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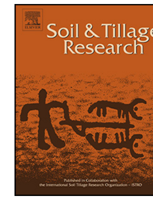

Carbon and nitrogen sequestration in soils under different management in the semi-arid Pampa (Argentina)

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ABSTRACT

Soil management affects distribution and the stocks of soil organic carbon and total nitrogen. The aim of this study was to evaluate the effect of different crop sequences and tillage systems on the vertical distribution and stocks of soil carbon and nitrogen. We hypothesized that no-tillage promotes surface organic carbon and total nitrogen accumulation, but does not affect the C and N stocks, when compared with reduced tillage. In addition, the incorporation of maize in the crop sequence increases total organic carbon and total nitrogen stocks. Observations were carried out in 2010 in an experiment located in the semiarid Argentine Pampa, on an Entic Haplustoll. A combination of three tillage systems (no tillage, no tillage with cover crop in winter and reduced tillage) and two crop sequences (soybean–maize and soybean monoculture) were assessed. After 15 years of management treatments, soil samples to a depth of 100 cm at seven intervals, were taken and analyzed for bulk density, organic carbon and total nitrogen. Total organic carbon stock up to a depth of 100 cm showed significant differences between soils under different tillage systems (reduced tillage < no tillage = no tillage with cover crop), the last ones having 8% more than the reduced tillage treatment. Soybean–maize had 3% more organic C up to 100 cm depth than the soybean monoculture. Total nitrogen stock was higher under no-till treatments than under reduced tillage, both at 0–50 and 0–100 cm depths. Total organic carbon stratification ratios (0–5 cm/5–10 cm) were around 1.6 under no-till and lower under reduced tillage. The stratification ratio explains less than 40% of soil carbon stock. Tillage system had a greater impact on soil carbon stock than crop sequence.

1. Introduction

Soil organic matter (SOM), a component associated to agroecosystem productivity (Bauer and Black, 1994), normally decreases through cropping, often due to the decrease in the supply of crop residues and acceleration of mineralization (Richter et al., 1990). This decline is directly associated with an increase in carbon dioxide (CO_2) production, one of the main greenhouse gases (Urquiaga et al., 2004).

Several studies have highlighted the environmental importance of soil C sequestration and its impact on climate change (Lal, 2004; Jantalia, 2005) by reducing gas emissions, especially CO_2. Soil has an important role in the production of CO_2 and other greenhouse gases.

In some regions, total organic carbon (TOC) has been lost through conversion of natural forests to agricultural production, with soil C content stabilizing at 40–60% of the original values. The value of a new equilibrium will depend upon several factors such as climate, physical and chemical soil characteristics and crop management (tillage system, crop sequence, vegetation cover and waste management) (Robertson and Paul, 2000). The Argentine Rolling Pampa has lost around one third of topsoil C content due to the agriculturization process (Alvarez, 2005). López-Bellido et al. (2010) found in a wide region of the United States that only under certain agricultural practices, soil organic carbon (SOC) has been maintained after 38 years from the start of the experiment.

According to some authors, no-tillage (NT) promotes accumulation of TOC and total nitrogen (TN) when compared with other tillage systems (Díaz Zorita, 1999; Sisti et al., 2004; Steinbach and Alvarez, 2006; Du et al., 2010), while others obtained different

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results (Alvarez et al., 1998; Costantini et al., 2006). These seemingly contradictory findings may be due to differences in experimental conditions: soil and climate conditions, historical soil management, SOM stratification, sampling depths and C and N determined in relation to soil volume instead of soil mass.

Sisti et al. (2004) found that NT as an only practice does not improve TOC and TN soil content and suggest that to increase soil TOC contents grass pastures should be included in the cropping sequence. Their elimination from the crop sequence is another factor which has negatively influenced soil C content (Andriulo et al., 2008), due to the lower C contribution of legumes compared with grasses (Alvarez and Steinbach, 2012). Cover crops (cc) can be an important tool for managing C and N dynamics in current agricultural systems (Wagger et al., 1998). Reicosky and Archer (2005) found that a desirable characteristic of including cc in the cropping sequence was N retention by avoiding potentially leachable nitrate losses. The combination of NT (no soil removal) and presence of surface crop residues under conservation practices result in accumulation of SOM in the topsoil or its stratification (Díaz Zorita and Grove, 2002). Franzluebbers (2002) proposed the use of the degree of stratification ratio of TOC as an indicator of soil quality (TOC concentration 0–5 cm/5–10 cm or 0–5 cm/10–20 cm depth), as topsoil SOM is essential for erosion control, infiltration and water conservation.

Tillage systems and machinery traffic cause changes in topsoil bulk density compared with areas of native vegetation. This determines that when calculating soil mass under both those situations, higher soil mass values can be found at a given depth, in a cropping area, due to compaction (Jantalia, 2005; Alvarez et al., 2009). Ignoring this fact when quantifying C and N stocks, can lead to misinterpretation of results (Ellert and Bettany, 1995; Neill et al., 1997). According to Du et al. (2010) it is important to increase sampling depth, to allow assessment of C input changes with depth due to different root distribution patterns, consequence of tillage practice and/or crop sequence. Sampling depths > 30 cm should be considered to be able to detect effects of conservation tillage on soil TOC and TN.

The aim of this study was to evaluate the effect of different tillage systems and crop sequences on the distribution and stock of TOC and TN. We hypothesized that NT promotes surface TOC and TN accumulation, but does not affect the C and N stocks, when compared with reduced tillage. In addition, the incorporation of maize in the crop sequence increases TOC and TN stocks when compared with soybean monoculture.

2. Materials and methods

2.1. Experimental site

Measurements were carried out within the framework of a long-term experiment that started in 1995, in the INTA Manfredi Experimental Station, Córdoba, Argentina (31.5° S, 63.5° W, 292 m asl), in the semiarid Pampa. The soil is a deep, well drained, developed on silty-loam materials Entic Haplustoll (Haplic Chernozem), with an available water storage capacity of 307 mm up to 200 cm depth (Jarsun et al., 1987). Particle soil analysis of surface horizon is: clay 167 g kg^{-1}, silt 687 g kg^{-1} and sand 146 g kg^{-1} (Jarsun et al., 1987). Average rainfall in the region is 757 mm yr^{-1}, with 80% occurring during spring and summer. Average annual temperature is 16.6 °C, with an average of 9.5 °C in the coldest month and 23.4 °C in the hottest (Jarsun et al., 1987).

A 110 m × 35 m bifactorial experiment was designed. One factor was the tillage system, with the following levels: no-tillage with chemical fallow (NT), no-tillage with a triticale (*Triticosecale*) cover crop (NTcc) and reduced tillage (RT) with a disk harrow as the main tillage practice. Cropping sequence was the other factor with two levels: soybean (*Glycine max* (L)) monoculture (sy-sy) and soybean–corn (*Zea mays*) rotation (sy-mz). The combination of the different levels resulted in 6 treatments: sy-sy RT (n = 3), sy-mz RT (n = 4), sy-sy NT (n = 3), sy-mz NT (n = 4), sy-sy NTcc (n = 3) and sy-mz NTcc (n = 4).

The RT treatment included a disk harrow tillage at the end of winter and soil refinement with a vibro-cultivator before crop sowing. In the NT treatment weeds were herbicide-controlled during fallow. The cover crop (triticale) was sown after soybean to generate more surface residue cover: every year in the soybean–soybean sequence (sy-sy NTcc), and every other year (sowing the cc after soybean and a chemical fallow after the corn crop) in the soybean–maize sequence (sy-mz NTcc). The cc was killed with herbicide at the stem elongation phenological stage.

2.2. Sampling and analytical determinations

2.2.1. Total organic carbon and total nitrogen

Fifteen years after the experiment had started, two composite samples per replication were taken. Each sample consisted of 15 sub-samples, taken at 0–5, 5–10, 10–20, 20–30, 30–50, 50–70, 70–100 cm depths. TOC and TN determinations were performed with a complete-combustion auto-analyzer (LECO Corporation, St. MI, USA). Prior to the analysis, carbonate presence/absence was determined qualitatively with hydrochloric acid in each sample. When the reaction was positive, decarbonation with sulfurous acid was carried out, following Skjemstad and Baldock (2008).

2.2.2. Bulk density

Bulk density was determined by the core method (Burke et al., 1986). The core was 5 cm high and 100 cm^3 volume. Within each experimental unit two samples were taken at the following depths: 0–5, 5–10, 10–20, 20–30 cm. At deeper layers (30–50, 50–70, 70–100 cm) quintuplicate samples were taken only in two treatments because when clay content does not increase significantly greatly in depth (approximately 100 g kg^{-1}), management effect is considered minimal (Diekow et al., 2005).

2.2.3. Unit mass correction

To compare soil TOC and TN stocks (kg ha^{-1}) a correction was made to bring soil profiles to mass-equivalent up to the depth that was being evaluated (Neill et al., 1997), that can be expressed mathematically (Sisti et al., 2004, Eq. (1)).

$$C_s = \sum_{i=1}^{n-1} C_{Ti} + \left[M_{Tn} - \left(\sum_{i=1}^{n} M_{Ti} - \sum_{i=1}^{n} M_{Si} \right) \right] C_{Tn} \quad (1)$$

where C_s is total soil carbon stock (Mg ha^{-1}) to a depth where soil mass is the same as in the reference profile. $\sum_{i=1}^{n-1} C_{Ti}$ is the summed total carbon content (Mg ha^{-1}) from layer 1 (surface) to layer "$n-1$" (penultimate) of the treatment profile, "M_{Tn}" is the soil mass in the deepest layer in the treatment profile, $\sum_{i=1}^{n} M_{Ti}$ is the summed soil mass (Mg ha^{-1}) from layers 1 (surface) to "n" (deepest layer) in the soil profile of a given treatment, $\sum_{i=1}^{n} M_{Si}$ is the summed soil mass (Mg ha^{-1}) from layers 1 (surface) to "n" (deepest layer) of the reference soil profile, "C_{Tn}" is the carbon content (Mg Mg^{-1} soil) of the soil profile in the deepest layer of a given treatment.

2.2.4. Stratification ratios

The stratification ratios (S-ratio) were calculated as the ratio between TOC concentration (g kg^{-1}) at 0–5 cm and at 5–10 or 10–20 cm depth (Franzluebbers, 2002).

Table 1
Total organic carbon at different soil depths.

Crop sequence	Tillage system	Total organic carbon (g kg^{-1} soil)													
		0–5 cm	SE	5–10 cm	SE	10–20 cm	SE	20–30 cm	SE	30–50 cm	SE	50–70 cm	SE	70–100 cm	SE
sy-mz	RT	13.8	0.33	12.4	0.30	9.5b	0.24	7.2	0.27	4.9	0.27	3.2	0.08	2.6	0.06
	NT	19.2	0.63	11.4	0.24	9.9ab	0.10	7.9	0.16	4.4	0.25	3.3	0.07	3.1	0.24
	NTcc	20.7	0.52	12.5	0.23	10.5a	0.11	8.3	0.26	5.2	0.15	3.4	0.08	2.9	0.05
sy-sy	RT	12.6	0.34	12.0	0.23	9.9ab	0.26	7.5	0.31	4.6	0.23	3.3	0.14	3.1	0.25
	NT	16.2	0.71	10.3	0.38	9.2b	0.33	7.4	0.27	4.7	0.11	3.1	0.11	2.9	0.13
	NTcc	17.8	0.66	10.9	0.27	9.3b	0.15	7.7	0.13	4.8	0.10	3.3	0.09	2.8	0.08
sy-mz		17.9a	0.68	12.1a	0.17	10.0	0.12	7.8a	0.16	4.8a	0.14	3.3a	0.05	2.9a	0.09
sy-sy		15.5b	0.62	11.1b	0.23	9.5	0.16	7.6a	0.14	4.7a	0.09	3.2a	0.06	2.9a	0.09
	RT	13.2c	0.29	12.2a	0.20	9.7	0.18	7.3b	0.20	4.7a	0.18	3.2a	0.07	2.8a	0.12
	NT	17.7b	0.60	10.9b	0.25	9.6	0.18	7.7ab	0.15	4.6a	0.15	3.2a	0.06	3.0a	0.15
	NTcc	19.3a	0.56	11.8a	0.27	9.9	0.18	8.0a	0.17	5.0a	0.11	3.4a	0.06	2.9a	0.04
		p-Value													
Crop sequence × tillage system		NS		NS		(0.0017)		NS		NS		NS		NS	
Crop sequence		(0.0001)[a]		(0.0001)		(0.0051)		NS		NS		NS		NS	
Tillage system		(<0.0001)		(0.0002)		NS		(0.0269)		NS		NS		NS	

SE: standard error; NS: not significant ($P > 0.05$). Different letters indicate significant differences within each column for factors or their interaction as appropriate; Tukey test ($P < 0.05$). sy-mz, soybean–maize; sy-sy, soybean monoculture; RT, reduced tillage; NT, no-tillage; NTcc, no-till with a cover crop.

2.3. Statistical analysis

ANOVA was used for fixed effect models and significant differences were tested with Tukey mean comparison test ($P \leq 0.05$) (Di Rienzo et al., 2012). Simple and multiple (Stepwise method) regressions were performed to determine the relationships between variables (Neter and Wasserman, 1974).

3. Results

3.1. Total organic carbon and total nitrogen concentration

Total organic carbon concentration in the topsoil 5 cm showed significant differences ($P \leq 0.001$) between cropping sequence and tillage systems (Table 1), with higher values under sy-mz rotation than under soybean monoculture and with NTcc > NT > RT. Significant differences were also found at 5–10 cm depth, showing the same tendency for cropping sequence, while for tillage system the ranking was NTcc = RT > NT. In the 10–20 cm layer a significant interaction ($P = 0.0017$) between the two factors was found, but the least significant difference was minimal when percentage TOC concentration is considered. A significant effect of tillage system ($P \leq 0.05$) was also found at 20–30 cm depth, where NTcc and NT showed the highest TOC concentrations, although no difference of the latter with RT was found. No significant differences among treatments or interaction between factors were found at greater depths (30–50, 50–70 and 70–100 cm).

TN concentrations (g kg^{-1}) (Table 2) showed significant differences ($P \leq 0.001$) between tillage systems at 0–5 cm with RT < NT < NTcc. At 5–10 cm depth, significant differences ($P \leq 0.001$) were found, with RT = NTcc > NT. No differences for any of the two factors were found at greater depths. TOC and TN values showed a strong correlation ($r = 0.97$), with a 9.14 average C/N relationship. A decrease in the soil C/N relationship was observed at greater depths, to a value of 7.5 between 30 and 100 cm depth.

3.2. Total organic carbon and total nitrogen stock

C and N stocks were calculated for 0–30, 0–50, and 0–100 cm soil depths (Tables 3 and 4). A significant interaction ($P \leq 0.05$) between crop sequence and tillage system was found for TOC stock up to 30 cm. The treatment combinations sy-mz NTcc and sy-mz NT had the largest TOC stock, treatments under RT (sy-sy and sy-mz) the lowest and sy-sy NT and sy-sy NTcc, intermediate values. At 0–50 cm, TOC stock differed between tillage systems with

Table 2
Nitrogen at different soil depths.

Crop sequence	Tillage system	Total organic nitrogen (g kg^{-1} soil)													
		0–5 cm	SE	5–10 cm	SE	10–20 cm	SE	20–30 cm	SE	30–50 cm	SE	50–70 cm	SE	70–100 cm	SE
sy-mz		1.62a	0.06	1.12a	0.02	0.88a	0.01	0.83a	0.02	0.64a	0.02	0.46a	0.02	0.42a	0.02
sy-sy		1.55a	0.07	1.10a	0.04	0.89a	0.01	0.86a	0.01	0.61a	0.02	0.44a	0.02	0.38a	0.01
	RT	1.25c	0.03	1.19a	0.02	0.90a	0.02	0.83a	0.02	0.58a	0.02	0.43a	0.02	0.38a	0.02
	NT	1.67b	0.06	1.03b	0.03	0.87a	0.01	0.86a	0.01	0.63a	0.04	0.44a	0.02	0.41a	0.02
	NTcc	1.84a	0.04	1.12a	0.03	0.89a	0.01	0.85a	0.01	0.65a	0.02	0.48a	0.02	0.41a	0.02
		p-Value													
Crop sequence × tillage system		NS		NS		NS		NS		NS		NS		NS	
Crop sequence		NS		NS		NS		NS		NS		NS		NS	
Tillage system		(<0.0001)		(0.0026)		NS		NS		NS		NS		NS	

SE: standard error; NS: not significant ($P > 0.05$). Different letters indicate significant differences within each column for factors or their interaction as appropriate; Tukey test ($P < 0.05$). sy-mz, soybean–maize; sy-sy, soybean monoculture; RT, reduced tillage; NT, no-tillage; NTcc, no-till with a cover crop.

Table 3
Total organic carbon stock as mass equivalent (Mg ha^{-1}) at depths of up to 30, 50 and 100 cm.

Crop sequence	Tillage system	Soil C stock (Mg ha^{-1})					
		0–30 cm	S.E.	0–50 cm	S.E.	0–100 cm	S.E.
sy-mz	RT	36b	0.90	47	1.03	61	1.12
	NT	41a	0.59	52	0.91	67	1.31
	NTcc	42a	0.49	55	0.78	70	0.87
sy-sy	RT	36b	0.89	47	1.21	62	1.43
	NT	37b	1.34	48	1.55	63	1.38
	NTcc	39ab	0.76	51	0.92	66	1.12
				Crop sequence			
sy-mz		40	0.68	51a	0.80	66a	0.99
sy-sy		37	0.63	49b	0.77	64b	0.82
				Tillage system			
	RT	36	0.62	47b	0.75	62b	0.87
	NT	39	0.82	50b	0.92	65a	1.07
	NTcc	41	0.61	53a	0.78	68a	0.84
				p-Value			
Crop sequence × tillage system		(0.034)[a]		NS		NS	
Crop sequence		(<0.001)		(<0.001)		(0.031)	
Tillage system		(<0.001)		(<0.001)		(<0.001)	

SE: standard error; NS: not significant ($P > 0.05$). Different letters indicate significant differences within each column for factors or their interaction as appropriate; Tukey test ($P < 0.05$). sy-mz, soybean–maize; sy-sy, soybean monoculture; RT, reduced tillage; NT, no-tillage; NTcc, no-till with a cover crop.

NTcc > NT = RT, and between cropping sequences, with sy-mz > sy-sy. Considering the total profile depth (0–100 cm), significantly higher TOC was found under sy-mz than under sy-sy ($P \leq 0.05$) with RT systems showing significantly lower ($P \leq 0.001$) TOC stock than NT and NTcc, which did not differ.

The TN stock results showed a significant interaction between crop sequence and tillage system ($P \leq 0.05$) in the first 30 cm: sy-sy NTcc presented the highest TN stock values and the RT system (both sy-sy and sy-mz) the lowest (Table 4). The interaction was affected by the no-till treatments because, under the sy-mz sequence, NT did not differ from NTcc while under the sy-sy sequence it did. Tillage system was the only factor that had a significant effect ($P \leq 0.001$) on TN stock up to 50 cm depth, with NTcc = NT > RT, the same behavior being observed up to 100 cm depth. No significant differences were found between cropping sequences.

3.3. Total organic carbon stratification ratios

Carbon stratification ratios (S-ratios) calculated from TOC concentrations between 0–5/5–10 and 0–5/10–20 cm depths showed the same trends (Fig. 1a and b). The 0–5/5–10 ratio had

Table 4
Total nitrogen stock as mass equivalent (Mg ha^{-1}) at depths of up to 30, 50 and 100 cm.

Crop sequence	Tillage system	Soil N Stock (Mg ha^{-1})					
		0–30 cm	S.E.	0–50 cm	S.E.	0–100 cm	S.E.
sy.mz	RT	3.5c	0.10	4.9	0.10	6.8	0.16
	NT	3.9ab	0.03	5.4	0.12	7.6	0.18
	NTcc	3.9ab	0.04	5.5	0.06	7.8	0.14
sy-sy	RT	3.7bc	0.04	5.1	0.13	7.0	0.17
	NT	3.7bc	0.08	5.2	0.13	7.3	0.10
	NTcc	4.0a	0.07	5.4	0.07	7.5	0.08
				Crop sequence			
sy-mz		3.8	0.05	5.3a	0.08	7.3a	0.13
sy-sy		3.7	0.05	5.2a	0.07	7.4a	0.09
				Tillage system			
	RT	3.6	0.06	5.0b	0.08	6.9b	0.12
	NT	3.8	0.04	5.3a	0.09	7.4a	0.11
	NTcc	3.9	0.04	5.5a	0.05	7.7a	0.09
				p-Value			
Crop sequence × tillage system		(0.037)[a]		NS		NS	
Crop sequence		NS		NS		NS	
Tillage system		(<0.001)		(<0.001)		(<0.001)	

SE: standard error; NS: not significant ($P > 0.05$). Different letters indicate significant differences within each column for factors or their interaction as appropriate; Tukey test ($P < 0.05$). sy-mz, soybean–maize; sy-sy, soybean monoculure; RT, reduced tillage; NT, no-tillage; NTcc, no-till with a cover crop.

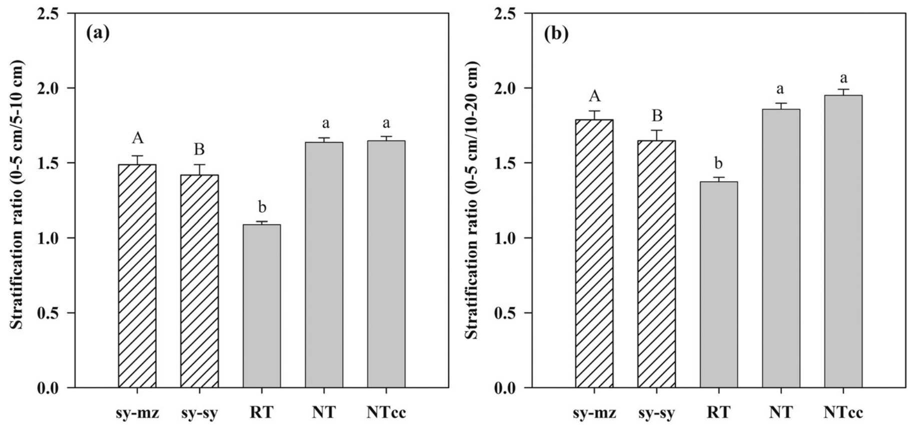

Fig. 1. Carbon stratification ratios: (a) 0–5/5–10 cm, (b) 0–5/10–20 cm for different crop sequence and tillage system. Different capital letters indicate significant differences (Tukey, $P \leq 0.05$) between cropping sequence and lowercase letters between tillage systems within each stratification ratio. sy-mz, sy-maize; sy-sy, soybean monoculture; RT, reduced tillage; NT, no-tillage, NTcc, no-till with a cover crop. Bars indicate standard error.

values ranging between 1.0 and 1.7, NTcc and NT being equal and statistically greater than RT. The sy-mz cropping sequence had a higher stratification ratio than sy-sy ($P \leq 0.01$). Total organic carbon S-ratios between 0–5/10–20 cm soil depths presented higher absolute values (1.37–1.95) but with the same differences between tillage systems (NTcc = NT > RT, $P \leq 0.001$) and between cropping sequences (sy-mz > sy-sy, $P \leq 0.001$).

TOC stocks up to 100 cm depth was lineally associated to the S-ratio (0–5 cm/5–10 cm; 0–5/10–20 cm) as shown in Fig. 2a and b. S-ratio explained around 40% of TOC stock variability. The crop sequence as a dummy variable (sy-sy = 0; sy-mz = 1) could not be included in a multiple regression model ($P > 0.15$). Highest S-ratios and the greater TOC stock values were observed in the NTcc treatments, followed by NT and finally RT.

4. Discussion

Total organic carbon and TN concentrations in the topsoil 10 cm were higher under NT than under RT (Tables 1 and 2). Similar results were obtained for U.S. soils by Díaz Zorita and Grove (2002) and Franzluebbers (2002), who argued that, as NT management maintains surface residues, there is an increase in TOC and TN concentrations in the first centimeters of the soil profile. Similar responses have been found in other studies within semiarid Argentina (Nuñez Vázquez et al., 1996; Díaz Zorita et al., 2004; Apezteguía, 2005) and in other sub-regions of the Argentine Pampas (Alvarez et al., 2009).

Cover crop incorporation further increased TOC and TN concentrations in the 0–5 cm topsoil. Wander and Traina (1996), in a soybean–corn sequence, observed significantly higher organic matter concentration when a winter cereal cover crop was included. This increase in surface TN concentration can be related to N retention, which would avoid potentially leachable nitrate losses (Reicosky and Archer, 2005). The C/N relationship showed similar average values to those reported by Batjes (1996) for Chernozem soils; the ratio decreased with depth.

Total organic carbon stock up to 50 cm depth showed differences between tillage systems, NTcc having 3 Mg ha^{-1} and 6 Mg ha^{-1} more than NT and RT, respectively. However up to 100 cm depth, RT only differed from NT systems. NT treatments had 5 Mg ha^{-1} more than RT. Lower TOC stocks under RT than under NT and NTcc can be attributed to tillage practices that favor organic matter mineralization through higher temperature and lower physical protection causing nutrient release and C losses as CO_2 (Abril et al., 2005). However for SOM to accumulate, in addition to an increase in crop C residues contribution, it is necessary to have extra N input (Sisti et al., 2004) or less N losses. Total organic carbon stocks under NTcc did not differ significantly from those under NT. The same differences in TOC stocks between management systems were observed below 30 cm depth, which is consistent with results obtained by Sisti et al. (2004) and VandenBygaart et al. (2011). For this reason, some authors consider that determining TOC stock up to a depth of 15 cm (VandenBygaart et al., 2011) or 30 cm (Du et al., 2010) is sufficient to detect differences between management systems. However, if the objective is to estimate the balance between carbon sequestration and greenhouse gas emissions, it is important to sample up to greater depths (Dou et al., 2007; Jantalia et al., 2007).

Differences in TOC stock due to management system both up to 50 and up to 100 cm depths (approximately 2 Mg ha^{-1} more under mz-sy than under soybean monoculture) can be explained by the greater residue contribution of the corn crop in the sy-mz sequence (Alvarez and Steinbach, 2012). For the mean yields of the experiment, maize would contribute with 7178 Mg ha^{-1} yr^{-1} of dry matter as crop residue, while soybean with 3373 Mg ha^{-1} yr^{-1} of dry matter.

Tillage system had a greater impact on TOC stocks than crop sequence. Up to 100 cm depth, the NT treatments accumulated 333 kg ha^{-1} yr^{-1} of TOC more than RT, while the sy-mz sequence accumulated only 133 kg ha^{-1} yr^{-1} more than soybean monoculture. At 0–30 cm depth, the NT treatments had 267 kg ha^{-1} yr^{-1} of TOC more than the RT treatment. In soils of southeastern U.S. (in a hot and humid climate), Franzluebbers (2010) has estimated a sequestered TOC rate of 450 kg ha^{-1} yr^{-1}, whereas VandenBygaart et al. (2008) for Canadian soils estimated between 60 and 160 kg ha^{-1} yr^{-1} more TOC in NT than in tilled soils. Steinbach and Alvarez (2006), analyzing the rate of TOC stock change between NT and RT in Argentine Pampa soils, found that the relative annual increase in NT was around 460 kg ha^{-1} yr^{-1}, and that the rate of change is greater between 4 and 9 years after starting NT practices.

Total nitrogen stocks up to 50 and 100 cm depths showed a trend similar to that of TOC stock, with NT treatments having higher TN values than RT (43 kg ha^{-1} yr^{-1} more in NT treatments than RT up 100 cm depth). Similar tendencies were observed in southeastern Brazilian (Sisti et al., 2004) and in southern USA soils (Dou et al., 2007). Crop sequences had no impact on TN stock.

Total organic carbon S-ratios after 15 years were around 1.6 under NT and lower under RT. Similar values were found in

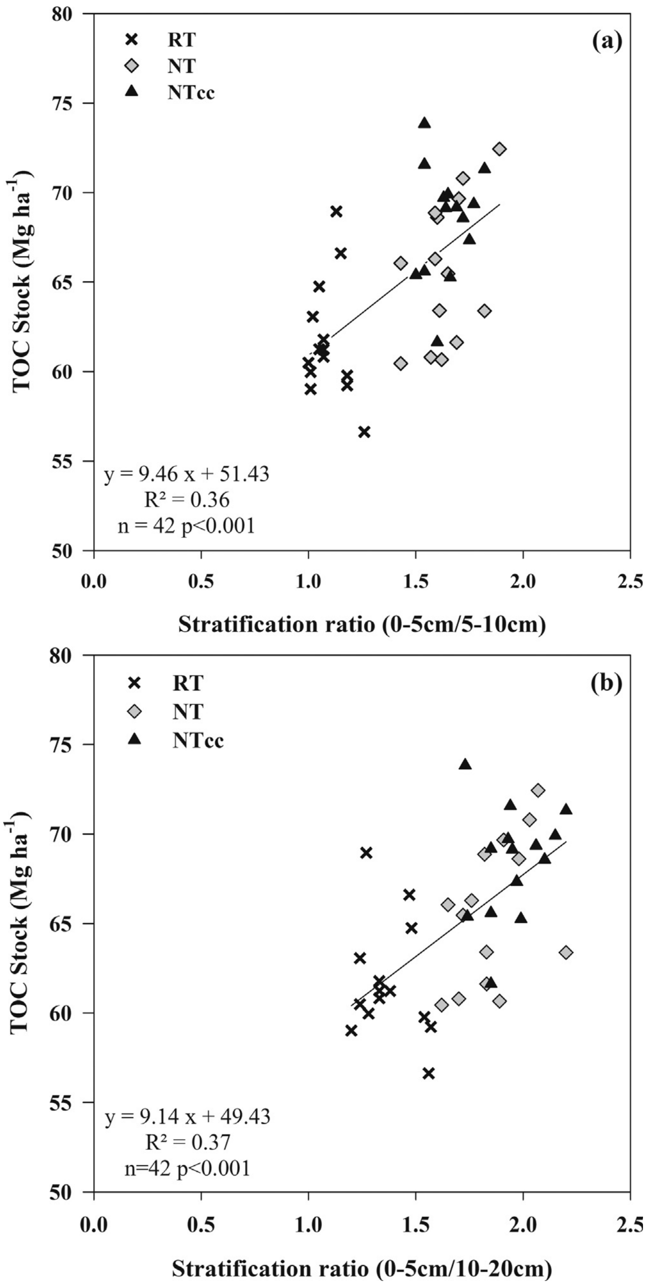

Fig. 2. (a) Relationship between corrected TOC stock up to a depth of 100 cm per unit mass and carbon stratification ratios for (a) 0–5/5–10 and (b) 0–5/10–20 cm, for the different tillage systems: (×) reduced tillage, (◇) no-tillage, (▲) no-till with cover crop.

semiarid Argentina after 12 years of treatment by Díaz Zorita et al. (2004). According to Franzluebbers (2002), stabilized systems under conservation management are those with >2.0 TOC S-ratios. Several other authors also reported S-ratio TOC values >2.0 under NT systems and <2.0 under conventional tillage (plow or disk as primary practice) (Díaz Zorita and Grove, 2002; Hernanz et al., 2009; Du et al., 2010). All S-ratios obtained in our study were <2.0; the highest corresponded to the ratio 0–5/10–20 cm depth. Sá et al. (2009) found a strong positive correlation between TOC S-ratio (0–5/5–10 cm) and TOC stock up to 40 cm depth. In our study we found a weakness relationship between up to 100 cm depth TOC stock and the S-ratios of the 0–5 cm/5–10 cm or 0–5/10–20 cm layers. Functions fitted to these relationships (Fig. 2a and b) only explained 40% of variation, with 60% of carbon stock unexplained. Fit did not improve when considering the crop sequences as a dummy variable. This indicates that S-ratio was influenced by both crop sequences and tillage systems. This agrees with ANOVA analysis which also showed significant effect of these factors on S-ratio (Fig. 1a and b). The highest TOC S-ratios were obtained in the treatments with higher stocks (NTcc ≥ NT ≥ RT), which coincides with Franzluebbers (2009) and Causarano et al. (2008) results for southeastern U.S. soils. Changes in TOC concentration after soils were brought into NT management allow us to infer that, in the studied soils, the soil is acting as C sink under NT compared with its RT management. NT has been often considered a practice to reduce net emissions of greenhouse gases.

5. Conclusions

As we hypothesized NT promotes surface TOC and TN accumulation, but also increases TOC and TN stocks when compared with RT. We also observed the importance of include maize in the crop sequence in order to increase TOC stock, when compared with soybean monoculture. Tillage system has a greater impact on TOC stock than crop sequence, at least under the conditions of this study. The TOC S-ratio explained only a part of the C stock variability.

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