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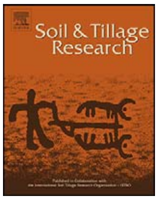

Distribution of soil organic carbon in different size fractions, under pasture and crop rotations with conventional tillage and no-till systems

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ABSTRACT

Soil organic carbon (SOC) is one of the principal indicators of soil quality. Its size fractions have been proposed as high sensitivity indicators in order to detect changes generated by different soil use and management intensities. The objective was to compare the impact of different soil management practices after 10 years on SOC distribution and its size fractions. Treatments consisted in two rotation systems (rotations of continuous annual crops and rotations of 3 years of crops and 3 years of pastures), performed with conventional tillage (CT) and no-till (NT). In 2000, NT treatments were additionally split into C_3 or C_4 summer crops. In 2003, soil was sampled at 0–3, 3–6, 6–12, 12–18, 18–40, 40–60 and 60–80 cm depths and SOC was determined. At the first four depths, SOC associated with particulate organic matter (POM-C) and with the soil mineral fraction (MAOM-C) were determined. Changes in carbon indicators (SOC and its size fractions) occurred mainly in the first 3 cm of soil, and with the exception of POM-C, were diluted when considering the 0–18 cm depth. Inclusion of pastures in the rotation was a better alternative to continuous cropping in CT systems, since it had better C indicator values. However, NT improved indicator values compared with LC, especially when C_4 species were included in the rotation; no differences were found between continuous cropping or crop-pasture rotations. These results allowed discriminate different combinations of crops and tillage systems that contribute to maintain or increase SOC, suggesting a sustainable management of the soil resource.

1. Introduction

Conventional tillage (CT) increase soil erosion and degradation processes, which cause significant losses in soil organic matter (SOM) content. These processes promote the deterioration of chemical, physical and biological soil properties; and, in consequence, the soil quality (Cambardella and Elliot, 1992; Six et al., 1999; Terra and García Préchac, 2001; Díaz Rossello, 2003; Morón and Sawchik, 2003).

Pastures are associated with environmental sustainability and productivity because they present a significant potential to mitigate soil degradation processes and to recover its productive capacity (Díaz Rossello, 2003). Globally, the use of crop rotations and pastures is unusual. In general, crop-pasture rotations have disappeared due to specialization of the grain crops production. In the last decade the study and use of crop-pasture rotations have regained interest in developed countries (Díaz Rossello, 2003). Uruguay and some areas of Argentina are exceptions in which crop-pasture rotations dominate over continuous cropping (García Préchac et al., 2004).

Crop-pasture rotations with CT, performed for 26 years in a Typic Argiudoll (Colonia-Uruguay), maintained soil productivity and produced between 18% and 26% higher yield than continuous cropping systems. The Ap soil horizon under continuous cropping had an average loss of soil organic carbon (SOC) of 540 kg ha^{-1} $year^{-1}$. In contrast, SOC loss under crop-pasture rotation was only 80 kg ha^{-1} $year^{-1}$, being that the majority of SOC lost during the crops phase was recovered during the subsequent pasture phase (García Préchac et al., 2004).

Other management practices utilized to maintain or increase SOM include reduction in soil tillage intensity and use of crops that maximize the amount of residues left on the surface (Martino, 1997; Six et al., 1999; Bayer et al., 2000). Reviews of long term experiments have shown that no-till (NT) systems had, in general, higher SOC than tillage systems (Franzluebbers, 2005). However, rates of SOC accumulation found under NT have been highly variable, since its dynamics not only depend on soil management, but also on its mineralogy, climatic conditions, residues amount, and N inputs.

Many researchers agree that SOM is one of the principal indicators of sustainability and soil quality, given that influence on

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Table 1
Crops sequence for the different rotations during the 10 years of evaluation.

Year	CCCT	CCSD-C_3	CCSD-C_4	CPCT	CPSD-C_3	CPSD-C_4
1993	Barley/sorghum	Barley/sorghum	Barley/sorghum	Barley/sorghum	Barley/sorghum	Barley/sorghum
1994	Wheat/sunflower	Wheat/sunflower	Wheat/sunflower	Wheat/sunflower	Wheat/sunflower	Wheat/sunflower
1995	Wheat/sorghum	Wheat/sorghum	Wheat/sorghum	Wheat with PP/PP	Wheat with PP/PP	Wheat with PP/PP
1996	Fallow/corn	Fallow/corn	Fallow/corn	PP/PP	PP/PP	PP/PP
1997	Oat/soybean	Oat/soybean	Oat/soybean	PP/PP	PP/PP	PP/PP
1998	Fallow/corn	Fallow/corn	Fallow/corn	Fallow/corn	Fallow/corn	Fallow/corn
1999	Wheat/fallow	Wheat/fallow	Wheat/fallow	Wheat/fallow	Wheat/fallow	Wheat/fallow
2000	Wheat/soybean	Wheat/soybean	Wheat/sorghum	Wheat/soybean	Wheat/soybean	Wheat/sorghum
2001	Fallow/sunflower	Fallow/sunflower	Fallow/corn	Fallow/sunflower	Fallow/sunflower	Fallow/corn
2002	Wheat/soybean	Wheat/soybean	Wheat/sorghum	Wheat PP/PP	Wheat PP/PP	Wheat PP/PP

PP: perennial pasture (*Festuca arundinacea*, *Lotus corniculatus* and *Trifolium repens*). *Note*: CCCT: continuous cropping conventional tillage; CPCT: crop-pasture conventional tillage; CCNT-C_3: continuous crop no-till C_3; CCNT-C_4: continuous cropping no-till C_4; CPNT-C_3: crop-pasture no-till C_3; CPNT-C_4: crop-pasture no-till C_4.

many other soil properties (Reeves, 1997; Brady and Weil, 2002). However, SOM is not a homogenous substance, but rather is composed of substances with different chemical compositions and different recycling rates (Cambardella and Elliot, 1992). These authors have proposed a simple method of size fractioning SOM that separates the particulate organic matter (POM) and the mineral associated organic matter (MAOM). The POM is young, minimally transformed and is less associated with mineral constituents of the soil. Therefore, POM constitutes a dynamic fraction of SOM and is associated with short-term nutrient availability. The MAOM, or humified organic matter, is a fraction that is quite stable over time and is difficult to degrade due to its complex structure and high grade of stabilization by the mineral fraction (Galantini et al., 2004).

Morón and Sawchik (2003) compared the sensitivity of different soil quality indicators based on changes generated by different long term crop rotations, under CT in Uruguay. They found that the C associated with POM (POM-C) greater than 212 μm was the most sensitive size fraction to changes in management practices, followed by, the fraction of POM-C between 53 and 212 μm and, finally, the C associated with MAOM (MAOM-C). The traditional determination of total SOC showed a poor sensitivity of changes determined by management practices. Other authors also reported that POM-C is a highly sensitive indicator to detect changes produced by different soil uses and management practices (Cambardella and Elliot, 1992; Elliot et al., 1994; Bayer et al., 2001).

Our hypothesis was that agricultural systems with perennial contribution of residues and less soil disturbance (pasture rotations and NT), would have greater content of SOC and POM-C than systems with CT and more intensive soil disturbance (continuous cropping with CT). The objective of this study was to quantify SOC content at different soil depths and its distribution in different size fractions of SOM, under continuous cropping and crop-pasture rotations, using CT or NT.

2. Materials and methods

The experiment was initiated in 1993 at the Experimental Station Mario A. Cassinoni of the College of Agronomy, 10 km away from Paysandú, Uruguay (32°21′S and 58°02′W). The region is sub-humid, with average annual, winter and summer temperatures of 17, 12 and 24 °C, respectively. According to the USDA soil classification, the soil is a fine, mixed, active, thermic Typic Argiudoll, located on a slope of less than 1%, with an A horizon of 18 cm depth, pH 5.7, and 289, 437, 273 g kg^{-1} clay, silt and sand contents respectively.

Between 1970 and 1986 the soil has been under a crop-pasture rotation with CT. The 7 years prior the installation of the experiment, the field was under perennial pastures (*Festuca arundinacea* Schreb., *Lotus corniculatus* L. and *Trifolium repens* L.), which was progressively invaded by *Cynodon dactylon*. The experiment was installed in fall of 1993, and contrasted two rotation systems: continuous cropping and crop-pasture rotation. Each rotation was evaluated with two tillage alternatives: CT and NT. The cropping sequence was the same for both rotations systems (Table 1). In 2000, NT rotations were split into sequences with C_3 or C_4 summer crops. Rotations under CT were maintained only with C_3 crops (Table 1).

In 2003 we compared: (i) continuous cropping rotation with CT (CCCT), (ii) crop-pasture rotation with CT (CPCT), (iii) continuous cropping rotation with NT including C_4 summer crops after 2000 (CCNT-C_4), (iv) continuous cropping rotation with NT including C_3 summer crops after 2000 (CCNT-C_3), (v) crop-pasture rotations with NT including C_4 summer crops after 2000 (CPNT-C_4), (vi) crop-pasture rotations with NT including C_3 summer crops after 2000 (CPNT-C_3).

The continuous cropping rotations (CCCT, CCNT-C_3 and CCNT-C_4) consisted of a two-crops-per-year sequence, while the crop-pasture rotation (CPCT, CPNT-C_3 and CPNT-C_4) consisted of 3 years of crops (two crops per year) and 3 years of pasture, which were grazed with livestock. The CT was done with chisel plow and excentric disc harrow, at 15–20 cm depth each. On average, soil preparation for winter crops involved four plowing operations, while summer crops involved two. Agrichemical management (fertilizers, herbicides, insecticides and fungicides) depended on requirements of each rotation and tillage system. During winter, wheat (*Triticum aestivum* L.) (C_3), barley (*Hordeum vulgare* L.) (C_3), and oats (*Avena sativa* L.) (C_3) were cultivated, while corn (*Zea mays* L.) (C_4), sorghum (*Sorghum bicolor* L.) (C_4), sunflower (*Helianthus annus* L.) (C_3) and soybean (*Glycine max* L.) (C_3) were cultivated in summer. Pastures mixes included *Festuca arundinacea* Schreb., *Lotus corniculatus* L. and *Trifolium repens* L. and were present between 1996 and 1998 (first cycle) and from 2002 to 2003 (first year of its second cycle). Plot size was 10 m × 50 m and the experiment was analyzed as a random randomized complete block design with three replications.

In 2003, at the end of the summer crop (sorghum and soybean depending on the rotation) or at the end of the first year of pastures, depending on the treatments, the soil was sampled to 0–3, 3–6, 6–12, 12–18, 18–40, 40–60 and 60–80 cm depths. Prior to collecting each sample, the aboveground crop residues were removed from the soil surface. For the first four depths, samples were composed of 20 cores per plot, while for the remaining depths, samples were composed of 10 cores. At each soil depth, undisturbed samples were collected to determine bulk density. For this, the cylinder methodology was used, consisting of a ring sampler with a height of 3 cm and width of 5.4 cm. Three replications per plot of the first four soil depths were taken. For the

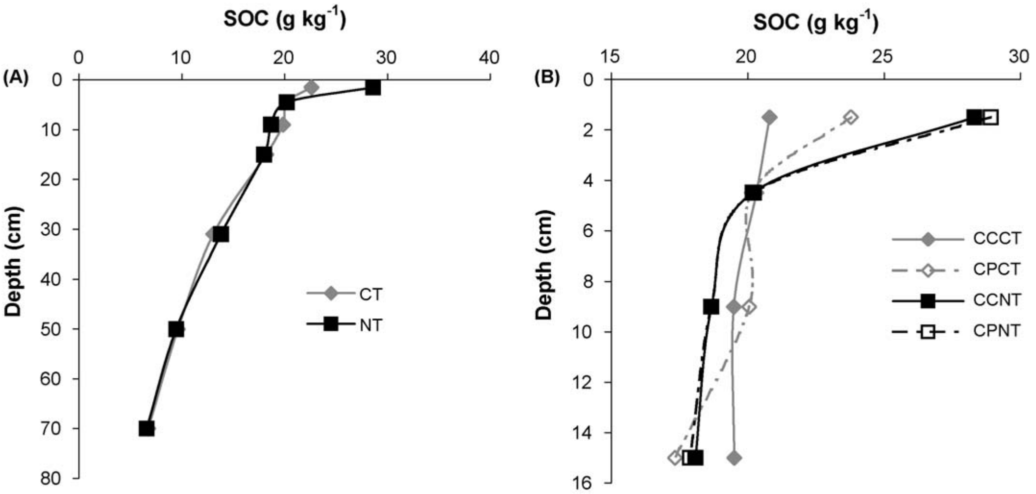

Fig. 1. (A) Soil organic carbon (SOC) concentration in systems with CT and with NT, from 0 to 80 cm of depth; (B) SOC concentration from 0 to 18 cm under continuous cropping and crop-pasture rotations in CT and NT. *Note*: CCCT: continuous cropping under conventional tillage; CPCT: crop-pasture under conventional tillage; CCNT: continuous cropping under no-till; CPNT: crop-pasture under no-till.

remaining depths, unaffected by tillage, three replications were collected for the entire experiment.

Only 0–18 cm soil samples were physically fractionated for SOM. Soils samples were screened to less than 2 mm and then physically fractionated in accordance with Cambardella and Elliot (1992), separating coarse and fine POM (greater than 200 μm and between 200 and 50 μm, respectively) from MAOM (less than 50 μm). Carbon content of each depth and size fraction was determined by dry combustion (Flash EA 112 elemental analyzer). MAOM-C was obtained by calculating the difference between total organic C and POM-C.

An analysis of variance was performed utilizing the SAS® GLM procedure (SAS, 1990). Comparison of means was performed using orthogonal contrasts, comparing: (a) seeding systems (CT vs. NT); (b) within each seeding system, continuous cropping rotations vs. crop-pasture rotations (CCCT vs. CPCT, CCNT vs. CPNT); and (c) within the no-till systems, crop sequences C_3 and crop sequences C_4 (CCNT-C_3 vs. CCNT-C_4, CPNT-C_3 vs. CPNT-C_4). Differences were considered statistically significant at $P \leq 0.05$.

3. Results and discussion

3.1. Changes in the concentration and soil organic carbon reserve

After 10 years, the concentration of C under NT was greater than under CT, only in the first 3 cm layer ($P < 0.001$) (Fig. 1(A)). At the same depth, it was a great trend in CT that crop-pasture rotations had higher SOC concentration compared with continuous cropping ($P < 0.13$) (Fig. 1(B)). No significant differences were found in NT between rotations with or without perennial pastures (CCNT vs. CPNT; $P > 0.15$).

Considering the first 18 cm of soil as a single stratum, no differences were found in the SOC concentration between treatments, with an average SOC concentration of 20.2 g kg^{-1}. Ernst et al. (2005), working in the same experiment and considering the same depth, reported a SOC concentration of 22.2 g kg^{-1} for the year 1993, signifying that, the different soil usage intensities did not generate changes in SOC concentrations after 10 years.

The greatest variations in bulk density were observed in the 0–3 cm layer, where CCCT had the lowest values and CPNT-C_4 and CPCT had the highest values (data not shown). Although no significant differences in bulk density were detected in the other depths, for C stock estimation, bulk density values corresponding to each plot were used.

In the last decades, it has been argued whether comparisons of C stock between treatments should be done for constant depths or for a determined soil mass (Ellert and Bettany, 1995; Alvarez and Steinbach, 2006a). In this study, the soil mass of each treatment for the first 18 cm was estimated. Soil under continuous cropping performed with CT, which had the lowest mass, was taken as the base to estimate to what depths other treatments should have been sampled in order to maintain an equivalent soil mass. Therefore, the minimum depth to sample should have been 17.7 cm. The differences were not significant, and so the decision of whether to perform comparisons at constant depth or at equivalent mass was irrelevant.

Differences in C stock occurred only in the first 3 cm layer (Table 2). At this depth, rotations under NT had 29% more C than

Table 2
Soil organic carbon stock as a function of depth for different rotation systems.

Depth (cm)	Treatments						Significant differences
	CCCT SOC (Mg ha^{-1})	CPCT	CCNT-C_3	CCNT-C_4	CPNT-C_3	CPNT-C_4	
0–3	7.0	8.7	9.8	10.1	9.8	11.0	[a]
3–6	7.8	7.8	7.9	7.9	7.5	8.2	NS
6–12	14.9	15.3	14.4	15.2	14.4	14.3	NS
12–18	14.9	13.2	13.2	13.9	13.4	13.3	NS
0–18	44.7	44.9	45.3	47.1	45.2	46.8	NS

[a] CT vs. NT ($P < 0.01$); CCCT vs. CPCT ($P < 0.05$); CPNT-C_4 vs. CPNT-C_3 ($P < 0.03$). *Note*: CCCT: continuous cropping conventional tillage; CPCT: crop-pasture conventional tillage; CCNT-C_3: continuous cropping no-till C_3; CCNT-C_4: continuous cropping no-till C_4; CPNT-C_3: crop-pasture no-till C_3; CPNT-C_4: crop-pasture no-till C_4.

those under CT. The inclusion of pastures significantly increased SOC stock by 23% compared with continuous cropping, but only under CT. In crop-pasture rotation systems under NT, those that included summer C_4 crops had 12% more C than those that included C_3 crops. This effect was not significant in continuous cropping rotations.

The discussion was mainly focused on the first 18 cm of soil that were most affected by tillage practices. Differences in C from 0 to 3 cm, were diluted from 0 to 18 cm, where differences in C stock were not found between the evaluated treatments (Table 2). The lowest values occurred in CT systems (44.8 Mg ha^{-1}), the highest occurred in NT systems with the inclusion of C_4 species in the rotation (47.0 Mg ha^{-1}), and the NT systems with the rotations of C_3 species were in between (45.3 Mg ha^{-1}). The SOC mass in the arable layer at the beginning of the experiment was 48.7 Mg ha^{-1} (Ernst et al., 2005), indicating that neither system gained C and that systems under NT had a greater capacity of maintaining SOC levels than CT systems. For the 80 cm soil depth, the C stock was 129 Mg C ha^{-1} in 2003 (without significant differences among treatments).

It has been proposed that the use of NT as an alternative to CT promotes increases in SOC, since it minimizes losses from oxidation and erosion (Lal et al., 1999; Mielniczuk et al., 2003; VandenBygaart et al., 2003; Alvarez and Steinbach, 2006a). In studies with similar duration to this study, was reported that changes occurred mainly in the first centimeters of soil and did not always translate into significant increases in the arable layer (Alvarez et al., 1998; Fabrizzi et al., 2003; Liebig et al., 2004; Leifeld and Kogel-Knabner, 2005). Factors that contribute to SOC losses and gains include, among others: soil preparation, crops sequence, initial state of degradation, soil texture, slope, and climate.

The continuous cropping rotation with CT, considered in this experiment as the most intensive usage, did not contrast much with other rotation systems, given that it had two harvests per year leaving the residues over the soil surface. Erosion was minimized by shortening the period in which the soil was exposed and the relatively flat slope (0–1%). Clérici et al. (2004) estimated the impact of different soil use management systems on erosion rates and SOC content utilizing USLE/RUSLE and CENTURY models, respectively. They had shown that soil erosion would explain most of total C losses (50–90% for the continuous cropping rotations), and that losses were proportionately greater in medium texture soils than in clayey soils. Hence, for the rotation system studied in this study, the minimal slope and the soil texture are factors that counteracted significant losses in C for the period considered (10 years). In addition, Leifeld and Kogel-Knabner (2005) mentioned that SOC indicators should be observed mostly in the first centimeters of soil for NT and CT systems.

Other studies done in Uruguay have reported higher impacts on SOC between continuous cropping systems and crop-pasture systems (Baethgen, 2003; Terra et al., 2006). In similar soils, but with 2–4% slope, SOC stock decreased 14% (0–20 cm depth) respect to initial condition after 10 years of a continuous cropping system with CT and 55% of the time under fallow (Baethgen, 2003). This was significantly different from the crop-pasture rotation under CT (50% of the time under pastures with perennial grasses and legumes), which only had a decrease of 0.5% (Baethgen, 2003). It is important to point out that tillage in all cases was performed in the slope direction, resulting in higher soil losses due to erosion. Moreover, in both cases, the forage from crop-pasture rotation was not grazed but cut and returned to the soil, resulting in more return of carbon to the system.

In another experiment, SOC (0–15 cm depth), after 8 years of continuous cropping under NT, was 17% lower than SOC in crop-pasture rotations (with a high proportion of perennial pastures) for the same period of time (Terra et al., 2006). In this experiment, both rotation systems that included some proportion of pastures had similar SOC to adjacent undisturbed soil under native pasture. However, in the mentioned experiment, soil had a coarse to medium texture with 2–3% slopes, and crops were grazed or harvested for forage reserves, resulting in less C inputs to the system.

Resulting SOC content is the net difference between inputs (quantity of biomass incorporated) and outputs (oxidation and erosion), which is strongly affected by site characteristics (climate, soil texture and degradation state). Therefore, the magnitude and rates of change will depend on each particular situation.

3.2. Changes in the size fractions of soil organic carbon

Soil uses and management practices not only affected total SOC content, but also its composition. The POM-C, as well as SOC, was mostly affected in the first 3 cm (Tables 3 and 4).

In the 0–3 cm layer, NT systems had an increase in coarse and fine grain POM-C (207% and 134%, respectively) and MAOM-C (11%) compared with CT systems ($P < 0.01$, $P < 0.001$, $P < 0.001$, respectively). Under NT, approximately 25% of the total SOC present in the first 3 cm was POM-C, which is double the mass of POM-C under CT ($P < 0.001$). The POM has been associated with soil properties and nutrient dynamics (Chan, 1997; Galantini et al., 2004), microbial activity (Alvarez et al., 1998) and the formation and stability of macro-aggregates in soil (Chan, 1997; Six et al., 2002); factors highly related to seed bed condition and water infiltration under NT. Specific studies on the effect of POM-C on such soil properties have not yet been performed in this experiment.

In the crop-pasture rotation under CT, the higher SOC stock from 0 to 3 cm compared to the continuous cropping system was explained by a higher POM-C content (although not significant, $P < 0.14$) and 17% more MAOM-C (Tables 3 and 4). This could be related by the fact that during the pasture cycle, soil was undisturbed which reduces oxidation and favors SOC stratification.

For the same layer, crop-pasture rotations under NT had less POM-C content (although not significant; $P > 0.15$) and 12.5% more MAOM-C than the continuous cropping systems (Tables 3 and 4). There were no differences in total SOC between the continuous cropping systems and the crop-pasture rotations under NT in the first 3 cm (Table 2). We speculated that there was a greater SOC humification (POM-C transferred to MAOM-C) in systems including pastures in the rotation. The proportion of POM-C of the total SOC in crop-pasture rotations was 20% lower than those found in the continuous cropping systems (Table 3). In the other hand, there were no changes in MAOM-C in the 0–6-cm depth in continuous cropping systems under NT compared with the initial content at the site in 1994 (14.25 Mg ha^{-1}), however a 7% increase was observed in crop-pasture systems with NT (15.25 Mg ha^{-1}) after 10 years. This also supports the hypothesis that a greater humification under the mixed crop-pasture systems has a benefitial effect if we consider the stabilization of the captured C.

In crop-pasture systems, the contribution of N from legumes may have favored humification processes in lightest SOC fractions (POM-C). In addition, medium to heavy textures of this soil, favor the retention mechanisms of most transformed C. Some authors mention that in order to increase stabilized SOM, it is necessary to incorporate material with high lignin and/or polyphenol contents and high N contents (Collins et al., 1990; Palm et al., 2001), a condition similar to that of the crop-pasture rotations, where residues of different compositions are mixed.

The absence of significant differences in POM-C and in MAOM-C at depths greater than 3 cm, between continuous cropping and crop-pasture systems, could be related to the fact that the evaluation was performed in the first year of the second cycle of

Table 3
Soil organic carbon (SOC) associated with size fractions for the rotations systems at different soil depths.

Depth (cm)	Fraction (μm)	Treatment					
		CCCT	CPCT	CCNT-C_3	CCNT-C_4	CPNT-C_3	CPNT-C_4
		C-fraction ($Mg\ ha^{-1}$)					
0–3	POM-C_{200}	0.27	0.60	1.24	1.69	0.96	1.38
	POM-C_{50}	0.43	0.64	1.24	1.32	1.06	1.33
	MAOM-C	6.35	7.42	7.32	7.05	7.83	8.34
	POM-C/SOC	9.80	13.93	25.44	29.87	20.17	24.20
3–6	POM-C_{200}	0.30	0.20	0.18	0.20	0.14	0.22
	POM-C_{50}	0.49	0.51	0.57	0.65	0.42	0.63
	MAOM-C	7.03	7.05	7.18	7.01	6.99	7.33
	POM-C/SOC	10.18	9.50	9.61	10.80	7.47	10.51
6–12	POM-C_{200}	0.31	0.18	0.19	0.27	0.16	0.22
	POM-C_{50}	0.64	0.64	0.53	0.63	0.44	1.00
	MAOM-C	14.00	14.52	13.70	14.32	13.78	13.13
	POM-C/SOC	6.42	5.38	4.98	5.97	4.25	8.63
12–18	POM-C_{200}	0.15	0.11	0.14	0.15	0.14	0.15
	POM-C_{50}	0.44	0.27	0.51	0.40	0.34	0.39
	MAOM-C	14.33	12.79	12.55	13.36	12.96	12.73
	POM-C/SOC	3.92	3.00	4.89	3.95	3.57	4.02
0–18	POM-C_{200}	1.01	1.10	1.75	2.32	1.40	1.97
	POM-C_{50}	2.00	2.05	2.84	3.00	2.25	3.35
	MAOM-C	41.70	41.78	40.75	41.75	41.57	41.52
	POM-C/SOC	6.76	7.08	10.26	11.31	8.09	11.33

Note: CCCT: continuous cropping conventional tillage; CPCT: crop-pasture conventional tillage; CCNT-C_3: continuous cropping no-till C_3; CCNT-C_4: continuous cropping no-till C_4; CPNT-C_3: crop-pasture no-till C_3; CPNT-C_4: crop-pasture no-till C_4. POM-C_{200}: fraction of particulate organic matter greater than 200 μm; POM-C_{50}: fraction of particulate organic matter between 50 and 200 μm; MAOM-C: C in mineral associated organic matter; POM-C: carbon associated with the particulate organic matter (fraction between 50 and 2000 μm).

pasture. According to Franzluebbers (2002), only the first layer of soil is initially affected with a change in the vegetation.

In crop-pasture rotations with NT, C_4 crops increased the POM-C in the 12 cm depth (CPNT-C_4 vs. CPNT-C_3), but this effect was not detected in continuous cropping (Tables 3 and 4). The average grain yield for the C_4 species, started in 2000, was 66% greater than the summer crops C_3 (2.5 $Mg\ ha^{-1}$). However, since the C_4 species have an average harvest index of 0.5 (Bolinder et al., 2007; Alvarez and Steinbach, 2006b) compared to 0.35 for C_3 species (Alvarez and Steinbach, 2006b), the aboveground biomass contribution to the soil for these species is not much different. A possible explanation for the higher POM-C content under rotations with C_4 species may be due to the fact that they have greater C input via roots with respect to C_3 species and/or that differences in the quality of incorporated residues resulted in different rates of decomposition of them. Ernst et al. (2002) working in the same experiment, found that the rate of decomposition of soybean residue was 2.5 faster than corn residue. Moreover, these authors found that the decomposition of wheat straw on top of soybean residue was faster than on top of corn residue.

In contrast with the SOC stock, differences in POM-C between treatments observed in the surface layers were maintained considering the 18 cm of soil as a single stratum (Tables 3 and 4). The soil under NT had 52% more POM-C than that under CT. On the other hand, the crop-pasture rotation under NT with C_4 summer crops had 43% more POM-C than with C_3 summer crops. As mentioned by other authors (Cambardella and Elliot, 1992; Elliot et al., 1994; Bayer et al., 2001; Morón and Sawchik, 2003; Liebig et al., 2004), the results suggest that POM-C was a more sensitive indicator of the effect of changes in land use and soil management than SOC content.

Table 4
Significance of the orthogonal contrasts performed for the POM-C and MAOM-C, according to depth.

Depth (cm)	Fraction (μm)	Contrasts				
		CT vs. NT	CCCT vs. CPCT	CCNT vs. CPNT	CCNT-C_3 vs. CCNT-C_4	CPNT-C_3 vs. CPNT-C_4
0–3	POM-C	0.0003	NS	NS	NS	NS
	MAOM-C	0.0007	0.0023	0.0002	NS	0.0437
3–6	POM-C	NS	NS	NS	NS	0.0375
	MAOM-C	NS	NS	NS	NS	NS
6–12	POM-C	NS	NS	NS	NS	0.0183
	MAOM-C	NS	NS	NS	NS	0.0232
12–18	POM-C	NS	NS	NS	NS	NS
	MAOM-C	NS	NS	NS	NS	NS
0–18	POM-C	0.0020	NS	NS	NS	0.0312
	MAOM-C	NS	NS	NS	NS	NS

Note: CCCT: continuous cropping conventional tillage; CPCTP: crop-pasture conventional tillage; CCNT-C_3: continuous cropping no-till C_3; CCNT-C_4: continuous cropping no-till C_4; CPNT-C_3: crop-pasture no-till C_3; CPNT-C_4: crop-pasture no-till C_4; POM-C: carbon associated with the particulate organic matter; MAOM-C: C in mineral associated organic matter. NS: not significant ($P > 0.05$).

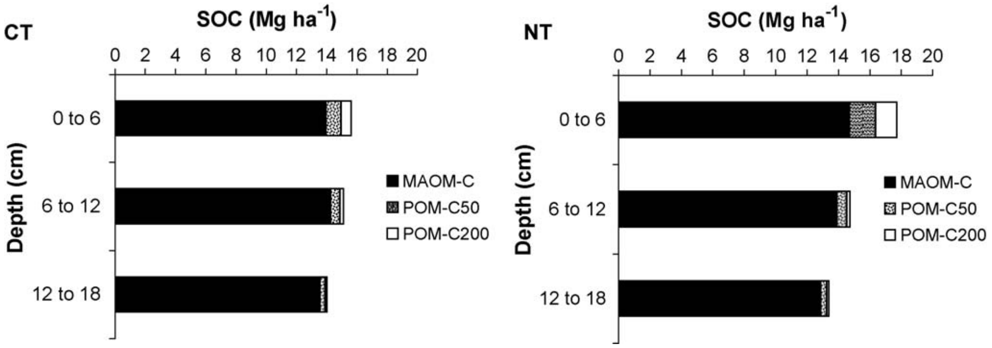

Fig. 2. Soil organic carbon (SOC) content in the different size fractions according to depth, for the average of the treatments with CT and NT. *Note*: MAOM-C: C in mineral associated organic matter; POM-C_{50}: C in fraction of particulate organic matter between 50 and 200 μm; POM-C_{200}: C in fraction of particulate organic matter greater than 200 μm.

Unexpected, no significant differences between continuous cropping and crop-pasture rotations systems were found in POM-C content at 0–18 cm depth. In a long term experiment in Uruguay, Morón and Sawchik (2003) found that after 36 years of tillage, POM-C (0–15-cm depth) in a crop-pasture rotation was two times higher compared with a continuous cropping system. Meanwhile, in another experiment that evaluated different forage crops (grazed or for hay), it was observed that after 8 years of continuous annual cropping under NT, there was 32% lower POM-C >200 μm than a permanent pasture (Terra et al., 2006). In that experiment, none of the treatments with some proportion of pastures in the rotation differed in SOC or in POM-C contents compared with the permanent pasture treatment.

Changes in SOC and its physical fractions were most pronounced between soil tillage systems than between whether or not pastures were was included in the rotation. We speculated that the combined use of crops and pastures has not been able to clearly demonstrate its benefits on C yet, given that the sampling was done when the pasture had not completed its second cycle, and an unbalanced rotation in terms of years of crops and years of pastures (6 and 4 years, respectively; see Table 1). In contrast, tillage systems were present during the 10 years under continuous farming and during 6 years in crop-pasture rotations. For both comparisons (CT vs. NT and CC vs. CP), the changes were small in magnitude, given the high inputs of C from having two crops per year, a short period that the soil is susceptible to C losses and the relatively flat land slope.

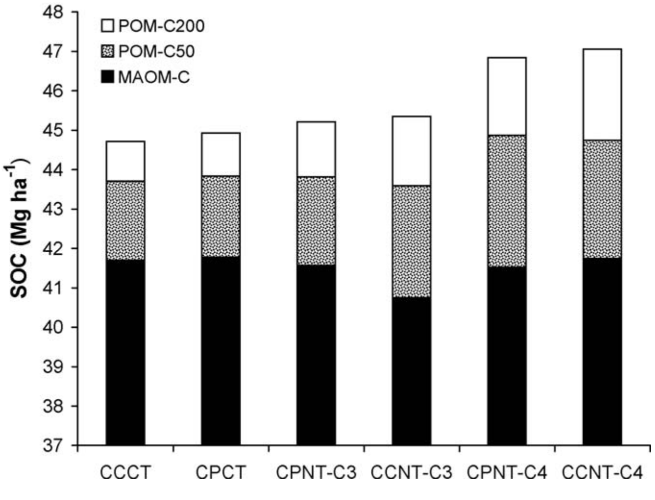

Fig. 3. Soil organic carbon (SOC) content in the different size fractions from 0 to 18 cm of soil, for the different rotation systems. *Note*: POM-C_{200}: C in fraction of particulate organic matter greater than 200 μm; POM-C_{50}: C in fraction of particulate organic matter between 50 and 200 μm; MAOM-C: C in mineral associated organic matter; CCCT: continuous cropping conventional tillage; CPCT: crop-pasture conventional tillage; CCNT-C_3: continuous cropping no-till C_3; CPNT-C_3: crop-pasture no-till C_3; CPNT-C_4: crop-pasture no-till C_4; CCNT-C_4: continuous cropping no-till C_4.

In agreement with Alvarez et al. (1998) and Franzluebbers (2002), NT caused stratification of SOC and POM-C (Fig. 2). On average, rotations under NT had 4.2 times more POM-C (Mg ha^{-1}) in the 0–6 cm depth than in the 6–12 cm depth. In contrast, in systems with CT, POM-C in the 0–6 cm layer was only 1.95 times greater than in the 6–12 cm layer. Tillage operations tend to homogenize the soil within the depth affected by implements, unlike NT where the residue accumulates on the surface and does not involve soil disturbance and movement. According to Franzluebbers (2002), the main changes between tillage with soil inversion and NT or pasture soil will be found in the first few centimeters of soil.

The variations found in the total SOC contents for the first 18 cm of soil, although not significant, were mainly due to variations in the POM-C contents (Fig. 3). Rotations under NT that included C_4 summer crops for continuous cropping and crop-pasture rotations had the greatest values of SOC and POM-C, the latter representing 11.3% of the SOC (average of the rotations with C_4 species).

4. Conclusions

The main impacts of tillage and rotation systems after 10 years on SOC and its fractions were found only in the 0–3 cm layer. However, while the differences in concentration and in SOC stock were diluted when considering the arable layer (0–18 cm), the POM-C maintained the differences, appearing to be more sensitive than MAOM-C and SOC in detecting changes from soil usage intensities and management practices.

No-till systems had a higher proportion of POM-C (0–3 and 0–18 cm) and greater accumulation in the soil surface (0–3 cm) than CT systems. Given that the POM-C content is positively associated with certain soil properties, NT systems would promote an improved soil quality.

Carbon indicators (SOC and its size fractions) suggest that in CT systems, inclusion of pastures in rotations would be preferred alternative rather than continuous cropping systems. However, the use of NT would have an additive beneficial effect contributing to the sustainability of the resource, especially when C_4 is included in the rotation.

Under NT, the C indicators did not differ between rotations including pasture compared with continuous cropping systems, showing that the systems with reduced tillage allow for SOC conservation. The combined effect of NT practices and crop-pasture rotation systems likely allows for a longer duration to increase SOC contents, which extends beyond the period considered in this work.

References

Alvarez, R., Steinbach, H.S., 2006a. Efecto del sistema de labranza sobre la materia orgánica. In: Pascale, A.J. (Ed.), Materia orgánica: Valor agronómico y dinámica en suelos pampeanos. Facultad de Agronomía, Universidad de Buenos Aires, pp. 69–78.

Alvarez, R., Steinbach, H.S., 2006b. Efecto de la agricultura sobre el nivel de materia orgánica. In: Pascale, A.J. (Ed.), Materia orgánica: Valor agronómico y dinámica en suelos pampeanos. Facultad de Agronomía, Universidad de Buenos Aires, pp. 41–53.

Alvarez, R., Russo, M.E., Prystupa, P., Scheiner, J.D., Blotta, L., 1998. Soil carbon under conventional and no-till systems in the Argentine Rolling Pampa. Agron. J. 90, 138–143.

Baethgen, W.E., 2003. Utilización del modelo Century para estudiar la dinámica de carbono y nitrógeno. In: 40 años de rotaciones agrícolas-ganaderas. Serie técnica 134, INIA La Estanzuela, pp. 9–18.

Bayer, C., Mielniczuk, J., Amado, T.J.C., Martin-Neto, L., Fernández, S.V., 2000. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. Soil Till. Res. 54, 101–109.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C.N., Sangoi, L., 2001. Changes in soil organic matter fractions under subtropical no-till cropping systems. Soil Sci. Soc. Am. J. 65, 1473–1478.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Anger, D.A., VandenBygaart, A.J., 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agr. Ecosyst. Environ. 118, 29–42.

Brady, N.C., Weil, R.R., 2002. The nature and properties of soils, 13th ed. Prentice Hall, New Jersey, United States of America, pp. 498–542.

Cambardella, C.A., Elliot, E.T., 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777–783.

Chan, K.Y., 1997. Consequences of changes in particulate organic carbon in Vertisols under pasture and cropping. Soil Sci. Soc. Am. J. 61, 1376–1382.

Clérici, C., Baethgen, W., García Préchac, F., Hill, M., 2004. Estimación del impacto de la soja sobre erosión y carbono orgánico en suelos agrícolas del Uruguay. In: Quintero, C.E., Boschetti, N.G., y Díaz, E.L. (Eds.), Resúmenes del XIX Congreso Argentino de la Ciencias del Suelo. II Simposio Nacional sobre Suelos Vertisólicos, 22–25 Junio 2004, Paraná, Argentina, p. 337.

Collins, H.P., Elliot, L.F., Rickman, R.W., Bezdicek, D.F., Papendick, R.I., 1990. Decomposition and interactions among wheat residue components. Soil Sci. Soc. Am. J. 54, 780–781.

Díaz Rossello, R., 2003. 40 años de rotaciones. Introducción a la actividad experimental. In: 40 años de rotaciones agrícolas-ganaderas. Serie Técnica 134, INIA La Estanzuela, pp. IX–XIII.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil. Sci. 75, 529–538.

Elliot, E.T., Burke, I.C., Monz, C.A., Frey, S.D., Paustian, K.H., Collins, H.P., Paul, E.A., Cole, C.V., Belvins, R.L., Frye, W.W., Lyon, D.J., Halvorson, A., Huggins, D.R., Turco, R.F., Hickman, M.V., 1994. Terrestrial carbon pools preliminary data from the Corn Belt and Great Plain Regions. In: Doran, J.W., Coleman, D.C., Bezdieck, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Special Publication Number 35, pp. 179–191.

Ernst, O., Bentancur, O., Borges, R., 2002. Descomposición de rastrojo de cultivos en siembra sin laboreo: trigo, maíz, soja y trigo después de maíz o de soja. Agrociencia 6 (1), 20–26.

Ernst, O., Siri-Prieto, G., Cano, J.D., 2005. Rotación pastura-cultivo y sistema de laboreo en el Uruguay: A) Cambios del contenido de carbono y nitrógeno del suelo. In: Anais. Simposio sobre Plantío Direto e Meio Ambiente, Sequestro de Carbono e Qualidade da Agua, pp. 213–215.

Fabrizzi, K.P., Morón, A., García, F.O., 2003. Soil carbon and nitrogen organic fractions in degraded vs. non-degraded Mollisols in Argentina. Soil Sci. Soc. Am. J. 67, 1831–1841.

Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till. Res. 66, 95–106.

Franzluebbers, A.J., 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America: introduction. Soil Till. Res. 83, 1–8.

Galantini, J.A., Iglesias, J.O., Rossell, R.A., 2004. Calidad y dinámica de las fracciones orgánicas en la región semiárida pampeana. In: XIX Congreso Argentino de la Ciencia del Suelo. II Simposio Nacional sobre Suelos Vertisólicos. Paraná, Argentina CD-ROM.

García Préchac, F., Ernst, O., Siri Prieto, G., Terra, J.A., 2004. Integrating no-till crop-pasture rotations in Uruguay. Soil Till. Res. 77, 1–13.

Lal, R., Follet, R.F., Kimble, J., Cole, C.V., 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 5, 374–381.

Leifeld, J., Kogel-Knabner, I., 2005. Soil organic matter fractions as early indicators for carbon stock changes under different land use? Geoderma 124, 143–155.

Liebig, M.A., Tanaka, D.L., Wienhold, B.J., 2004. Tillage and cropping effects on soil quality indicators in the northern Great Plains. Soil Till. Res. 78, 131–141.

Martino, D., 1997. Siembra directa en los sistemas agrícola-ganaderos del litoral. INIA La Estanzuela. Serie Técnica 82 28 pp.

Mielniczuk, J., Bayer, C., Vezzani, F.M., Lovato, T., Fernándes, F.F., Debarba, L., 2003. Tópicos em Ciencia do Solo. Sociedade Brasileira de Ciencia do Solo. 3, 165–208.

Morón, A., Sawchik, J., 2003. Soil quality indicators in a long-term crop-pasture rotation experiment in Uruguay. In: 40 años de rotaciones agrícolas-ganaderas. Serie Técnica 134, INIA La Estanzuela, pp. 67–76.

Palm, C.A., Giller, K.E., Mafongoya, P.L., Swift, M.J., 2001. Management of organic matter in the tropics: translating theory into practice. Nutr. Cycl. Agroecosyst. 61, 63–75.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Till. Res. 43, 131–167.

SAS Institute. 1990. SAS/STAT user‘s guide. Versión 6. 4th ed. Vol.1. SAS Inst., Cary, N.C.

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-till systems. Soil Sci. Soc. Am. J. 63, 1350–1358.

Six, J., Feller, C., Deneb, K., Ogle, S., Moraes Sa, J., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils – effects of no tillage. Agronomie 22, 755–775.

Terra, J.A., García Préchac, F., 2001. Siembra directa y rotaciones forrajeras en las lomadas del este: síntesis 1995–2000. Serie Técnica 125. INIA Treinta y Tres, pp. 100.

Terra, J.A., García-Prechac, F., Salvo, L., Hernández, J., 2006. Soil use intensity impacts on total and particulate soil organic matter in no-till crop-pasture rotations under direct grazing. In: Horn, R., Fleige, H., Peth, S., Peng, X. (Eds.), Sustainability – Its Impact on Soil Management and Environment. Adv. Geoecol., vol. 38. pp. 233–241.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agriculture management on soil organic carbon: a compendium and assessment of Canadian studies. Can. J. Soil Sci. 83, 363–380.