CARBON STOCK AND ITS COMPARTMENTS IN A SUBTROPICAL OXISOL UNDER LONG-TERM TILLAGE AND CROP ROTATION SYSTEMS[1]

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ABSTRACT

Soil organic matter (SOM) plays a crucial role in soil quality and can act as an atmospheric C-CO_2 sink under conservationist management systems. This study aimed to evaluate the long-term effects (19 years) of tillage (CT-conventional tillage and NT-no tillage) and crop rotations (R0-monoculture system, R1-winter crop rotation, and R2- intensive crop rotation) on total, particulate and mineral-associated organic carbon (C) stocks of an originally degraded Red Oxisol in Cruz Alta, RS, Southern Brazil. The climate is humid subtropical Cfa 2a (Köppen classification), the mean annual precipitation 1,774 mm and mean annual temperature 19.2 °C. The plots were divided into four segments, of which each was sampled in the layers 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m. Sampling was performed manually by opening small trenches. The SOM pools were determined by physical fractionation. Soil C stocks had a linear relationship with annual crop C inputs, regardless of the tillage systems. Thus, soil disturbance had a minor effect on SOM turnover. In the 0–0.30 m layer, soil C sequestration ranged from 0 to 0.51 Mg ha^{-1} yr^{-1}, using the CT R0 treatment as base-line; crop rotation systems had more influence on soil stock C than tillage systems. The mean C sequestration rate of the cropping systems was 0.13 Mg ha^{-1} yr^{-1} higher in NT than CT. This result was associated to the higher C input by crops due to the improvement in soil quality under long-term no-tillage. The particulate C fraction

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was a sensitive indicator of soil management quality, while mineral-associated organic C was the main pool of atmospheric C fixed in this clayey Oxisol. The C retention in this stable SOM fraction accounts for 81 and 89 % of total C sequestration in the treatments NT R1 and NT R2, respectively, in relation to the same cropping systems under CT. The highest C management index was observed in NT R2, confirming the capacity of this soil management practice to improve the soil C stock qualitatively in relation to CT R0. The results highlighted the diversification of crop rotation with cover crops as a crucial strategy for atmospheric C-CO_2 sequestration and SOM quality improvement in highly weathered subtropical Oxisols.

Index terms: carbon sequestration, no-tillage, conventional tillage, soil management.

RESUMO: *ESTOQUE E COMPARTIMENTOS DE CARBONO EM UM LATOSSOLO VERMELHO SUBTROPICAL SOB DIFERENTES SISTEMAS DE LONGO PRAZO DE PREPARO E ROTAÇÃO DE CULTURAS*

A matéria orgânica do solo (MOS) desempenha papel relevante na qualidade do solo e pode atuar como dreno de C-CO_2 atmosférico em solos sob sistemas de manejo conservacionista. Este estudo foi realizado com o objetivo de investigar o efeito de longo prazo (19 anos) de sistemas de preparo do solo (PC-preparo convencional e PD-plantio direto) e de rotação de culturas (R0- sucessão de monoculturas, R1- rotação de culturas de inverno e R2- rotação intensiva de culturas) no estoque de carbono (C) orgânico total, particulado e associado a minerais de um Latossolo Vermelho, originalmente degradado, do Sul do Brasil. O clima é subtropical úmido Cfa 2, segundo a classificação de Köppen, com média anual de precipitação pluvial de 1.774 mm e média anual de temperatura de 19,2 °C. As parcelas experimentais foram divididas em três segmentos, e em cada um destes foram coletadas amostras nas profundidades de 0–0,05, 0,05–0,10, 0,10–0,20 e 0,20–0,30 m. As amostras foram coletadas por meio da abertura manual de pequenas trincheiras. O estoque de C no solo apresentou relação linear com o aporte anual de C, independentemente do sistema de preparo investigado. Assim, o preparo do solo teve pequeno efeito no incremento da taxa de decomposição da MOS. Na camada de 0–0,30 m, a taxa de sequestro de C variou de zero a 0,51 Mg ha^{-1} ano^{-1} considerando o tratamento CT R0 como referência, sendo a rotação de culturas uma estratégia mais eficiente em determinar o acúmulo de C do que os sistemas de preparo. Na média dos sistemas de cultura, uma taxa de sequestro de C de 0,13 Mg $ha^{-1}ano^{-1}$ foi observada sob PD em relação ao PC. Isso é claro? Esse resultado foi determinado pelo maior aporte de C proporcionado pela melhoria da qualidade do solo em PD adotado por longo prazo. A fração particulada de C foi um indicador eficiente da qualidade dos sistemas de manejo, enquanto o C orgânico associado aos minerais foi um importante dreno de C-CO_2 atmosférico nesse Latossolo argiloso. A retenção de C nessa fração estável da MOS contribuiu com 81 e 89 % do total de C sequestrado no solo em PD, nos sistemas R1 e R2, respectivamente. O maior índice de manejo de C foi verificado sob PD R2, confirmando o potencial de práticas de manejo em melhorar qualitativamente o C armazenado no solo, em relação ao PC R0. Esses resultados mostram que a diversificação da rotação de culturas, notadamente com a inclusão de plantas de cobertura, é uma importante estratégia para o sequestro de C-CO_2 atmosférico e melhoria da qualidade da MOS em Latossolos subtropicais intemperizados.

Termos de indexação: sequestro de carbono, plantio direto, preparo convencional, sistemas de manejo.

INTRODUCTION

Soil organic matter plays multiple roles in agricultural soils, acting as nutrient source for crops and increasing the cation exchange capacity, bioneutralization of xenobiotic compounds, soil structural stability, water retention, soil aeration, biologic activity, and biodiversity (Lal & Sanchez, 1992; Reeves, 1997). Recently, with the uncertainties brought about the current climate change, soil C sequestration in agricultural ecosystem has been considered and important biological sink option for atmospheric C-CO_2 (Lal & Kimble, 1997; West & Post, 2002; Rice, 2006).

Among the soil management strategies for enhancing C sequestration, the principal options are reduction in soil tillage intensity and intensification in the diversity of cropping systems (Lal et al., 1998; Sisti el al., 2004; Amado et al., 2006). West & Post (2002) reported a global average C sequestration rate of 0.57±0.14 Mg ha^{-1} yr^{-1} with the conversion from tilled in untilled soils, and 0.20±0.12 Mg ha^{-1} yr^{-1} by improvement in the cropping systems. Vanden Bygaart et al. (2003) found, in the mean of 37 experiments, a C sequestration rate of 0.38±0.72 Mg ha^{-1} yr^{-1} under NT in relation to CT. In addition, Bayer et al. (2006a) reported a C sequestration rate of 0.48 Mg ha^{-1} yr^{-1} in South Brazilian soils. Recently, Bayer et al. (2009) investigated the role of cover crops in the cropping systems and found soil C sequestration rates under NT ranging from 0.11 to 0.68 Mg ha^{-1} yr^{-1} in a sandy Acrisol. As one of the principal Brazilian strategies for greenhouse gas mitigation in COP15 Copenhague, 2009, the projected increase in NT area in Brazil of 12 Mha until 2020 could represent an offset of 8 % of the total national C-CO_2 emissions. In this prediction, C sequestration in untilled Brazilian soils was estimated at 0.5 Mg ha^{-1} yr^{-1}. This estimation has to be corroborated in long-term experiments in different regions of Brazil.

The contribution of crop rotations and cover crops in enhancing C sequestration in tropical and subtropical environments is not yet well-documented, mostly because the main focus have been the effects of tillage. Legume cover crops are particularly important as alternative to increase the N input in tropical soils, resulting in increased biomass production and soil C and N accumulation (Boddey et al., 1997; Barthes et al., 2004; Sisti et al., 2004; Dieckow et al., 2005; Amado et al., 2006; Urquiaga et al., 2010). Although the area under NT is currently an impressive 32 Mha, the use of cover crops in Brazil is still restricted to grass crops, in other words, there is a challenge of improving cropping systems by the use of legume cover crops.

In temperate soils of Canada and USA, the efficiency of NT to act as a biologic C-CO_2 sink has been recently questioned, mostly because in some specific ecosystems the C gain in shallow soil layers under NT is counterbalanced by C lost in deeper layers in comparison with conventionally tilled soils (Carter, 2005; Baker et al., 2006; Blanco-Canqui & Lal, 2008). However, in tropical and subtropical Brazilian soils this C redistribution in the soil profile due to tillage operation has not been reported yet. In fact, evaluating tillage effects on the deep C pool, in four long-term experiments in Southern Brazil, Boddey et al. (2010) reported higher C accumulation rates when layers to a depth of 1.0 m were considered and compared to shallow layers. In the cited study, the authors also reported that C stocks under NT and CT were more similar when deep layers were evaluated.

Long-term tillage and cropping systems can affect the SOM quality and pool (Dieckow et al., 2005). The long-term input of different types of crop residues in soils managed under conservation tillage associated with crop rotation increase the C pools with higher lability (Conceição et al., 2005; Bayer et al., 2009). To measure these changes in SOM quality, it is necessary to evaluate different C pools by fractionation techniques (Blair et al., 1995; Dieckow et al., 2005). Among the options to evaluate the SOM quality, one is to split the C pool in two functional fractions: the particulate organic carbon (POC) and the mineral-associated organic C fraction (Bayer et al., 2009). The particulate pool has a fast turnover and is influenced by cropping and tillage systems. The passive pool is more recalcitrant and has a slow turnover, being less affected by soil management. It has been proposed to use the increase in SOM lability as an indicator of soil quality and efficiency of soil management (Janzen et al., 1992; Conceição et al., 2005). The C management index (CMI) proposed by Blair et al. (1995) has been used to evaluate the effect of soil tillage and cropping systems on SOM. Dieckow et al. (2005), Vieira et al. (2007) and Bayer et al. (2009) estimated CMI by considering the particulate C obtained through physical fractionation of the labile fraction that is equivalent to labile soil C oxidized by $KMnO_4$, as proposed by Blair et al. (1995). The use of CMI in long-term soil management experiments could be a very efficient tool to assess the impact on SOM quality.

Oxisols, the most important agricultural soil order in tropical regions, have distinct soil C dynamics compared to other soil orders, such as the Mollisols of temperate regions. Differences in drainage pattern, soil structure, texture and mineralogy affect the intensity of SOM stabilization (Six et al., 2002; Zinn et al., 2007). The interaction of SOM with soil minerals promotes structural physical and colloidal protection (Duxbury et al., 1989). The aggregation has been indicated as the main SOM stabilization mechanism in 2:1 clay mineral temperate NT soils (Six et al., 2002). However, in tropical and subtropical Oxisols with predominance of kaolinite clay mineral and iron and aluminum oxides, the aggregation and biologic SOM stabilization processes could play a secondary role (Fabrizzi et al., 2009). In these soils, the texture could play the main role due to the high sorption of organic compounds to the surface of clay particles (Zinn et al., 2007). Blanco-Canqui & Lal (2008) pointed out that soil tillage and crop system effects on C stocks and SOM quality depend on the soil type. Thus, it is important to increase the available information regarding changes in SOM induced by different managements of Oxisols.

This study aimed to evaluate soil C sequestration under tillage and cropping systems in a long-term (19 years) experiment and to assess the improvement in SOM quality by measuring changes in particulate and mineral-associated organic C fractions in a subtropical Oxisol in Southern Brazil.

MATERIAL AND METHODS

Soil and climate characteristics

This study was carried out in a long-term experiment set up in 1985 at the research center FUNDACEP (Fundação Centro de Experimentação e Pesquisa) (Ruedell, 1995), near the city of Cruz Alta, Rio Grande do Sul State (28 º 36 ' S, 53 º 40 ' W; 409 m asl), Brazil. The climate is humid subtropical, Köppen classification Cfa 2a, (Moreno, 1961) with mean annual precipitation of 1,774 mm (data of 1974-2003 of the meteorological station FUNDACEP) evenly distributed along the year. The mean annual temperature is 19.2 ºC, mean maximum temperature 30.0 ºC in January, and mean minimum temperature 8.6 ºC in July (Moreno, 1961). The soil is a clayey Oxisol (Latossolo Vermelho Distrófico típico according to Brazilian classification soil system and a Red Dystroferric Latosol by the US taxonomy), with kaolinite clay and Fe and Al oxides as main constituents of the clay fraction (Streck et al., 2002). Soil analysis by DCB (dithionite-citrate-bicarbonate) in 2004 detected 63.5 g kg^{-1} of Fe oxide.

Experimental characteristics and treatments

Before the experiment, the area was under poor soil management for 30 years, with wheat straw burning and high frequency and intensity of soil tillage. At that time, there was rill erosion and evidence of physical soil degradation. When the experiment was set up, the soil was acidic (Table 1) and 5 Mg ha^{-1} of lime was broadcast and incorporated by disk plow (0.12 m depth) followed by tandem disk harrowing (0.08 m depth).

The experiment was arranged in a factorial design with two factors: soil tillage and cropping system. The experiment had three blocks with tillage treatments in main plots and rotations in subplots. The subplot dimensions were 13.3 x 30.0 m. The first factor was represented by the soil tillage systems (conventional tillage-CT and no tillage-NT), and the second by cropping systems (monoculture system (R0) – wheat (*Triticum aestivum* L.) /soybean (*Glycine max* (L.) Merrill); winter crop rotation (R1) – wheat/soybean/ black oat (*Avena strigosa* Schreb)/soybean; and intensive crop rotation (R2) – black oat/soybean/ black oat+common vetch (*Vicia sativa* L.)/maize (*Zea mays* L.)/oilseed radish (*Raphanus sativus var. oleiferus* Metzg.)/wheat /soybean). The CT system consisted of disk plow and disk tandem in the autumn and spring seasons every year and NT consisted of seeding on crop residues with minimum soil disturbance, only in sowing row. In the R1 treatment, the winter crop rotation was two years of black oat and one year of wheat, until the fourth year of the experiment, and then the two crops were alternated annually. Ten years after the beginning of the experiment (1994/95), lime was applied at a rate of 5 Mg ha^{-1}. Under NT, lime was broadcast on the soil surface without incorporation. Wheat was fertilized with 60 kg ha^{-1} N and maize 90 kg ha^{-1}. N P-fertilization consisted of 52 and 62 kg ha^{-1} of P_2O_5 to R1 and R2, respectively. K fertilization consisted of 75 and 105 kg ha^{-1} of K_2O to R1 and R2, respectively (Boddey et al., 2010). In the last 10 years, in view of the high soil nutrient contents, a standard fertilization of 50 kg ha^{-1} of P_2O_5 and K_2O was applied. A detailed description of this experiment is given by Ruedell (1995).

Estimate of crop carbon input

The crop C input (cover crops and cash crops) was estimated after sampling 1 m^2 of aboveground biomass from 1998 to 2000 and other sporadic years. In the other experimental years, the dry matter was

Table 1. Chemical characteristics and particle size distribution of the subtropical Oxisol (0–0.20 m) under native grassland, at the beginning of the experiment in 1985), and after 17 and 25 years under two tillage systems (CT-conventional tillage, and NT- no tillage) and three crop rotations (R0=wheat/soybean; R1=wheat/soybean/ black oat/soybean; R2=black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/ soybean)

Treatment	pH_{H_2O}	P	K^+	$Ca^{2+} + Mg^{2+}$	Al^{3+}	Sand	Silt	Clay
		mg kg^{-1}	——	$cmol_c\ kg^{-1}$	——	——	g kg^{-1}	——
Native grassland	5.1	2	0.40	3.2	1.6	225	240	535
Initial (1985)(1)	4.5	19	0.21	4.2	1.2	-	-	-
NT (2002)(2)	5.5	17	0.38	6.6	0.2	240	240	520
CT (2002)(2)	5.4	13	0.45	6.6	0.4	240	250	510
CT – R0 (2010)(3)	5.1	6.5	0.29	4.9	1.0	-	-	-
CT – R1 (2010)(3)	5.3	10.3	0.29	7.2	0.5	-	-	-
CT – R3 (2010)(3)	5.0	7.7	0.31	5.6	1.1	-	-	-
NT – R0 (2010)(3)	4.8	14.9	0.23	5.2	1.4	-	-	-
NT – R1 (2010)(3)	5.0	7.2	0.19	7.4	0.6	-	-	-
NT – R2 (2010)(3)	4.9	5.3	0.12	7.0	0.9	-	-	-

(1) Initial: conditions at the beginning of the experiment. (2) Average of three crop rotations. (3) Fiorin (2010), unpublished data. Source: Adapted from Jantalia et al. (2006) and Fabrizzi et al. (2009).

estimated based on means of the sampled period and apparent grain harvest indexes (grain/grain + aboveground biomass) of 0.35 for soybean and 0.40 for wheat and maize (Campos, 2006). The root contribution was estimated as 30 % of aboveground dry matter (Bolinder et al., 1997; Zanatta et al., 2007). The C concentration in dry matter sampled from 1998 to 2000 was determined according to Tedesco et al. (1995). Details of crop C input estimates were reported by Campos (2006).

Soil sampling

In this study, all treatments of the experiment were evaluated, the plots were divided in four segments and, in each one, the soil was sampled in the layers 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m. Soil sampling was performed manually by opening 24 trenches (0.3 x 0.3 m, 0.4 m deep); the sample of each plot segment was considered a pseudo-replicate. The soil was collected in May 2004, after soybean harvest, from the front side of the trenches; a block (width 0.10 m, length 0.5 m) in the center of each layer was collected using a spatula; soil subsamples were transferred to a buck and homogenized to compose a sample.

To determine soil bulk density (Table 2), undisturbed samples were taken in all plots from the layers 0–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, and 0.25–0.30 m with steel cylinders (diameter 0.05 m, height 0.04 m) (Nicoloso, 2009).

Significant differences in soil bulk density were only observed in the 0–0.05 m layer (p = 0.0729 in the interaction of tillage and crop rotation treatments), ranging from 1.03 to 1.23 Mg m^{-3} for the treatments CT R0 and NT R1, respectively. No statistical differences were found below this layer. Average soil bulk density and the mean standard deviation were 1.12±0.06, 1.29±0.04, 1.32±0.06, 1.33±0.04, 1.34±0.04, and 1.33±0.03 Mg m^{-3} for the 0–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, and 0.25–0.30 m layers, respectively (Nicoloso, 2009).

Table 2. Soil bulk in stratified soil layers under tillage and crop rotation systems in a subtropical Oxisol. CT = conventional tillage; NT = no tillage; R0=wheat/soybean; R1=wheat/soybean/black oat/soybean; R2 = black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/soybean

Depth	NT			CT		
	R0	R1	R2	R0	R1	R2
m	Mg m^{-3}					
0–0.05	1.10	1.23	1.11	1.03	1.09	1.15
0.05–0.10	1.33	1.27	1.34	1.27	1.32	1.24
0.10–0.15	1.36	1.40	1.36	1.27	1.31	1.23
0.15–0.20	1.33	1.33	1.38	1.28	1.38	1.30
0.20–0.25	1.33	1.35	1.35	1.29	1.41	1.34
0.25–0.30	1.30	1.33	1.31	1.32	1.40	1.34

Source: Nicoloso (2009).

Prior to the soil sampling in this study in 2004, Jantalia et al. (2006) in 2002, and Fabrizzi et al. (2009) in 2005 and Nicoloso (2009) in 2007 also sampled the same experiment.

Soil C fractionation

The isolation of SOM particulate from the mineral-associated fraction was performed by physical fractionation (Cambardella & Elliott, 1992). The soil samples were air-dried, crushed with a wood roll and sieved (< 2 mm) and stored in plastic pots. Soil sub-samples of 20 g were placed in snap-cap flasks and dispersed with 60 mL of sodium hexametaphosphate $[(NaPO_3)_6]$ solution at 8.17 mmol L^{-1} (5 g L^{-1}) and horizontal shaking (60 cycles min^{-1}) for 15 h. Afterward, the suspension was passed through a 53 µm mesh and washed with distilled water to separate organic material from sand. The material retained in the sieve was considered the particulate fraction and the material that passed through the sieve was considered the mineral-associated fraction, which was collected in a plastic bucket. The mineral-associated fraction was quantified by a 1 L graduated cylinder. The material was homogenized and a 100 mL sub-sample was collected. To this fraction, 0.5 mL $CaCl_2$ (110 g L^{-1}) was added for clay flocculation and to facilitate water evaporation. The particulate and mineral-associated fractions were dried at 90 ºC in the first days and then at 50 ºC until dry. After drying and weighing, the particulate fraction samples were ground with a pestle and a mortar for C analysis.

Organic carbon pools

Total organic carbon (TOC) was determined by a modified Mebius method in a digestion block (Nelson & Sommers, 1996; Reinheimer et al., 2008), assessing particulate organic carbon (POC) and the mineral-associated organic carbon (MAOC). The C content in MAOC was calculated by the difference between the C content in the whole soil and in the POC fraction. The C stocks were calculated based on the equivalent soil mass method (Ellert & Bettany, 1995), taking the soil mass of the management system CT R0 as control.

Carbon management index

Carbon Management Index (CMI) (Blair et al., 1995) was calculated based on the C physical fractionation method as proposed by Vieira et al. (2007). The CMI is constituted by the carbon pool index (CPI) and the lability index (LI), both calculated taking CT R0 as control (CMI=100, CPI=1, and LI=1). All these properties were calculated as following:

$$CMI = CPI \times LI \times 100 \quad (1)$$

$$CPI = \frac{\text{Total C stock in the treatment}}{\text{Total C stock of control}} \quad (2)$$

$$LI = \frac{\text{Lability in the treatment}}{\text{Lability in the control}} \quad (3)$$

$$L = \frac{\text{Labile C stock}}{\text{Non-labile C stock}} \quad (4)$$

where CMI= carbon management index; CPI= carbon pool index; LI= lability index; L= carbon lability.

In this study, the POC fraction was taken as the labile fraction of the SOM, and the MAOC as the non-labile fraction (Bayer et al., 2009).

Statistical analysis

Data were subjected to analysis of variance using SAS software (SAS, 2001). Data normality of residues was verified by the Shapiro-Wilk test (10 % significance); the data are normally distributed below this critical level. Treatment effects were considered significant (5 % significance) for the isolated variation sources (tillage or crop system) or at 10 % level for their interaction.

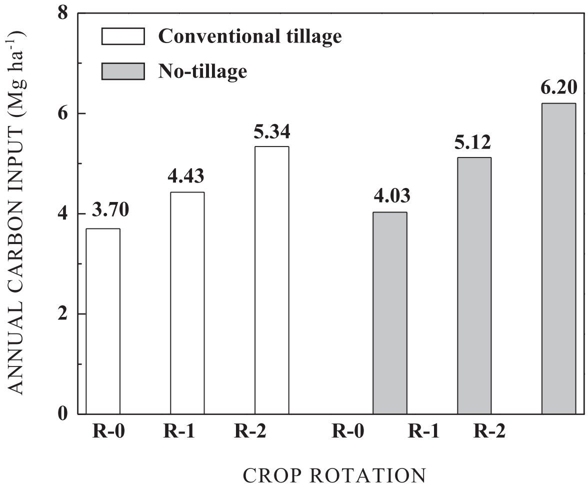

Figure 1. Average annual carbon input by crop rotations in a subtropical Oxisol under conventional and no-tillage systems during the period of 1985/86 to 2003/04. (R0=wheat/soybean; R1=wheat/soybean/black oat/soybean; R2=black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/soybean). Vertical bars represent the LSD (0.79) by the t test at 5%.

RESULTS AND DISCUSSION

Carbon input by cropping systems

Annual crop C inputs ranged from 3.70 to 6.20 Mg C ha^{-1} (Figure 1), which was similar to the range reported in other long-term experiments in southern Brazil (Amado et al., 2006; Bayer et al., 2009; Boddey et al., 2010). The C input was mainly affected by cropping systems in the order: R0 < R1 < R2. In comparison to monocropping (R0), the higher C input in R1 was mainly due to the inclusion of black oat as cover crop in rotation with wheat, in the winter season. In turn, R2 crop rotation had higher C input associated to the consortium of winter cover crops (black oat + common vetch) and, growth of oilseed radish to fill up an autumn window before wheat crop, as well as maize/soybean rotation, during summer season (Campos, 2006). The annual C input in NT, at the average of the cropping systems, was 13.5 % higher than CT soil (Figure 1), probably due to improvement in soil quality for plant growth in the not disturbed soil (Conceição et al., 2005). The difference of C input between tillage systems increased following the diversification of crop system, thus these results were 8.9, 15.6 and 16.1 % to R0, R1 and R2, respectively higher under NT in relation to CT.

Soil carbon content

The soil C contents under tillage and crop rotation systems are presented in figure 2. Under NT, the recurrent crop residue deposition on soil surface resulted in higher TOC contents in the 0–0.05 m layer in relation to CT treatment (Amado et al., 2006; Bayer et al., 2009). The soil C content follows the order: R2 > R1 > R0, showing that the diversification of cropping systems increased the difference in TOC among treatments. In the 0.05–0.10 and 0.10–0.20 m layers, the differences in C content between treatments decreased to zero in the 0.20–0.30 m layer. Similar results had previously been reported by Baker et al. (2006) and Blanco-Canqui & Lal (2008).

In relation to crop rotation effects below 0.05 m, the monoculture system (R0) under NT had lower C contents than other treatments. In Southern Brazil, wheat/soybean monoculture led to yield and biomass reduction by the the increase in disease incidence associated to the humid winter and favorable temperature for pathogen dissemination; this effect seems to be reinforced in NT.

Carbon stocks in the whole soil

The main variable affecting soil C stocks in the 0–0.30 m layer was the annual C input by crop rotation (Figure 3). In this Oxisol, a linear relationship between annual crop C input and soil C stock was observed, for the tillage and cropping systems under study. Previously, Bayer et al. (2006b) also reported linear relationships between C crop residue input (dry matter basis) and soil C stock of tillage systems on a Southern Brazil Acrisol, with angular coefficients of 3.73 and 3.33 to NT and CT, respectively. In our study, the angular coefficient of this linear relationship was 4.07, in the mean of the tillage systems. This result suggests that tillage systems, in this highly

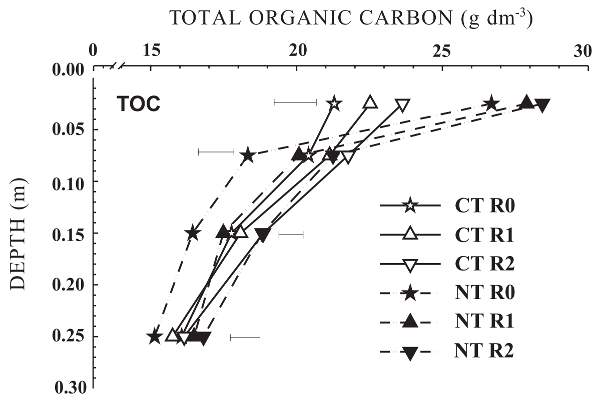

Figure 2. Contents of total organic carbon (TOC) in subtropical Oxisol under conventional tillage (CT) and no tillage (NT) systems under three cropping systems (R0=wheat/soybean, R1=wheat/soybean/black oat/soybean, R2=black oat/soybean/ black oat+common vetch/maize/ oilseed radish/wheat/soybean). Horizontal bars represent the LSD by t test at 5% probability.

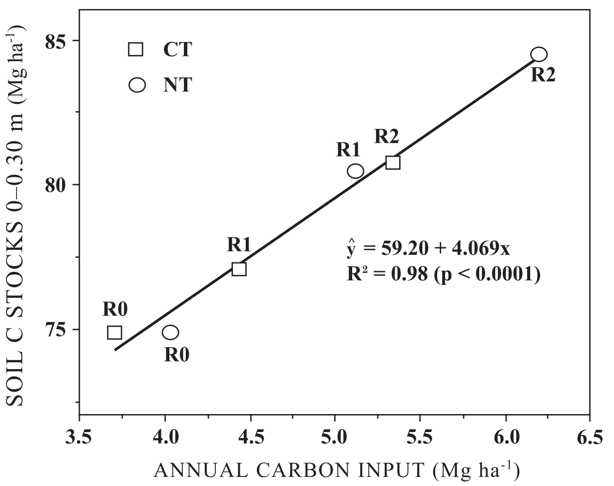

Figure 3. Relationship between annual carbon input and soil organic stocks (0–0.30m) of a subtropical Oxisol under conventional (CT) and no-tillage (NT) systems under three crop rotations (R0=wheat/soybean; R1=wheat/ soybean/black oat/soybean; R2=black oat/ soybean/black oat+common vetch/maize/oilseed radish/wheat/soybean).

stable clayey Oxisol, had little effect on the increase of the SOM decomposition rate. This contrasts with results previously reported by Bayer et al. (2006b) for a sandy Acrisol, where tillage systems were the main factor driving C accumulation. For this clayey oxidic soil, the increase in TOC was more influenced by the annual crop C input than by the tillage system (Figure 2). In the same experiment, Chavez et al. (2009) found that the soil C-CO_2 emission peak induced by soil tillage had short duration and there was no difference between NT and CT in soil C-CO_2 efflux in a 30-day period. Also, Campos et al. (in press) found similar soil C-CO_2 efflux values from NT and CT in a two-year period in the same experiment. These results reinforce that SOM stabilized by strong colloidal interaction with mineral fraction rich in Fe and Al oxides is practically not impacted by soil tillage disturbance. These results confirm that SOM was stabilized by strong colloidal interaction with mineral fractions rich in Fe and Al oxides and was practically unaffected by soil tillage disturbance. It should be highlighted that from the beginning of the experiment, soil erosion associated to CT was not an important source of soil C depletion, once the adjacent fields are terraces under NT.

The particulate C pool was, as expected, more sensitive to soil management systems than the mineral-associated and total C pools (Table 3), similar as observed in previous studies (Janzen et al., 1992; Conceição et al., 2005). The sensitivity of SOM to soil management could be assessed by a relative change of C contents in different C fractions, which ranged from 23.7 to 41.0 % for POC and ranged from 0 to 11.5 % for MAOC, considering the CT R0 as base line (Table 3). This sensitivity of POC to management practices confirmed the efficiency of this SOM fraction as an indicator for monitoring soil quality changes influenced by land use and soil management (Conceição et al., 2005; Dieckow et al., 2005).

Carbon stocks in stratified soil layers

In the 0–0.05 m layer, most affected by soil management systems, no interaction of soil tillage with crop rotation was observed in the C stocks in SOM fractions (Table 3). Thus, the effect of tillage systems on C stocks showed that NT had 88.3, 21.4 and 12.4 % higher POC, TOC and MAOC stocks than CT, respectively, in the mean of cropping systems. The relative change in the POC pool was seven times higher than in the MAOC pool. The cropping system also affected the soil C fractions, with the exception of POC. The R2 had 10.9 and 9.7 % higher TOC and MAOC than R0, respectively, averaged across soil tillage systems. The increase of the MAOC pool under NT in relation to CT (12.4 %) and R2 in relation to R0 (9.7 %) is environmentally important, since the turnover of this pool is longer than of POC (Gulde et al., 2008).

In the 0.05–0.10 m layer, there was no interaction of the main factors either for POC and TOC. Conversely, in this layer, the POC and TOC stocks were 89.7 and 6.8 % higher in CT than NT, respectively, averaged across cropping systems (Table 3). The higher C stocks under CT in this soil layer are probably related to the disk tandem operation that incorporates aboveground crop residues evenly into this specific layer. This hypothesis is reinforced by the higher relative increase (13-fold) in the POC pool in relation to increase in TOC, in the comparison of tillage systems. Although there was no interaction

Table 3. Particulate organic carbon (POC), mineral-associated organic carbon (MAOC) and total (TOC) organic carbon pools of a subtropical Oxisol under conventional tillage (CT) and no tillage systems (NT) under three cropping systems (R0=wheat/soybean, R1=wheat/soybean/black oat/soybean, R2=black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/soybean)

Crop rotations	POC			MAOC			TOC		
	CT	NT	Mean	CT	NT	Mean	CT	NT	Mean
	Mg ha^{-1}								
					0-0.05 m				
Monoculture	1.40	3.27	2.33	12.98	14.25	13.61 b	14.37	17.52	15.94 c
Winter crop	1.98	3.45	2.72	13.23	15.13	14.18 b	15.21	18.58	16.89 a
Intensive	2.02	3.48	2.75	14.03	15.82	14.93 a	16.05	19.30	17.67 a
Mean	1.80 B[(1)]	3.39 A		13.41 B	15.07 A		15.21 B	18.47 A	
					0.05-0.10 m				
Monoculture	1.13	0.56	0.84	13.05	12.10	12.58 c	14.19	12.65	13.42
Winter crop rotation	1.41	0.67	1.04	13.47	13.38	13.42 b	14.88	14.05	14.46 b
Intensive crop rotation	1.35	0.83	1.09	14.14	14.22	14.18 a	15.49	15.04	15.26 a
Mean	1.29	0.68 B		13.55	13.23		14.85 A	13.91 B	
					0.10-0.20 m				
Monoculture	0.80	0.67	0.73	24.62	24.19	24.40 c	25.42	24.86	25.14 c
Winter crop rotation	1.00	0.76	0.88	25.53	25.51	24.52 b	26.53	26.27	26.40 b
Intensive crop rotation	1.13	0.59	0.86	27.09	27.57	27.33 a	28.22	28.15	28.18 a
Mean	0.97 A	0.67 B		25.75	25.75		26.72	26.43	
					0.20-0.30 m				
Monoculture	0.47 Aa	0.29 Bb	0.38	20.41	19.58	20.00	20.88	19.87	20.38
Winter crop rotation	0.31 Bb	0.47 Aa	0.39	20.17	21.08	20.62	20.48	21.55	21.01
Intensive crop rotation	0.36 Aab	0.37 Aab	0.36	20.64	21.61	21.12	21.00	21.97	21.48
Mean	0.38	0.38		20.41	20.75		20.79	21.13	
					0-0.30 m				
Monoculture	3.80	4.78	4.29	71.06 Ab	70.11 Ac	70.59	74.86	74.90	74.88 c
Winter rotation	4.70	5.36	5.03	72.39 Bb	75.09 Ab	73.74	77.09	80.44	78.76 b
Intensive rotation	4.86	5.26	5.06	75.89 Ba	79.20 Aa	77.55	80.75	84.46	82.60 a
Mean	4.45 B	5.13 A		73.11	74.80		77.56 B	79.93 A	

(1) Means followed by the same uppercase letter in rows for soil tillage systems and lowercase letter in columns for crop rotations do not differ significantly by the Tukey test at 5 %.

between factors, the CT effect to increase TOC in this soil layer in relation to NT was more pronounced under monoculture (12 %), decreasing under winter crop rotation (6 %), and even more in intensive crop rotation (3 %). Thus, the intensification of crop rotation seems to compensate the drawback of NT in relation to CT in the deep C accumulation.

In the 0.10–0.20 m layer, only with regard to the POC pool, CT had superior stocks than NT. The other C pools were similar in the soil tillage systems. However, crop rotation intensification increased the MAOC and TOC stocks by about 12 %, averaged across soil tillage systems; the R2 increased TOC stocks by 0.16 Mg C ha^{-1} yr^{-1} in relation to R0. The effect of crop rotation in increasing C stocks, in this soil layer, was probably linked to the cover crop root system. Previously, Dieckow et al. (2007) reported that 36 and 63 % of the gain in soil C stocks associated to the use of pigeon pea (*Cajanus cajan* (L.) Milsp.)/maize and lablab bean (*Dolichos lablab* L.)/maize, respectively, occurred below 0.175 m depth. The increase in C stocks in subsoil induced by cover crops could be an important strategy for C sequestration because the deep soil layers are less affected by disturbance under grain production (Lorenz & Lal, 2005).

The 0.20–0.30 m layer was nearly unaffected by the management systems, with the exception of the POC pool. In summary, soil tillage systems only had significant effects on TOC stocks in the first two soil layers (top to 0.10 m depth), while cropping systems affected the first three layers (top to 0.20 m depth). These results support that the use of cover crops in crop rotation is an important strategy of C sequestration (Amado et al., 2006; West & Six, 2007). Soil characteristics and duration of the experiment could influence the magnitude of C stock alterations and soil layer affected by management systems. Bayer & Mielniczuk (1997), in a temporal analysis in an Acrisol in Southern Brazil, verified changes in C stock in the 0–0.05 m layer only after five years; after nine years, the treatment effects were noticed in 0–0.10 m layer (Bayer et al., 2000), and, after 13 years, they reached the 0–0.175 m layer (Lovato et al., 2004).

In this Oxisol, the MAOC accounted for a range of 81.4 % (NT R0 and NT R1 in the 0–0.05 m layer) to 98.5 % (NT R0 in the 0.20–0.30 m layer) of the TOC (Table 3). In an Acrisol in Southern Brazil, Bayer et al. (2009) found a proportion of MAOC ranging from 91 to 93 % of TOC in the 0–0.20 m layer. In this study the proportion of MAOC increased with increasing soil depth. The high MAOC content in clayey soils was previously reported by Zinn et al. (2007). A high MAOC proportion could indicate longer residence time of C in the soil and a higher soil C storage capacity (Gulde et al., 2008). Nevertheless, the MAOC pool was less sensitive to soil tillage systems than POC, but more sensitive to cropping systems. In contrast, the POC fraction had significant stock alterations under tillage systems in all stratified soil layers although it was not as efficient to discriminate cropping systems. The POC is predominantly constituted by labile C as plant material that still contains remains of the cellular structure (Bayer et al., 2009), but some more humified organic matter with longer soil residence time could also be found in this pool.

Soil carbon sequestration rates

Assuming the system CT R0 as base line, soil C sequestration rates ranged from 0 to 0.51 Mg ha^{-1} yr^{-1} C in the 0–0.30 m layer (Figure 4). This way, there was no C sequestration in the NT R0 system, indicating that NT with low C input was not as efficient to enhance C sequestration in this subtropical Oxisol. On the other hand, the highest C sequestration rate was observed in NT R2. Even under CT, the R1 and R2 crop rotations determined C sequestration rates of 0.12 and 0.31 Mg ha^{-1} yr^{-1} C respectively. This result is coherent with the low effect of soil disturbance on SOM turnover. It is stressed that the rates of soil C sequestration in these crop rotations were higher in untilled soil (0.29 and 0.51 Mg ha^{-1} yr^{-1} C, respectively).

Among the crop rotations tested, the C sequestration rate in NT was 0.13 Mg ha^{-1} yr^{-1} C higher than in the CT system. This C sequestration rate is lower than the average global rate reported by West & Post (2002) of 0.57 Mg ha^{-1} yr^{-1} C. Previously, Zinn et al. (2007) also reported lower C sequestration rates in clayey Oxisols. The proportion of this C sequestration was highest in the mineral-associated C (Figure 4), which accounted for 81 and 89 % of total C sequestration in R1 and R2, respectively (Table 3). The higher proportion of MAOC pool to the total soil C sequestration agrees with the fast turnover of POC pool under tropical and subtropical climate conditions (Six et al., 2002) which leads to a rapid decomposition of the labile SOM pool, diminishing its proportion in the TOC. MAOC is a highly stable fraction in Oxisols due to the organo-mineral interaction with the clay particles, resulting in high resistance to microbial decomposition (Razafimbelo et al., 2008) and a longer residence time in the soil. These results reinforce the importance of this humified SOM fraction as atmospheric C sink, since this C retention process is not easily reversible (Dieckow et al., 2005; Conceição et al., 2005). However, an increase of POC fraction was noticed in the 0–0.05 m layer for NT treatments, and in 0.05–0.10 and 0.10–0.15 m for CT treatments. Increase of POC is closely related to crop C inputs on the soil surface in NT or incorporated in CT, since it is composed of partially decomposed plant residues (Dieckow et al., 2005). Relative increase of POC was greater than MAOC reflecting the more sensitive nature of the POC fraction to changes in soil management (Bayer et al., 2001).

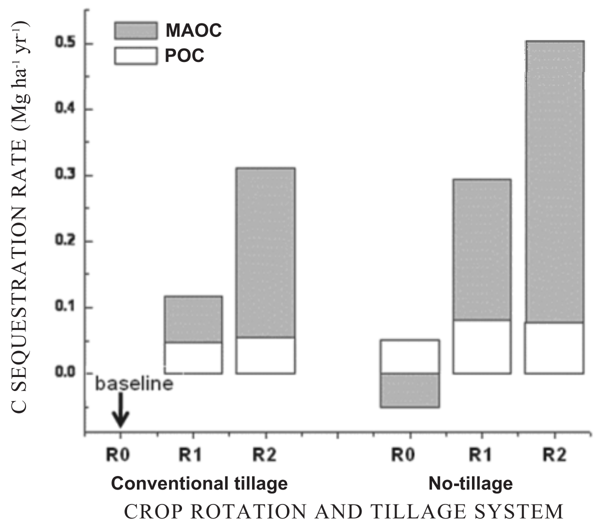

Figure 4. Annual carbon sequestration rates in the 0–0.30 m layer of a subtropical Oxisol under two tillage systems (conventional tillage-CT and no tillage-NT) under three crop rotations (R0=wheat/soybean; R1=wheat/soybean/ black oat/soybean; R2=black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/ soybean) taking (baseline) the traditional soil management system adopted by farmers (CT R0) as control. POC = particulate organic carbon; MAOC= mineral-associated organic carbon.

In figure 5, it can be observed that the soil C sequestration rate in the whole soil (TOC) had a strong relationship with C sequestration from the MAOC ($p < 0.001$). On the other hand, C sequestration from particulate SOM fraction played a secondary role in the total C sequestration from soil as verified by the low probability of the determination coefficient ($p = 0.16$).

Taking into account the average of the tillage systems, the C sequestration rate of R2 was 0.41 Mg ha^{-1} yr^{-1} C, in relation to R0. This value is about 3.2 times higher than the C sequestration rate under NT (0.13 Mg ha^{-1} yr^{-1} C), in disagreement with the results of West & Post (2002) and West & Six

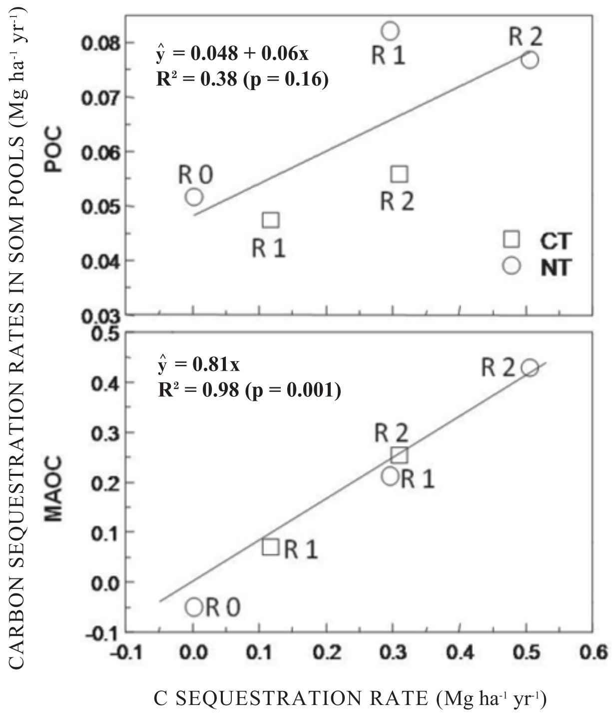

Figure 5. Annual carbon sequestration rates in whole soil (0–0.30 m) and in particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) of a subtropical Oxisol under two tillage systems (conventional-CT and no-tillage-NT) under three crop rotations (R0=wheat/soybean; R1=wheat/soybean/ black oat/soybean; R2=black oat/soybean/black oat+common vetch/maize/oilseed radish/wheat/ soybean) using the traditional soil management system (CT R0) as control (baseline).

(2007) who reported a 2.9 and 2.6 times higher effect of soil tillage, respectively, than of the intensification in cropping systems in a global scale. Therefore, in humid tropical and subtropical environments, the intensification of crop rotations is a very important tool to increase C sequestration.

Carbon management index

The CMI index integrates the effects of soil tillage and cropping systems on soil C stock and C lability and could therefore be used as SOM quality index (Blair et al., 1995; Bayer et al., 2009). The CMI of tillage and crop systems studied is shown in table 4. Vieira et al. (2007) found a close relationship between CMI index and improvement in soil chemical, physical, and biological properties. The increase in C lability has been associated to a high crop residue input in the soils that generally are proportionally more recovered by POC than by MAOC pool (Bayer et al., 2009). Because POC has a faster turnover than other more recalcitrant pools, it is an important plant nutrient source and contributes to greater energy and C fluxes through the activity of heterotrophic soil microorganisms that improve soil aggregation, increase cation exchange capacity and stabilize soil porosity (Bayer et al., 2009). In our study, the highest CMI was observed in NT R2 (158), confirming the potential of this intensive crop rotation to improve the soil C stock qualitatively in relation to CT R0 (control system) (Table 4). The cover crop rotation of R2 includes legume such as common vetch that provide biological N input and a cover crop (oilseed radish) with high efficiency in N cycling. Previously, in two long-term experiments carried out in Acrisols in Southern Brazil , the highest CMI was also observed under NT combined with a legume cropping system (Dieckow et al., 2005; Vieira et al., 2007). Bayer et al. (2009) reported CMI=127 in a grass C /winter legume cover crop system (rye+vetch/maize) and CMI=168 in a summer legume cover crop / maize system (velvet bean/maize). The role of biological N fixation by legume cover crops in soil C stock increases was revised by Urquiaga et al. (2010). The C and N dynamics in soil are closely linked and the N derived from legumes is more efficient in increasing the C stock and SOM quality than a system based on mineral N fertilization (Lovato et al., 2004; Bayer et al., 2009). In this study, CMI was higher in NT than CT for the same cropping system, indicating higher SOM quality under NT than CT.

Table 4. Carbon stock index (CSI), C lability (L), C lability index (LI), and C management index (CMI) of the 0–0.30 m layer of a subtropical Oxisol subjected to conventional tillage (CT) and no tillage (NT) under three cropping systems (R0=wheat/soybean, R1=wheat/soybean/black oat/soybean, R2=black oat/ soybean/ black oat+common vetch/maize/oilseed radish/wheat/soybean)

Tillage	Crop rotation	CSI	L	LI	CMI
CT	R0 - Monoculture	1.00	0.05	1.00	100
	R1 - Winter crop rotation	1.03	0.07	1.40	144
	R2 - Intensive crop rotation	1.08	0.06	1.20	130
NT	R0 - Monoculture	1.00	0.07	1.40	140
	R1 - Winter crop rotation	1.08	0.07	1.40	151
	R2 - Intensive crop rotation	1.13	0.07	1.40	158

CSI: C stock in the treatment / C stock in the control (CT R0). L: POC/MAOC, where POC: particulate organic C and MAOC: mineral-associated organic C. LI: Lability of treatment / Lability of control system (CT R0). CMI: CSI x LI x 100.

CONCLUSIONS

1. The soil C input increases with the diversification of the cropping system. The intensive crop rotation system had the highest C input and monoculture the lowest. The crop C input under no tillage was higher than in the conventional tillage system.

2. Soil C stocks have a linear relationship with annual crop C input, regardless of the soil tillage system. Although, the tillage systems show different pattern of C accumulation in the soil profile, no till had C accumulation in shallow layers than conventional tillage. Nevertheless, the tillage systems differ in the pattern of C accumulation in the soil profile; under no tillage, more C was accumulated in the surface layers than in conventional tillage.

3. Particulate organic C is a sensitive indicator of soil management quality, while for this Oxisol, the mineral-associated organic C pool was a major sink of atmospheric C fixed by plants through photosynthesis.

4. No tillage in intensive cropping rotations has a C sequestration rate of 0.51 Mg ha^{-1} yr^{-1} in relation to the conventional tillage with monoculture system baseline. For this subtropical Oxisol with high SOM stability, the diversified cropping system is the main factor driving soil C accumulation.

5. Of the treatments investigated, SOM quality was best in no till associated with crop rotation system, assessed by the carbon management index.

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