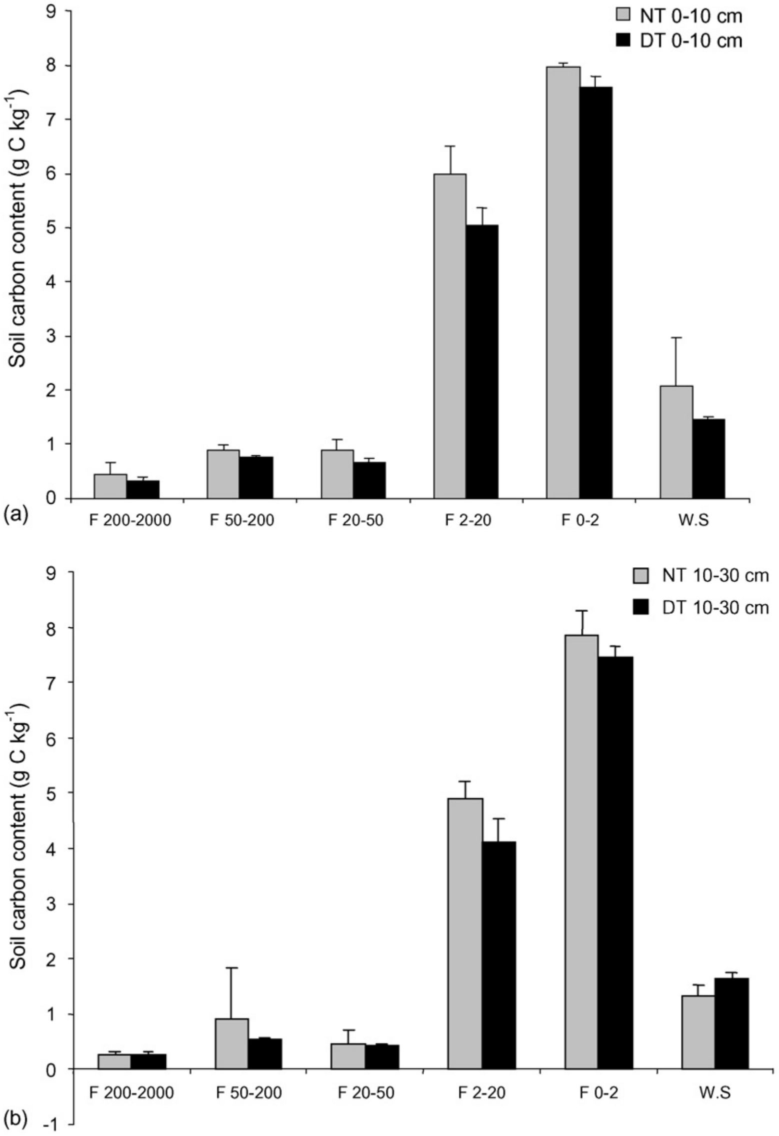

Fig. 3. SOC content (g C kg^{-1} soil) of the different fractions for the 0–10 cm (a) and 10–30 cm (b) soil layers for the no-tillage (NT) and disc tillage (DT) treatments.

For both layers, no significant effect of NT were observed for the fractions larger than 20 μm and the water soluble fractions. But differences were significant for both the 2–20 and 0–2 μm fractions ($p < 0.05$), the largest difference being observed for the finer silt fractions.

4. Discussion

SOC contents and stocks were at the equilibrium for the 2 DT plots (no significant variation) between 1998 and 2003. But a trend to increases of SOC contents and stocks was observed for NT plots in the 0–10 cm soil layer. That increase represents about 16% of the total SOC of the DT treatment soil.

It represents a mean SOC storage of 0.35 Mg C ha^{-1} year^{-1} which agrees with the general trend observed in the synthesis done by Bernoux et al. (2006) presented in Fig. 4 and the regression coefficient of 0.30 Mg C ha^{-1} year^{-1} determined from this review.

The organic carbon contributed by the cover crops in the NT treatment was estimated for the different plots: the aerial part represents 4 Mg ha^{-1} year^{-1} (dry matter), we assume that the whole cover (aerial part plus root system) plant represents 8 Mg ha^{-1} year^{-1}. We also assume that the C content of the whole cover is 42% of the total cover dry matter. Thus, the supplementary contribution in organic carbon due to NT treatments is about 3.36 Mg C ha^{-1} year^{-1}. Therefore the storage of about 0.35 Mg C ha^{-1} year^{-1} represents 10.5% of the restitutions which is in agreement with the general humification rates shown in the literature (Combeau and Quantin, 1964; Pansu, 1991).

For DT plots, SOC is mainly (78%) associated to the <20 μm fractions with a low C:N ratios (13.38–17.12). The >20 μm fractions (22%) exibit larger C:N ratios due to their plant debris origin (Feller and Beare, 1997). A general trend in decrease of the C:N ratio with the decrease of the size of the fraction is observed generally for tropical soils. These values were similar to those published by Rafazimbelo et al. (2003) for a clayey Oxisol cultivated under sugarcane in the state of São Paulo in Brazil.

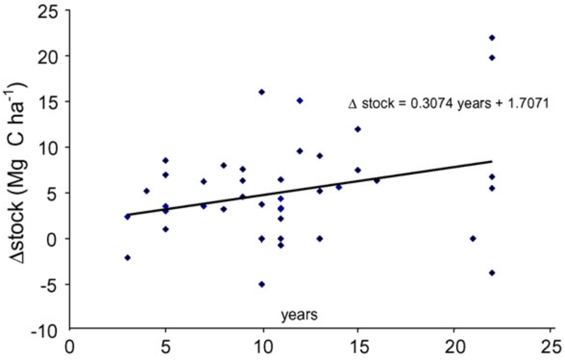

Fig. 4. Differences in SOC stocks (Mg C ha^{-1}) between various no-tillage (NT) and conventional (CT) systems for Brazilian situations (after Bernoux et al., 2006).

It is shown in Fig. 2 that the dispersion level by the fractionation method used was efficient down to 20 μm but not at a lower size: a non-negligible part of the organo-clay fraction remained associated with the organosilt in the form of microaggregates 2–20 μm. Therefore, it is difficult to discuss separately these two fractions. The increase in SOC contents and stocks observed after 4 years of NT for the 0–10 cm soil layer was mainly attributable to increases in the <20 μm fractions. Roscoe and Buurman (2003) used density fractionation to assess changes in SOM in an Oxisol for NT and plough tillage (PT) systems. The free light-fraction (F-LF) was most sensitive to changes in soil management. The proportion of C replacement in this fraction was higher in PT than in NT, suggesting a faster turnover time with ploughing. Nevertheless, C dynamics in the suited soil was controlled by the behaviour of the heavy fraction (HF) because most C (95%) was held in this fraction which has very slow decomposition rate. No difference was observed in density fractions between NT and PT, due to high clay content and Fe + Al oxi-hydroxides concentrations and high C supply by the crop.

SOM fractionation was also applied to various clayey tropical soils by Feller (1995) and Feller and Beare (1997) for different options of soil management, but not with NT treatments. These authors showed that when SOC increase is observed, it concerns both the >20 μm and <20 μm fractions and not only the <20 μm fractions. Therefore, NT treatments present a different process of SOC storage. This effect was also observed for NT or mulch based systems in Brazilian soils by other authors: Rafazimbelo et al. (2003) for unburnt sugarcane systems and Bayer et al. (2000b) for different NT systems. Two main processes can be involved to explain this specific enrichment of SOC in the silt and clay fraction:

(i) storage of a water soluble C in the field originated from the cover plant material (aerial and roots) and transfered into the 0–10 cm soil layer under rainfall; if we consider the water soluble (WS) fraction obtained from PSOM fractionation, WS was not significantly different between NT and DT treatments;

Table 4
A summary from literature of data from some experiments on the effect of earthworms on the distribution of SOC content in two particle-size fractions: >50 μm (50–2000 μm) and <50 μm (0–50 μm)

Experiment number[*] (type and duration)	Location	Earthworm	SOC content (g kg^{-1} soil)	Clay content (g kg^{-1} soil)	Differences in SOC content (g kg^{-1} soil) of > and <50 μm fractions between EW + and EW−[***]	
					>50 μm	<50 μm
1 (Incubation, 1 day)	Lamto (Ivory Coast)	*Millsonia anomala*	10.9	95	−0.47	+0.24
2 (Incubation, 7 days)	Yurimaguas (Mexico)	*Pontoscolex corethrurus*	22.8	90	−5.38	+4.00
3 (Cultivation, Yam, 3 years)	Lamto	*Millsonia anomala*	8.5	60	+0.1	+0.4
4a (Cultivation, Maize, 3 years, E[**])	Lamto	*Millsonia anomala*	12.0	50	−0.5	+0.2
4b (Cultivation, Maize, 3 years, L[**])	Lamto	*Millsonia anomala*	12.0	50	−0.2	−0.6
5 (Cultivation, Maize, 6 years, E)	Yurimaguas	*Pontoscolex corethrurus*	15.0	230	−0.6	+0.3

Differences were recalculated from the original primary data.

[*] Experiment: (1) Martin (1991); (2) Chapuis-Lardy et al. (1998); (3–5) Villenave et al. (1999).

[**] E: litter exported, L: litter incorporated.

[***] EW+ and EW− = experiment with or without earthworms activity, respectively. Negative and positive differences indicate a loss or a gain respectively in SOC content of the given fraction.

(ii) effect of soil biota and especially fauna activity.

Concerning the effect of fauna activity, it could be explained by the following fauna hypothesis:

(i) NT systems do not involve an immediate and mechanical incorporation of above plant residues into the soil as is the case for tillage systems. That incorporation is actually mainly done by soil fauna activity;
(ii) soil fauna activity is dramatically increased in NT systems. That was shown by Cerri et al. (2004) for the same soil type in Brazil (São Paulo state). In only 3–4 years the biomass and diversity of soil fauna due to the mulch of sugarcane leaves were drastically restored to a level of soil fauna activity similar to that under forest. Close to our experiment (Fazenda Santa Helena, state of Goiás, Brazil), NT systems were also studied for soil fauna and it was shown (Minette, 2000; Blanchart, personal communication) that for the first year of NT a large increase in soil fauna biomass was observed and especially in earthworms;
(iii) there are few data for tropical areas on the effect of soil fauna on SOM distribution within the different particle-size fractions. The main ones concern earthworms and a summary of some published data is given in Table 4.

In incubation (without plant) studies with (EW+) or without (EW−) earthworms (EW), both Martin (1991) and Chapuis-Lardy et al. (1998) showed that after 1 and 7 days incubation, respectively, the presence of EW lead to a decrease of SOC content (g kg^{-1} soil) in the >50 μm fractions and an increase in the <50 μm fractions. On the other hand, for four pot experiments with plants (cultivation during 3–6 years) and with or without EW, Villenave et al. (1999) showed also that for three of the four experiments, an increase of SOC in the <50 μm fractions in presence of EW was also observed. So a general trend of enrichment of SOC in the <50 μm fraction due to earthworm activity is observed, and supports the hypothesis of a major role of the fauna activity in a specific increase of the SOC in the <50 μm or <20 μm fraction for the NT and cover plant systems.

5. Conclusions

No-tillage with cover crops systems returns great amounts of C to the soil. The comparison between NT and CT systems showed a 0.35 Mg C ha^{-1} year^{-1} increase in the SOC content in the 10 cm topsoil layer in no-tillage system (NT) compared with tilled system (DT) in the Cerrados due to high crop-residue input and lack of soil disturbance. This enrichment corresponds to a 10.5% humification rate.

For the period under study, carbon enrichment mainly affected the 0–2 μm fraction and to a lesser extent, the 2–20 μm 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.

According to this study, and besides the well-known agronomic standpoint, NT is also beneficial regarding its C sequestration balance. However, C sequestration (Bernoux et al., 2006) for a specific agro-ecosystem in comparison with a reference one, should be considered as the result (for a given period of time and portion of space) of the net balance of all greenhouse gases, expressed in C-CO_2, computing all emission sources at the soil–plant–atmosphere interface. As a consequence, comparing this NT system with this DT system means not only taking into account the carbon storage but also the resulting greenhouse effect gas fluxes such as CH_4 and N_2O fluxes. So, further research is needed especially in tropical soils, where data on this matter is lacking.

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